UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND APPLIED SCIENCE

THE EFFECTS OF LOW FREQUENCY Z-AXIS WHOLE-BODY VIBRATION ON PERFORMANCE OF A COMPLEX MANUAL CONTROL TASK

by

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ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE

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Doctor of Philosophy

THE EFFECTS OF WHOLE-BODY VIBRATION ON PERFORMANCE

OF A COMPLEX MANUAL CONTROL TASK

By Ronald Walter McLeod

This thesis investigates continuous manual control performance during exposure to z-axis whole-body vibration at frequencies between 0.5 and 10.0 Hz. The task involved first-order pursuit tracking with a simultaneous discrete target acquisition task. A major aim of the work was to determine the mechanisms underlying any vibration-induced impairment which occurred.

The literature is first reviewed (Chapter 2) and a model is presented summarising the mechanisms by which vibration has been suggested to disrupt performance (Chapter 3). Six experiments are then reported. Experiment 1 (Chapter 5) measured vibration-induced activity at the head, hand and at the output of the system dynamics. The results are discussed with reference to the mechanisms which could disrupt performance. Experiment 2 (Chapter 6) investigated performance during exposure to vibration at frequencies from 0.5 to 5.0 Hz. The magnitude of performance disruption was approximately constant at vibration frequencies below 2 Hz, and increased with the frequency of vibration to 5.0 Hz. Experiments 3 (Chapter 7) and 4 (Chapter 8) showed that the disruption at frequencies above 2.0 Hz could be attributed to visual impairment arising from relative translational movement between subjects` eyes and the display: collimating the display removed the impairment. Linear spectral analysis techniques were used to separate root-mean-square (rms) tracking error into components linearly and not linearly correlated with movements of the target. Changes in total rms error were mainly accompanied by changes in the linear components: closed-loop system transfer functions showed increased phase lags between movements of the target and the response of the controlled element. In experiment 5 (Chapter 9), three simple tasks were used to isolate non-visual mechanisms of disruption. The results suggested that whole-body vibration at 0.5 and 4.0 Hz could interfere with neuro-muscular processes. The results of experiment 5, and the increased phase lags observed in experiment 4, indicate changes in the way the task was performed during vibration: these are described as secondary vibration effects.

Experiment 6 investigated whether the effect of vibration on the system studied would be time-dependent. One-octave-band random vibration centred on 4 Hz was presented at a magnitude considerably above the ISO 2631 (1985) `fatigue-decreased-proficiency` limit for 180 minute vibration exposures. Performance declined with time, but vibration did not alter the time-dependence. The effect of duration was reduced when the task was performed over the entire duration on a second occasion.

It is concluded that impairments in continuous tracking performance during whole-body vibration exposure were mainly caused by interference with visual and neuro-muscular processes. The results also show secondary effects which may represent adaptive changes in performance during vibration. The behavioural model developed in Chapter 3 is used to summarise the mechanisms which were shown to be important, and to indicate other effects which could occur. Some suggestions for further research are offered.

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CONTENTS

		page number
Chapter 1	Introduction, Aims and Organisation	1
	1.0 General Introduction	1
	2.0 Aims	2
	3.0 Organisation	4
Chapter 2	Literature Review: The effects of translational whole-body vibration on manual control performance.	6
	1.0 Introduction	6
	2.0 Vibration variables	8
	2.1 Vibration Frequency in one axis	8
	2.1.1 Sinusoidal Vibration	8
	2.1.1.1. Vertical Axis	8
	(i) Constant Acceleration	8
	(ii) Constant Displacement	10
	(iii) Other studies	11
	(iv) Summary	13
	2.1.1.2 Horizontal Axes	14
	(i) Constant Acceleration	14
	(ii) Other studies	16
	(iii) Summary	16
	2.1.2 Non-sinusoidal Vibration	17
	2.2 Vibration Axis	19
	2.2.1 Comparison of Single-Axis Effects	19
	2.2.2 Multi-Axis Environments	21
	2.2.3 Summary	22
	2.3 Vibration Magnitude	22
	2.3.1 Sinusoidal Vibration	23
	2.3.2 Non-Sinusoidal Vibration	25
	2.3.3 Summary	26
	2.4 General Summary of the Effect of Vibration Variables	27

		page number
Chapter 2 (continued)	3.0 System Variables	28
	3.1 Control Stick Variables	28
	3.1.1 Stick Location and Arm Supports	29
	3.1.2 Control Shape	30
	3.1.3 Mechanical Characteristics	31
	3.1.4 Control Gain	33
	3.2 System Dynamics	35
	3.3 Displays	36
	3.4 Task Difficulty	37
	3.5 Adaptive Systems	38
	4.0 Mechanisms	40
	4.1 Vibration Breakthrough	41
	4.2 Visual Effects	43
	4.3 Neuro-muscular Interference	46
	4.4 Central Effects	51
	4.5 Summary of Mechanisms	53
	5.0 Exposure Duration	53
	5.1 Studies Showing Clear Time-Dependent Effects	56
	5.2 Studies Suggesting Time-Dependent Effects	59
	5.3 Studies Showing no Time-Dependent Effects	61
	5.4 Summary	61
	6.0 Summary of the Literature Review	63
Chapter 3	Models	64
	1.0 Introduction	64
	1.1 Adaptation and Strategies	64
	2.0 Models of Manual Control Performance	67
	2.1 The Optimal Control Model	67
	2.2 Pursuit Tracking	68
	3.0 Model of the Effects of Vibration on Manual Control Performance	73
	3.1 A Taxonomic Model	73
	3.2 Biodynamic Models	76
	4.0 A Behavioural Model	81
	4.1 Description	81
	4.1.1 Without Vibration	81
	4.1.2 Effects of Vibration	88
	5.0 Summary	93

		page number
Chapter 4	Introduction to Experimentation	94
	4.1 Tasks and Control System	94
	4.1.1 Tasks	96
	4.1.2 Forcing Functions	98
	4.1.3 Viewing Conditions	100
	4.1.4 Control and Arm Support	100
	4.1.5 System Dynamics	104
	4.2 Vibrators, Seating and Signal Conditioning Equipment	108
	4.3 Measurements	112
	4.3.1 Simple Performance Measures	112
	4.3.1.1 Probability Measures	112
	4.3.1.2 Total root-mean-square tracking Error	114
	4.3.2 Spectral Analysis	114
	4.3.2.1 Theory	115
	4.3.2.2 Measurement Procedures	124
	4.3.2.3 Spectral Estimates	126
	4.4 Subjects	128
Chapter 5	Experiment One: The transmission of vibration to the head, control and controlled element	131
	1.0 Introduction	131
	2.0 Method and Procedure	133
	3.0 Results	139
	3.1 Sinusoidal Vibration	140
	3.1.1 RMS data	148
	3.2 Broad-band Random Vibration	152
	3.3 Arm Support	160
	4.0 Discussion	160
	4.1 Activity at the Head	163
	4.2 Activity at the Control and Controlled Element	164
	4.3 Effect of the Arm Support	165
	5.0 Conclusions	165

		page number
Chapter 6	Experiment Two: The effect of sinusoidal vibration at frequencies from 0.5 to 5.0 Hz on performance of the complex manual control task.	167
	1.0 Introduction	167
	2.0 Method and Procedure	168
	2.1 Training	173
	3.0 Results and Discussion	174
	3.1 Continuous Task	174
	3.2 Discrete Task	182
	4.0 Conclusions	188
Chapter 7	Experiment Three: The effect of display collimation at vibration frequencies from 2.5 to 5.0 Hz.	190
	1.0 Introduction	190
	2.0 Method and Procedure	192
	3.0 Results and Discussion	195
	4.0 Conclusions	202
Chapter 8	Experiment Four: The effect of display collimation and vibration waveform at frequencies from 0.5 to 10.0 Hz.	204
	1.0 Introduction	204
	1.1 Display Collimation	204
	1.2 Vibration Waveform	205
	1.3 Components of Tracking Error	206
	2.0 Method and Procedure	208
	2.1 Tasks	208
	(i) System Dynamics	208
	(ii) Forcing Functions and Control Gain	209
	2.2 Performance Measures and Signal Conditioning	209
	2.3 Vibration	211
	2.4 Procedure	211
	3.0 Results and Discussion	216
	3.1 Main Effects of Independent Variables	216

		page number
Chapter 8 (contined)	3.1.1 Continuous Task	216
	3.1.2 Discrete Task	226
	3.2 Error Components	226
	3.3 Transfer Functions	242
	4.0 Summary and Conclusions	253
Chapter 9	Experiment Five: Induced control activity during exposure to sinusoidal vibration at 0.5 and 4.0 Hz.	256
	1.0 Introduction	256
	1.1 Tasks	257
	1.1.1 Task A	257
	1.1.2 Task B	260
	1.1.3 Task C	263
	1.2 Arm Support	264
	2.0 Method and Procedure	264
	3.0 Results	269
	3.1 The Effect of Task within Vibration Frequency	271
	3.2 The Effect of Vibration Frequency within Tasks	279
	4.0 Discussion	284
	5.0 Conclusions	291
Chapter 10	Experiment Six: The effect of exposure duration on complex task performance	293
	1.0 Introduction	293
	2.0 Method and Procedure	295
	2.1 Subjects	295
	2.2 Control Gain and Viewing Conditions	295
	2.3 Forcing Functions	298
	2.4 Vibration and Seating	298
	2.5 Data Recording and Acquisition	299
	2.6 Choice Reaction-Time Task and Questionnaires	300
	2.7 Procedure	301

		page number
Chapter 11 (continued)	3.0 Results	303
	3.1 Performance Data	305
	3.1.1 Probability Data	306
	3.1.2 RMS Error	312
	3.1.3 Transfer Functions	313
	3.1.4 Error Spectra	326
	3.2 Questionnaire Results	328
	3.2.1 Questionnaires A and B	328
	3.2.2 Questionnaire B	333
	3.2.3 Questionnaire C	336
	3.3 Choice Reaction-Time Task	339
	4.0 Discussion	341
	4.1 Effect of Duration	341
	4.2 Effect of Vibration	343
	4.3 Effect of Session	344
	5.0 Conclusions	345
Chapter 11	Conclusions and Recommendations	347
	1.0 Summary of Results and Main Conclusions	347
	1.1 Effects of Vibration on Performance	347
	1.2 Mechanisms and the behavioural model	348
	1.2.1 Visual impairment	348
	1.2.2 Neuro-muscular Interference	349
	1.2.3 Secondary Effects	350
	1.2.4 Other Effects	351
	2.0 Recommendations	352
	2.1 Standards	352
	2.2 Future Research	353
	2.2.1 Mechanisms	353
	2.2.2 Secondary Effects	354
	2.2.3 Duration	355
	2.3 Philosophical Considerations	355
	3.0 In Conclusion	356
References		358

page number

Appendices

Appendix A	Co-ordinate System for Axes of Vibration	368
Appendix B	Summary of the Literature	369
	B.1 Studies of Instantaneous Vibration Effects	369
	B.2 Studies of Time-Dependent Vibration Effects	378
Appendix C	Details of the System Dynamics	384
Appendix D	Training Data	389
Appendix E	Computer Programmes	414
Appendix F	Questionnaires	422
Appendix G	Data from Experiment 6	434

CHAPTER ONE

INTRODUCTION, AIMS AND ORGANISATION

1.0 General Introduction

Many engineering systems include humans as essential components in monitoring and controlling system behaviour. Humans are able to detect, store and retrieve information, make complex decisions, and adaptively respond to changing conditions, goals and priorities. These abilities provide a degree of flexibility which cannot be achieved by machinery alone.

Control activities performed by humans range from single operations, which could be considered to be discrete, to sequences of operations, which could be considered to be continuous. Turning a machine on, for example, may involve a discrete operation, such as pressing a button. Steering a car along a winding road, on the other hand, involves continuously acting on the steering wheel to control the heading of the vehicle. This latter type of activity, in which the human continuously acts to control the state of a system, is often known as 'continuous manual control' (Kelley, 1968; Poulton, 1979). Performance of a continuous manual control task is the principal subject of study in this thesis, (throughout the thesis the terms 'manual control' or 'tracking' will refer to continuous manual control).

Manual control performance has been extensively studied both as an example of a perceptual-motor skill and as a simulation of tasks performed in the real world. Tracking tasks have been used, for example, to investigate the ways in which humans acquire skills and adopt strategies in skilled performance (eg., Moray, 1978). They have also been applied in studying effects of external influences, such as sleep deprivation, drugs and environmental stresses on skilled behaviour. Powerful mathematical tools from control theory have been applied to develop quantitative predictive models of the performance of manual control systems (eg., Licklider, 1960; McRuer and Krendel, 1974).

In many systems, and particularly in military systems, extremely precise and reliable manual control performance can be required under often severe conditions of environmental stress. Exposure to heat, noise and vibration are often cited as examples of environmental stressors which can impair human performance. If the ways in which environmental conditions impair performance can be understood, it may be possible to take steps to minimise their influence. To achieve this, it is necessary not only to describe the effects which can occur, but to understand the ways in which the stress interferes with the physiological and psychological processes involved in task performance: ie., it is necessary to understand the mechanisms by which performance of the task is disrupted.

2.0 Aims

The major aim of this thesis was to investigate whether performance of a first-order manual control task (ie., a task in which the human has control over the rate at which the state of the system changes) would be sensitive to disruption by z-axis (vertical) whole-body vibration. If so, the thesis would try to determine the mechanisms responsible. In general, previous research has concentrated on describing the effects which can occur. There is little clear understanding of the mechanisms producing the disruption, particularly with first-order control tasks.

Only a few previous studies investigating effects on manual control performance have presented vibration at frequencies below 2 Hz, and none have investigated vibration at frequencies below 1 Hz. Acknowledging the lack of empirical evidence, the current International Standard on human response to vibration (ISO 2631, 1985), does not define a 'fatigue-decreased-proficiency' boundary for the frequency range from 0.5 to 1.0 Hz. The standard suggests that proficiency may be affected by vertical vibration if the acceleration magnitude exceeds 1.75 ms^{-2} rms in this region. The recently proposed British Standard (BSI, 1986) limits its guidance for effects on human activities to the frequency range from 1 to 80 Hz. Both of these standards provide guidance for motion sickness due to vibration in the frequency range from 0.1 to 0.5 Hz.

There is, therefore, a clear lack of information concerning effects on manual control performance of vibration at frequencies below 1 Hz. The experimental programme reported in this thesis investigated the effects of vibration at frequencies from 0.5 to 10 Hz.

ISO 2631 (1985) defines a time-dependent relationship between exposure to whole-body vibration and performance. The experimental literature, however, provides little support for any simple time-dependence. The proposed British Standard does not include a time-dependence for effects on activities. This thesis describes an experiment investigating whether vibration exposure would alter any time-dependence in performance.

3.0 Organisation

The thesis is presented in 11 chapters. Chapter 2 reviews the literature on effects of translational whole-body vibration on manual control performance.. Chapter 3 describes some models of manual control performance both without vibration and during vibration exposure. This chapter also presents a behavioural model summarising the various mechanisms which have been suggested to mediate effects of vibration. The model provides a basis for the experimental work described in the remainder of the thesis. Chapter 4 describes the equipment, tasks and measures used in the experimental chapters.

The first experiment is reported in chapter 5. The experiment measured the activity which can be expected at the head, at the control and at the output of the system dynamics during exposure to vibration at frequencies below 10 Hz. The results are discussed with reference to the mechanisms which could disrupt performance. Chapter 6 investigates the effects on performance of sinusoidal vibration at frequencies from 0.5 to 5.0 Hz. It was hypothesised that disruption at frequencies above about 2 Hz was caused by impaired visual ability.

Using a collimating lens, the experiment reported in Chapter 7 demonstrated that at vibration frequencies from 2.5 to 5.0 Hz, performance disruption could be attributed to impaired visual ability arising from relative translational movement between subjects' eyes and the display. Chapter 8 used a collimating lens at vibration frequencies from 0.5 to 10.0 Hz. Disruption was not attributed to visual impairment at frequencies below about 2 Hz. Measurements were made of total tracking error, and the components attributable to linear and non-linear operations on the target motion. Closed-loop system transfer functions relating movements of the target to the response of the system were also obtained.

In Chapter 9, an experiment is reported in which subjects performed three simple control tasks with different types of feedback and with or without vibration at 0.5 or 4.0 Hz. The results suggested that vibration interfered with neuro-muscular processes. This Chapter concludes the investigation of the mechanisms responsible for disrupting performance during vibration exposure. The experiment reported in Chapter 10 found that exposure to vibration for 180 minutes did not alter the relationship between performance and task duration.

The results of the experimental programme are summarised in Chapter 11. The main conclusions are summarised, and some suggestions for further research are offered.

CHAPTER TWO

LITERATURE REVIEW: THE EFFECTS OF TRANSLATIONAL WHOLE-BODY VIBRATION ON MANUAL CONTROL PERFORMANCE

1.0 Introduction

This Chapter reviews the published literature on the effects of translational whole-body vibration on manual control performance. Forty seven papers are included.

The review is divided into five Sections. Sections 2, 3 and 4 cover effects assumed to occur instantaneously with the onset of vibration. Section 2 reviews studies investigating effects of vibration variables, such as frequency, magnitude and axis. Section 3 reviews the effect that different system variables, such as control type or system dynamics can have on performance, and Section 4 reviews studies investigating the mechanisms by which vibration affects performance. Each of these sections are arranged into sub-sections on the basis of single topics or variables. For example, if an experiment investigated effects of vibration frequency in two axes with two different controls, the results would be discussed in Section 2 (frequency and axis) and Section 3 (controls). Within Section 2, the paper would be cited in separate sub-sections for effects of frequency and axis. There is therefore necessarily some repetition in the description of experiments. However, this organisation allows effects of single variables to be isolated and compared across different studies.

Within each sub-section of Section 2, studies are further divided according to whether subjects performed zero-order or first- or higher-order tasks. This allows studies which may involve different mechanisms of disruption to be distinguished. Studies investigating time-dependent effects are reviewed in Section 5.

The axes of vibration are described according to the convention x (front-to-back through the human), y (right-to-left), and z (vertical). Appendix A illustrates this convention. The sensitive axes of the control are described as fore-and-aft (equivalent to x-axis vibration) and side-to-side (equivalent to y-axis vibration). The axes of the display are described as vertical (x-axis vibration) and horizontal (y-axis vibration). Units of vibration magnitude are transformed, where necessary, to either ms^{-2} root-mean-square (rms) for acceleration or mm rms for displacement.

Unless otherwise stated, 'effects' described were found to be statistically significant. However, the power of a statistic (ie., its ability to correctly identify a treatment effect) is dependent upon both the size of the effect and the number of subjects used. Therefore the same 'effect' may be 'significant' in one experiment and 'not significant' in another experiment simply because the number of subjects used was different in each case. In very few cases is any indication of the variability of the data provided. Care is therefore needed in interpreting results from different studies, particularly when results appear to contradict each other.

Appendix B provides two tables summarising the literature reviewed. Appendix B1 summarises studies of instantaneous vibration effects and Appendix B2 summarises studies of time-dependent effects.

2.0 Vibration Variables

2.1 Vibration Frequency in one Axis

2.1.1 Sinusoidal Vibration

2.1.1.1 Vertical (z) Axis

Effects of sinusoidal vibration frequency in the z-axis on manual control performance have been investigated in 23 studies. Twelve of these presented the same root-mean-square (rms) acceleration magnitude at each frequency and four presented the same rms displacement. In the remaining seven studies magnitude varied with vibration frequency.

(i) Constant Acceleration

Seven of the studies which presented equal acceleration magnitudes investigated effects on zero-order tasks. The other five investigated effects on more complex first- or higher-order tasks.

Zero-order Tasks

Three studies failed to find a frequency dependence in the effect of z-axis sinusoidal vibration on zero-order tasks. With a simulated driving task, Hornick (1962) observed similar disruption at all vibration frequencies between 1.5 and 5.5 Hz at a magnitude of 2.5 ms^{-2} rms. In two separate studies Lovesey (1971, a and b) presented 2, 5 and 7 Hz vibration at 1.4 ms^{-2} rms, and 2 and 2.7 Hz vibration at 1.8 ms^{-2} rms respectively. All frequencies degraded performance with a side-arm control although there was no consistent frequency dependence. The frequency apparently producing greatest disruption depended upon whether a restraining harness was worn and the amount of force required to operate the control.

The remaining four studies using zero-order tasks demonstrated frequency dependent effects. Shoenberger and Wilburn (1973) found that 2, 6 and 10 Hz vibration at 2.8 ms^{-2} rms reduced performance compared with a static environment. The frequency producing greatest disruption depended upon either the location of the control or the presence of an arm-rest. In both conditions vibration at 6 Hz produced poor performance. Lewis and Griffin (1978) found that 5 Hz vibration was more disruptive than 3.15 Hz vibration at magnitudes up to 2.0 ms^{-2}. In a later study the same authors (1979) observed disruption at 4.0 Hz but not at 16 Hz. Lewis (1981) presented vibration at each preferred one-third-octave centre frequency between 2.5 and 12.5 Hz at 1.5 ms^{-2} rms. Subjects operated a side-arm control with no arm support. Performance was most disrupted by 5 Hz vibration and disruption reduced as the frequency increased or decreased. Trends for the 8 individual subjects were very similar to the averaged results.

In three of the above studies (Lovesey 1971, a and b; Lewis, 1981) greatest disruption occurred in the fore-and-aft axis of the control, corresponding with the vertical axis of the display.

Higher-order Tasks

Of the five studies investigating effects of z-axis sinusoidal vibration frequency on first- or higher-order tasks, only Shoenberger (1970) failed to find a frequency dependence. Shoenberger presented 1, 2, 5, 8 and 11 Hz vibration at both 1.4 and 2.8 ms^{-2} rms. Vibration at all frequencies disrupted performance equally at both acceleration magnitudes.

Lovesey (1971c) investigated effects of 1 and 4 Hz vibration at 0.7 and 1.4 ms^{-2} rms on a second-order task using a miniature side-arm control. At both magnitudes vibration at 4 Hz was more disruptive than at 1 Hz. At approximately equal magnitudes of 1.8 ms^{-2} rms, Harris and Shoenberger (1966) found that 5 Hz vibration produced more disruption on a first-order task than 7 Hz vibration. Both frequencies induced significant disruption, while 11 Hz vibration did not disrupt performance.

Two studies measured both the activity at the output of the control and overall system performance during vibration exposure. Allen, Jex and Magdaleno (1973) measured vibration-induced control activity ('feedthrough') at vibration frequencies of 2, 4, 6, 8 and 10 Hz at 2.8 ms^{-2} rms. Performance was measured with vibration at 2, 6 and 10 Hz at the same magnitude. With two different controls there was a clear maximum in control feedthrough with 4 Hz vibration. The authors estimated that, due to the attenuation of high frequency control activity performed by the system dynamics, display deflections arising from the feedthrough were less than 0.1 mm in amplitude. With two different sets of system dynamics, overall performance showed greatest disruption during vibration at 10 Hz followed by 6 and 2 Hz.

In the other study, Levison (1976) presented vibration at 2, 3.3, 5, 7 and 10 Hz at magnitudes of 1.0 and 2.1 ms^{-2} rms. The effect of vibration frequency was not explicitly discussed although some data were presented. Both control feedthrough and performance data appeared to show interactions between control type, acceleration magnitude and vibration frequency.

As with zero-order tasks, the observed effects in the above studies occurred mainly in the fore-and-aft axis of the control, corresponding with the vertical axis of the display.

(ii) Constant Displacement

All four studies investigating effects of vibration frequency at equal displacements used zero-order tasks. Fraser, Hoover and Ashe (1961) found effects of frequency between 2 and 12 Hz depended upon the amplitude. At displacements above about 2.2 mm rms, 7 and 12 Hz were more disruptive than 2 and 4 Hz. Catterson, Hoover and Ashe (1962) found no effect of vibration frequency between 2 and 15 Hz at 1 mm rms displacement. At 2.3 mm rms however 8 Hz produced greatest disruption and the effect reduced as the frequency increased or decreased. At displacements of 4.4 mm rms, Forbes (1960) found significant disruption at 3, 4 and 5 Hz with 4 Hz producing the greatest effect. Wilson (1974) presented vibration between 2 and 10 Hz at 6.5 mm rms. More disruption occurred at 10 Hz than at 4 or 6 Hz followed by 8 Hz, with 2 Hz producing least effect.

Three of the above studies (Fraser et al, 1961; Forbes, 1960; and Wilson, 1974) again demonstrated greatest effects in the fore-and-aft axis of the control, corresponding to the vertical axis of the display.

(iii) Other Studies

Seven studies investigating effects of vibration frequency on manual control performance have presented different magnitudes at each frequency. Four of these studies investigated effects on zero-order tasks and the other three used first-order tasks. In most cases the authors have attempted to equate the vibration magnitudes presented on the basis of some predicted equivalence of effect.

Zero-order Tasks

Using a zero-order task, Shurmer (1969) found that 2 Hz vibration at 1.76 ms^{-2} rms produced the same amount of error as 4 Hz vibration at 2.47 ms^{-2} rms with two different side-arm controls. He points out however that the accelerations were measured on the vibration rig rather than on the surface of the ejection seat used. The actual acceleration presented may therefore have been different at each frequency. Shurmer also notes that the vibration was not purely sinusoidal but included higher frequency components.

Coermann, Magid and Lange (1962) asked subjects to counteract induced rotational motion of their seats mounted on a platform undergoing translational sinusoidal motion at single frequencies between 2 and 20 Hz. The magnitudes of translational motion presented were based on previously determined 'short-time-tolerances' (Magid and Coermann, 1960). Accelerations were approximately constant at about 3.5 ms^{-2} rms between 4 and 8 Hz and increased with frequency below 4 Hz and above 8 Hz. Results were presented as the change in angular error of the seat per 'g' of translational vibration. Comparisons can therefore be made of the sensitivity of the task per unit acceleration at each frequency. Maximum sensitivity in both the pitch and roll axes of the chair occurred with translational vibration at frequencies between 6 and 8 Hz. These effects remained one minute after the vibration ended. Little effect occurred at frequencies above about 12 Hz.

Lewis (1980) varied acceleration magnitudes at frequencies from 2.5 Hz to 12.0 Hz in a similar manner to Coermann et al. Results showed a very similar frequency dependence to those of Coermann et al, although maximum sensitivity occured at 5 Hz.

Finally, Chaney and Parks (1964) presented vibration in the frequency range from 1 to 27 Hz at four 'subjective reaction levels' from 'definitely perceptible' to 'alarming'. Frequencies between 3 and 8 Hz were only presented at the two lowest magnitudes. The incomplete results obtained showed no effect of frequency on performance with a variety of controls.

Higher-order Tasks

Using a first-order task, Buckhout (1964) presented 5, 7 and 11 Hz vibration at acceleration magnitudes corresponding to 25, 30 and 35% of 'one minute human tolerance levels'. Magnitudes ranged from 1.8 to 2.5 ms^{-2} rms at 5 Hz and from 3.9 to 5.4 ms^{-2} rms at 11 Hz. Minimum disruption occurred at 7 Hz. Harris and Shoenberger (1966) investigated the minimum acceleration magnitude required to produce a significant disruption at 5, 7 and 11 Hz. Independent groups of ten subjects each were used at each frequency. Sensitivity was found to decrease (disruption first occurred at higher acceleration magnitudes) as the frequency decreased. Lewis (1980) presented vibration from 2.5 to 12.0 Hz and observed maximum sensitivity with 5 Hz vibration. With the exception of 2.5 Hz, which was more disruptive than 3.15 Hz, sensitivity reduced with increasing or decreasing frequency.

(iv) Summary of Effects of Vertical Vibration Frequency

No single simple relationship exists between the frequency of z-axis vibration and its effect on tracking performance. More than one study has demonstrated interactions between effects of vibration frequency and the vibration magnitude, the type of control used and whether or not a harness is worn.

While a single relationship may not exist, many tasks are maximally sensitive to z-axis vibration at frequencies between 4 and 8 Hz. Sensitivity reduces outside this range as the frequency either increases, to at least 20 Hz, or decreases, to at least 2 Hz. The frequency band from 4 to 8 Hz is also the range in which transmission of vibration to the shoulders and head is at a maximum (see Chapter 5). The literature suggests that in any particular study, the frequency of greatest effect will depend upon the biodynamic characteristics of the subjects used, the order of the system dynamics and sensitivity of the control, and the viewing distance to the display (see Section 4 discussing mechanisms). The most important exception to the general trend is the study by Shoenberger (1970). There is no obvious reason why this experiment - which was well designed and reported - did not produce a frequency dependent effect between 1 and 8 Hz at 2.8 ms^{-2} rms.

Some of the studies which used relatively high acceleration magnitudes (> 3 ms^{-2} rms) show a high degree of sensitivity at frequencies between 10 and 12 Hz. This may reflect a different mechanism to effects at lower magnitudes.

Finally, z-axis vibration has often been more disruptive in the fore-and-aft axis of the control (which in all studies corresponded to the vertical axis of the display) than in the side-to-side axis. This is true with both zero and first-order tasks and with a variety of controls. (No study used a control which was sensitive directly in the vertical axis).

2.1.1.2 Horizontal Axes

Only five studies have investigated effects of vibration frequency in the horizontal axes. Vibration was presented in the y-axis alone in all five studies and in the x-axis alone in three.

(i) Constant Acceleration

All five studies presented the same acceleration magnitude at each vibration frequency. Three of these investigated simple zero-order tasks and two used first-order tasks.

Zero-order Tasks

In two separate studies, Lovesey investigated effects of vibration frequency in the y-axis on zero-order tasks. At an acceleration magnitude of 1.0 ms^{-2} rms, 2 Hz produced consistently poorer performance than 2.7 Hz in various conditions (1971b). In the other study, 2 Hz vibration at 0.71 ms^{-2} rms produced more disruption than 5 or 7 Hz in the fore-and-aft axis of the control (1971a). In the side-to-side control axis, 5 Hz produced more effect. The statistical significance of these results however was not discussed.

Hornick (1962) presented vibration at frequencies from 1.5 to 5.5 Hz individually in both the x- and y-axes at magnitudes greater than 1.1 ms^{-2} rms. The simulated driving task was only disrupted by 1.5 Hz vibration in the y-axis. In both axes, disruption was said to increase with acceleration magnitude, although changes in frequency dependencies were not discussed.

Higher-order Tasks

Shoenberger (1970) investigated effects of sinusoidal vibration at frequencies from 1 to 11 Hz presented individually in the x- and y-axes on a first-order task. With x-axis vibration, greatest disruption occurred in the fore-and-aft control axis. Most disruption occurred at 1 Hz and least at 11 Hz. In the side-to-side control axis all frequencies except 11 Hz produced significant disruption. With y-axis vibration more disruption occurred in the side-to-side control axis. Vibration at 3 Hz had most effect followed by 1 and 5 Hz. Performance was not disrupted by 11 Hz vibration.

The other study which used a first-order task also investigated effects separately in the x- and y-axes. Allen, Jex and Magdaleno (1973) presented sinusoidal vibration at frequencies between 1.3 and 10 Hz at 2.8 ms^{-2} rms. Both control activity and overall system performance were measured. With x-axis vibration, control 'feedthrough' showed different frequency dependencies with 'stiff' and 'spring' controls. The 'spring' control showed maximum feedthrough with 3 Hz vibration while the 'stiff' control showed maxima at 1.3 and 4.5 Hz. Performance disruption reduced with increasing vibration frequency with the 'spring' stick, and showed greatest disruption at 1.3 and 7 Hz with the 'stiff' stick. With both controls, maximum feedthrough during y-axis vibration occurred at 1.3 Hz and reduced as the vibration frequency increased. System performance showed the same frequency dependence although feedthrough made only a small contribution to total error.

(ii) Other Studies

Shurmer (1969) investigated differences in the effect of 2 and 4 Hz vibration in both the x- and y-axes on performance. Slightly more disruption arose from 4 Hz vibration at 0.78 ms^{-2} rms than from 2 Hz vibration at 0.64 ms^{-2} rms. The significance of the difference was not reported although the trend was consistent with two different controls.

(iii) Summary of Effects of Horizontal Vibration Frequency

Both x- and y-axis vibration are most disruptive to performance at frequencies between about 1 and 3 Hz. The effect reduces as the vibration frequency increases up to at least 12 Hz. As with z-axis vibration, the frequency range of maximum sensitivity corresponds with the range of maximum transmission to the shoulder and head. Differences between studies may therefore be partly related to differences in subject characteristics.

Vibration in the y-axis is more disruptive in the fore-and-aft axis of the control than in the side-to-side axis of the control. With x-axis vibration the sensitivities are reversed. There is some evidence of interactions between vibration frequency and control type.

2.1.2 Non-Sinusoidal Vibration

Three studies have investigated effects of vibration frequency in the z-axis with both sinusoidal and random vibration. All three studies presented equal acceleration magnitudes at each frequency.

Zero-order Tasks

Using an isometric-type side-mounted control, Lewis (1981) compared the effect of sinusoidal and one-third-octave bandwidth random vibration (which may be considered amplitude modulated sine waves) centred on frequencies between 2.5 and 12.0 Hz at 1.5 ms^{-2} rms. Frequency dependencies were very similar with both types of vibration, with greatest disruption occurring at 5 Hz. Random vibration, however, produced significantly less total disruption at 5 Hz, and significantly less direct control 'breakthrough' in the fore-and-aft control axis at 2.5, 5.0, 6.3 and 8.0 Hz. The random vibration therefore induced less motion at the hand than the sinusoidal vibration.

Lewis and Griffin (1978) compared three methods of predicting the effect of dual frequency vibration having components at 3.15 and 5.0 Hz. Good predictions of total rms tracking error were obtained by weighting the acceleration time-history according to the sensitivity of the task to each sinusoidal frequency and taking the rms sum of the weighted components. In the study mentioned above, Lewis (1981) extended this technique to predict effects with one- and two-octave band random motions. Again, good predictions were obtained by weighting the acceleration time-history using the formula:

$$e_p = e_o + \left(\int_w S^2(f) . V(f) . df\right)^{\frac{1}{2}}$$

where:

e_p is the predicted rms tracking error,

e_o is the measured rms error with no vibration,

S(f) is the sensitivity of the task to disruption by vibration at frequency f,

V(f) is the power in the acceleration time-history at frequency f, and

w is the bandwidth of the vibration.

Slightly better predictions were obtained using weighting functions based on sinusoidal than one-third octave bandwidth random vibration.

Higher-order Tasks

Only one study has compared effects of random and sinusoidal vibration using a first-order task. Weisz, Goddard and Allen (1965) compared effects of 5 Hz sinusoidal, 5 Hz random amplitude and 4-12 Hz random vibration. At comparable acceleration magnitudes between 0.24 and 1.5 ms^{-2} rms there were no significant differences in performance with each type of vibration. However, results suggested complex interactions between vibration type, task difficulty and the duration of task performance.

2.2 Vibration Axis

2.2.1 Comparisons of Single-axis Effects

Five of the studies mentioned in Section 2.1 presented single axis vibration in more than one translational axis. Most of these studies did not explicitly compare relative effects between each axis. However, some information on the relative effects of each translational axis can be obtained from the results provided. (Unless otherwise stated, equal magnitudes - whether acceleration or displacement - were presented in each axis).

Zero-order Tasks

Results from Hornick (1962) showed that y-axis vibration produced more disruption at 1.5 Hz than vibration at any frequency in the x- or z-axes. Hornick used a steering wheel type control which was sensitive in the side-to-side axis of the body - ie., in the y-axis. Fraser, Hoover and Ashe (1961) found performance in the fore-and-aft control axis to be most sensitive to vibration in the z-axis followed by the y-axis at frequencies between 2 and 12 Hz. Performance in the side-to-side control axis was most sensitive to y-axis vibration. Vibration in the x-axis did not disrupt performance. Effects due to z- and y-axis motion were not statistically different.

With two different side-arm controls, Shurmer (1969) found that 2 Hz vibration at 1.2 ms^{-2} rms in the y-axis caused greater disruption than 2 Hz at 1.76 ms^{-2} rms in the z-axis. Similarly, 4 Hz at 0.78 ms^{-2} rms caused more disruption in the y-axis than in the z-axis. Shurmer did not analyse the relative disruption in each axis of the task.

In two studies, Lovesey presented vibration independently in both the z- and y-axes. The first study (1971a), showed that with 2, 5 and 7 Hz vibration at 1.4 ms^{-2} rms in the z-axis, more disruption occurred at each frequency than at 0.7 ms^{-2} rms in the y-axis. This difference is probably due to the greater magnitude in the z-axis. In the other study, (1971,b), 2 and 2.7 Hz z-axis vibration at 1.76 ms^{-2} rms tended to disrupt performance in the fore-and-aft control axis more than the same frequencies of y-axis vibration at 1.0 ms^{-2} rms. In the side-to-side control axis however, vibration in the y-axis caused more disruption than in the z-axis. These results indicate the close relationship between vibration axis and the sensitive axes of the control despite the greater magnitude of vibration in the z-axis.

Higher-order Tasks

The study by Shoenberger (1970) showed that between 1 and 11 Hz, y-axis vibration produced very much larger percentage increases in tracking error in the side-to-side control axis than either x- or z-axis vibration. In the fore-and-aft control axis, y-axis vibration also produced greatest disruption during 1 and 3 Hz vibration. Both x- and z-axis vibration produced more disruption in the fore-and-aft control axis than in the side-to-side axis. More disruption was caused by vibration in the x- than in the z-axis. It has been noted earlier however that this study by Shoenberger found no frequency dependence in the effect with z-axis vibration. This conficts with most other studies and generalisations from this data should therefore be made with care.

It is not possible to make simple cross-axis comparisons from the data presented by Allen, Jex and Magdaleno (1973). Different system dynamics and tasks were used with y-axis vibration than with x- or z-axis vibration. Their data suggest a complex interaction between vibration axis, control type and vibration frequency for x- and z-axis vibration.

2.2.2. Multi-axis Vibration Environments

The limited experimental evidence available indicates that vibration presented simultaneously in more than one axis will produce greater disruption than any of the single axis components presented individually.

Zero-order Tasks

Shurmer (1969) presented combined z- and y- and z-, y- and roll axis vibration. Performance in each multi-axis environment was poorer than in any single axis environment, and could be described as the product of the scaled response in each axis presented individually. The scaling factor depended only on the number of axes of vibration and was smaller with three axes than with two. Shurmer was unable to provide a physical interpretation explaining why the relationship held.

In two experiments, Lovesey (1971 a,b) presented vibration in the z- and y-axes simultaneously. In both cases he found generally greater disruption with the dual axis motion than with either single axis alone. The decrement in the two-axis environment could again be described as the scaled product of the decrement in each individual axis.

Higher-order Tasks

Lovesey (1971c) and Levison and Harrah (1977) have investigated effects of multi-axis vibration environments on second and first-order tasks respectively. Lovesey concluded, as before, that a multi-axis environment with sinusoidal components below 4 Hz produced poorer performance than either single-axis environment. However, his data are limited and observed effects are marginal. Levison and Harrah however, found no difference between multi-axis and single-axis environments. They presented a broad-band random environment with frequency components at 2, 3.3, 5, 7 and 10 Hz at acceleration magnitudes of less than 2.5 ms^{-2} rms. A number of single and dual axis motions were used. Results showed no consistent trend for dual axis environments to produce greater disruption than single-axis environments. Indeed, with a spring stick there was no effect of vibration on tracking performance.

2.2.3 Summary of the Effect of Vibration Axis

The effect of vibration in any axis on performance of a given task is largely dependent upon the sensitive axes of the control and display. Vibration in the x- and z-axis both produce control breakthrough in the fore-and-aft axis. With y-axis vibration breakthrough occurs mainly in the side-to-side control axis. In all of the studies reviewed, the control has been sensitive in one or both of these axes. This correspondence holds with both zero- and higher-order systems. However, none of the studies attempted to determine whether the relative effects were due to vibration breakthrough at the control or to visual effects, or both (see Section 4).

2.3 Vibration Magnitude

Nineteen studies have investigated the effect of vibration magnitude on manual control performance. Fourteen of these have investigated increasing magnitudes of sinusoidal vibration and five have used non-sinusoidal vibration.

2.3.1 Sinusoidal Vibration

Zero-order Tasks

The minimum vibration magnitude necessary to disrupt tracking performance on zero-order tasks has been demonstrated to depend upon both the vibration frequency and the characteristics of the control operated. Catterson, Hoover and Ashe (1962) found no performance decrements with seat displacements of 1.1 mm rms between 2 Hz and 15 Hz in the z-axis (acceleration from 0.2 to 10 ms^{-2} rms). All frequencies disrupted performance at 2.2 mm rms displacements (0.4 to 20 ms^{-2} rms). Lewis and Griffin (1978) observed disruption at 0.4 ms^{-2} rms and above (displacements of 0.41 mm rms) with 5 Hz z-axis vibration, but only at 0.8 ms^{-2} rms (displacements of 0.81 mm) and above with 3.15 Hz vibration. A later study (Lewis and Griffin, 1979), showed an interaction between acceleration magnitude and control type. With an isotonic control, 16 Hz vibration at magnitudes up to 4.0 ms^{-2} rms (displacement up to 0.4 mm rms) did not disrupt performance, while a strong linear relationship existed between rms tracking error and rms seat acceleration with 4 Hz vibration at magnitudes above 0.4 ms^{-2} rms (displacements above 0.63 mm). With an isometric control however, there were approximately linear increases in error with both 4 Hz and 16 Hz vibration above the lowest magnitude presented of 0.4 ms^{-2} rms. The rate of increase in error was less with the isotonic control than with the isometric control. The notable difference in the minimum magnitude producing disruption in the studies by Lewis and Griffin and Catterson et al is probably due to differences in the sensitivity of the controls, and the greater accuracy in measurement employed by Lewis and Griffin.

Seven experiments have demonstrated that the rate of increase in tracking error with increasing acceleration depends upon the vibration frequency. (Catterson, Hoover and Ashe, 1962; Forbes, 1960; Fraser, Hoover and Ashe, 1961; Hornick, 1962; Lewis and Griffin, 1978, 1979; Shurmer, 1969). The greatest rate of increase usually occurred with vibration at frequencies between 5 and 8 Hz (Catterson et al; Forbes; Lewis and Griffin).

Hornick (1962) presented vibration at frequencies between 1.5 and 5.5 Hz individually in the x-, y- and z-axes. He states that in each case, increasing the acceleration magnitude increased the errors. Results for y-axis vibration appear to show a non-linear increase in error with vibration magnitude. The results however are not fully described. Fraser et al (1961) also demonstrated increasing disruption with acceleration magnitude for all three translational axes, and Shurmer (1969) showed the same effect in the y-axis as in the z-axis.

Higher-order Tasks

Six studies have investigated the effect of vibration magnitude on first-order tasks. One of these failed to find deteriorating performance with increasing platform acceleration although there was a highly significant correlation between tracking error and acceleration measured at the subjects' sternum, (Buckhout, 1962). The remaining five studies all observed increased disruption with increases in rms acceleration at the subjects' seat (Harris et al, 1964; Harris and Shoenberger, 1965; Lovesey, 1971c; Shoenberger, 1970; Weisz et al, 1965).

As with zero-order tasks, the minumum vibration magnitude necessary to produce significant task disruption varies with vibration frequency. Harris et al (1964) found that 5 Hz z-axis vibration at 1.4 ms^{-2} rms (displacement of 1.4 mm rms) significantly disrupted performance of 10 subjects while 1.13 ms^{-2} rms (displacement of 1.1 mm rms) did not. Harris and Shoenberger (1965), also using 10 subjects, found that with vibration at 5, 7 and 11 Hz, significant disruption first occurred at acceleration magnitudes of 1.4, 1.8 and 2.6 ms^{-2} rms respectively (displacements of 1.4, 0.93 and 0.54 mm rms). This indicates the decreasing sensitivity to z-axis acceleration as the frequency increases above 5 Hz.

Shoenberger (1970) demonstrated that the rate of increase in disruption with increasing acceleration in the x- or y-axes is greatest at the frequency producing most disruption. (This frequency is therefore most sensitive to vibration). Results from Weisz, Goddard and Allen (1965) indicate that the relationship between task disruption and rms acceleration in the z-axis is approximately linear with 5 Hz sinusoidal vibration.

2.3.2 Non-sinusoidal Vibration

Five studies have looked at the effect of acceleration magnitude on performance using random vibration. Four of these looked at effects on first-order tasks and one used a zero-order task.

Zero-order Tasks

Lewis and Griffin (1976) used z-axis vibration having equal acceleration amplitude components at 3, 5 and 8 Hz. The composite vibration was presented at overall magnitudes of 0.43, 0.87 and 1.73 ms^{-2} rms. Results showed approximately linear relationships between rms acceleration magnitude and rms tracking error. However, the slope of the relationship was dependent upon the stiffness of the control used: increasing the control stiffness reduced the slope.

Higher-order Tasks

All four studies using first-order tasks demonstrated increasing disruption with increasing rms acceleration magnitudes. (Besco, 1961; Levison, 1976; Torle, 1965; Weisz et al, 1965). Approximately linear relationships were observed by Weisz et al (1965) with both 5 Hz random amplitude and broad-band random motion containing frequencies from 4 to 12 Hz, and by Levison (1976) with both sum-of-sines and random vibration containing frequency components from 2 to 10 Hz. The study by Besco (1961) suggested that the slope of the increase may vary according to the difficulty of the task.

2.3.3 Summary of the Effect of Vibration Magnitude

Performance disruption increases with vibration magnitude across a wide range of frequencies, magnitudes and task conditions. The minimum magnitude producing disruption depends upon the vibration frequency, the type and sensitivity of the control used and the order of the system dynamics. Zero-order tasks are more sensitive than first-order tasks.

For a wide range of tasks, the relationship between vibration magnitude and tracking error has been demonstrated to be approximately linear. The slope of the relationship (ie., the sensitivity of the task to vibration-induced disruption) depends, again, upon the vibration frequency and control type and, probably, the order of the system dynamics.

2.4 General Summary of the Effect of Vibration Variables

The effect that vibration has on performance of a manual control task is dependent upon the nature of the vibration. The variables described in this Section - the frequency content, axis and magnitude of the vibration - interact to determine the effect on a given system. For example, the effect of a given frequency depends upon both the axis it is presented in and its magnitude. The dependence upon magnitude may be implied by describing effects as the 'sensitivity per unit magnitude'. Effects also depend upon variables associated with both the system being controlled and the task performed. The interaction between variables is the single most important, and the most problematic, factor in determining the effect of vibration on manual control performance.

In nearly all the studies reviewed, the vibration environments used were very simple consisting, for example, of single sine waves in one axis presented at the subjects' seat. In many real-life environments, complex motion will occur in more than two axes and may be different at the subjects' seat, head, hands and feet. Considerable further research is required before effects of such complex environments can be properly understood. However, there is some evidence that the effect of a complex environment can be predicted from a knowledge of the effects on more simple environments.

3.0 System Variables

Twenty-two studies have investigated the role of system variables in determining the sensitivity of a task to disruption by whole-body vibration. These have studied the type of control operated (14), the form of display (3), the system dynamics (2), and the difficulty of the task performed (3). One study investigated the effect of providing an arm support and three have looked at techniques for adaptively changing the system to reduce the vibration effects.

3.1 Control Stick Variables

A control is defined by four parameters; its location, physical shape, sensitive axes and whether it moves. If it moves, it is further defined by the amount of force required to move it through a given distance, whether it incorporates any resistance to movement such as friction or dampers, and whether any force acts to return the control to the central position, such as springs. The gain or sensitivity of a control, defined as its output per unit force or displacement, is also important.

Pure isometric controls do not move: they respond only to the applied force. Pure isotonic controls offer no resistance to movement and respond only to displacement. Spring-centred or damped controls resist movement in proportion, respectively, to the displacement or velocity of control movement. As Lewis and Griffin (1976) point out, different sensory processes may be involved in muscular control depending upon whether isometric or isotonic controls are used.

3.1.1 Stick Location and Arm-supports

In some modern aircraft, primary flight controls are located at the side of the pilot. Three studies have investigated possible differences in the sensitivity of controls to vibration-induced disruption according to their location. Shoenberger and Wilburn (1973) compared performance with a conventional joystick located between the subjects' knees and a side-arm control during sinusoidal z-axis vibration at 2, 6 and 10 Hz. Both controls were isometric. Results showed a frequency dependence in the effect of control location. Performance with the side stick was most disrupted by vibration at 6 and 10 Hz, while the centre stick was most affected at 2 and 6 Hz. The differences in effect however could not be directly attributed to control location. With the side-arm control an arm-rest was provided which may have transmitted more vibration to the hand at 10 Hz than with the unsupported centre stick.

Levison and Houck (1975) compared 'spring' and 'stiff' controls in both the centre and side-arm locations. There was no effect of control location with broad-band z-axis vibration having equal acceleration at 2, 3.3, 5, 7 and 10 Hz. As in the study by Shoenberger and Wilburn, an arm-rest was used with the side-arm control. Inter actions between control location and vibration may have been masked by the broad-band nature of the vibration. Dimasi, Allen and Calcaterra (1972) also compared centre mounted and side-arm spring-centre controls. Again, there was no effect of control location during broad-band random vertical vibration.

The only study to directly investigate the effect of providing an arm-support was performed by Torle (1965). During random z-axis vibration, with power at frequencies between 0.1 and 5.0 Hz, providing either a 25 cm long board or a 4 cm cross-piece as arm-support substantially reduced the disruption. The improvement due to the arm-support was greater than could be achieved by incorporating either friction or backlash in the control.

In summary, the location of the control itself appears not to affect its vibration sensitivity. However, frequency dependent differences in performance may occur when the transmission of vibration to the hand is altered by the provision of an arm-support. At frequencies below about 5 Hz providing an arm-support may reduce the effect of vibration.

3.1.2 Control Shape

Control shapes from foot pedals and rotary knobs to steering wheels and joysticks have been used to study the effects of vibration on manual control performance. Bedi (1977) compared performance with ten different controls with and without vibration exposure. Without vibration, poorest performance occurred with large controls incorporating significant frictional resistance and inertia, such as steering wheels and levers. During exposure to random z-axis vibration, the large controls tended to show best performance. The greatest absolute decrement occurred with the two controls sensitive in the vertical axis (foot pedal and thumb control). Vibration breakthrough was assumed to be least in controls having greatest frictional resistance and inertia and whose sensitive axis did not coincide with the axis of greatest breakthrough at the hand.

Chaney and Parks (1964) compared performance with large and small knobs, levers and thumbwheels oriented in either the horizontal (lateral) or vertical axis during z-axis vibration. Vibration increased the time to adjust the lever and thumbwheel oriented in the vertical axis. Day and Paul (1978), evaluated a range of controls for fine aiming tasks. Differences in performance during vibration were attributed to differences in the static friction of the controls.

The relative sensitivity of side-arm joystick-type controls and rotary knobs during 4 Hz z-axis vibration was investigated by Lewis and Griffin (1977). Approximately equal amounts of disruption occurred with both types of control.

In summary, there is no evidence to suggest that the shape of a control, as such, alters the sensitivity of a task to disruption by vibration. Differences have been attributed to the force required to operate the controls and the sensitive axis of the control relative to the axis of vibration.

3.1.3 Mechanical Characteristics

Experimental comparisons of controls with very different mechanical properties have generally been confounded by uncontrolled factors. Within experiments, small numbers of subjects have used all controls, allowing for transfer of training effects. Due to the different physical units (eg. volts kg^{-1} or volts cm^{-1}), it is difficult to compare effects on stick output activity. Comparisons across experiments are confounded by differences in the forces required, control sensitivities and the frequency content of the tasks. Given these problems, the consistency in the data is surprising.

Four studies comparing 'stiff' and 'spring' controls (Allen et al, 1973; Levison, 1976; Levison and Houck, 1975 and Levison and Harrah, 1977) all found that 'stiff' sticks (requiring forces of 1.4, 2.4, 2.4 and 2.4 kg mm^{-1} respectively) produced better performance than 'spring' sticks (requiring 0.017, 0.127, 0.136 and 0.127 kg mm^{-1}) without vibration. (1.4 kg mm^{-1}, for example, means that for every 1.4 kg force applied, the handle of the control moves through 1 mm). With z-axis vibration the relative increase in tracking error was greatest with the stiff sticks. All four studies showed more vibration breakthrough with the stiff sticks due to their lack of damping. The same pattern was observed by McLeod, Poulton, Du Ross and Lewis (1980) although details of the controls' mechanical characteristics were not provided. Allen, Jex and Magdaleno (1973) observed wider bandwidths of tracking performance with the stiff stick without vibration. This was probably due to the lack of inertial resistance. With 10 Hz vibration the bandwidth of the stiff stick was reduced to the same as the spring stick.

Allen, Jex and Magdaleno also observed an interaction between the control type and the axis of vibration. With y-axis vibration, the spring stick showed more breakthrough and remnant (ie., control activity not linearly correlated with the task or vibration) than the stiff stick at frequencies below about 4 Hz. This effect was attributed to the large amplitudes of vibration-induced stick motion at these frequencies. Subjects commented that they felt unsure of the sticks' central position. This problem did not occur with the stiff stick. A similar effect occurred with x-axis vibration.

Levison and Houck (1975) and Lewis and Griffin (1976) investigated the effect of increasing the stiffness of a moving control (from 0.036 to 0.218 kg mm^{-1} and from 0 to 0.016 kg mm^{-1} respectively). Increasing the stiffness reduced the amount of breakthrough to the control output. Overall tracking error was not affected in the study by Levison and Houck, which used first-order dynamics. With the zero-order dynamics used by Lewis and Griffin, overall error reduced as the stiffness increased, although breakthrough was not a major component: the improvement in performance was accompanied by a reduction in the proportion of error at tracking frequencies below 1 Hz.

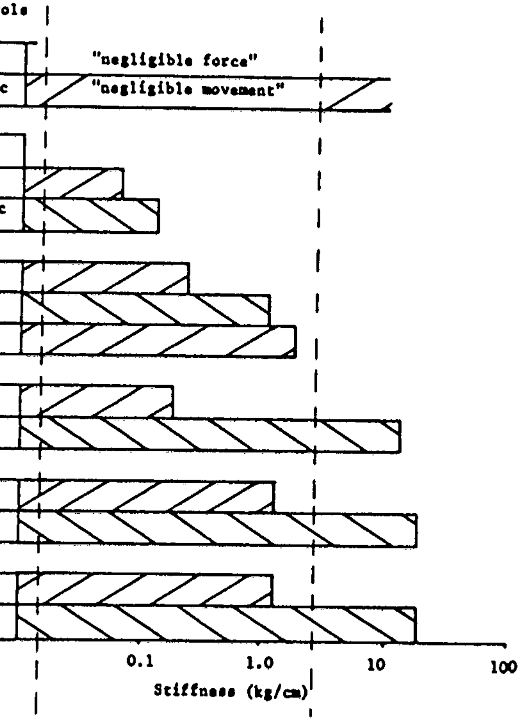
In a later study, Lewis and Griffin (1979) compared isotonic and isometric controls during increasing magnitudes of whole-body vibration at 4 and 16 Hz. At 4 Hz, the rate of increase of vibration-correlated control activity with increasing vibration magnitude was greatest with the isotonic control. (Such direct comparisons however should be treated with caution due to difficulties in equating the gains of isometric and isotonic controls).

Table 2.1 summarises the range of control stiffnesses studied and the results obtained. The table identifies three zones of control stiffness. Isotonic controls, responding to displacement and having stiffness less than about 0.005 kg mm^{-1} appear poorest both with and without vibration. Isometric controls responding to force and having stiffness greater than about 0.5 to 1.0 kg mm^{-1} appear most suitable for environments without vibration. Due to their lack of damping however, they are relatively sensitive to vibration breakthrough and other sources of disruption. Increasing the stiffness from about 0.005 to about 0.2 kg mm^{-1} in moving controls provides increasing resistence to vibration induced disruption. The optimum force-displacement characteristics probably occur in this region. However, too much stiffness may induce excessive fatigue in subjects if the task is performed for long durations.

3.1.4 Control Gain

Lewis and Griffin (1976) investigated the effect of varying the control gain on the sensitivity of a task to disruption by whole-body vibration. For isometric and isotonic joysticks and rotary knobs, optimum control gains were established both with and without vibration. Optimum gains were lower with vibration. In both environments, reducing the gain reduced the amounts of both vibration breakthrough and operator-induced noise, or remnant. The optimum gain was therefore a compromise between speed of response, operator-induced noise and vibration breakthrough.

Authors and Date	Authors' description of controls	RESULTS Best without vibration	Most sensitive to vibration	Details
Lewis and Griffin (1979)	Isotonic Isometric	Isometric	Isotonic	More breakthrough and remnant occured with the 'Isotonic' control. Rate of increase of error with increasing vibration magnitude greatest with the 'Isotonic' control.
Lewis and Griffin (1976)	Isotonic Spring Isometric	Isometric	Isotonic	Increasing stiffness reduced sensitivity to vibration. Increased error at tracking frequencies below 1 Hz.
Levison and Houck (1975)	Spring 1 Spring 2 Spring 3	Little difference	Control 1	Increasing stiffness reduced the magnitude of vibration breakthrough.
Allan, Jex and Magdaleno (1973)	Spring Stiff	Stiff	Stiff	Greatest magnitude of vibration breakthrough with the 'Stiff' control.
Levison (1977)	Spring Stiff	Stiff	Stiff	Greatest magnitude of vibration breakthrough with the 'Stiff' control.
Levison and Harrah (1977)	Spring Stiff	Stiff	Stiff	Greatest magnitude of vibration breakthrough with the 'Stiff' control.



'ISOTONIC': Performance poorest both with and without vibration.

'SPRING': Increasing stiffness reduces vibration sensitivity.

'ISOMETRIC': Performance best with no vibration. Second most sensitive to vibration.

Table 2.1 Comparison of studies investigating effects of control stiffness on manual control performance in vibration environments.

3.2 System Dynamics

The effects of control stick variables discussed in the previous section were generally related to the amount of vibration breakthrough occurring in the stick output. In zero-order systems, the amplification of breakthrough at the stick to produce controlled element motion is independent of vibration frequency. In higher-order systems, every integration in the system attenuates breakthrough at the system output by 6 dB for each doubling of vibration frequency. In general, the more complex a system is - in terms of the integrations, lags and leads in the dynamics - the more difficult it is for humans to control. In their classic treatment of human operators in control systems, McRuer and Krendel (1974) describe the increasingly complex behaviour required of the human operator as system complexity increases.

Lewis (1980) compared performance with zero-order (simple gain) and first-order (gain and integration) system dynamics during exposure to z-axis whole-body vibration at frequencies from 2.5 to 12.5 Hz. The total increase in tracking error per unit acceleration magnitude and the frequency dependencies were very similar in each case. However, the proportion of error caused by breakthrough was very much less with the first-order dynamics. Conversely the proportion of error not linearly related to the tracking task was very much greater with the first-order task. The more difficult first-order task was therefore more sensitive to non-breakthrough related effects of vibration. Tracking error without vibration was considerably greater for the first-order task. The relative increase in error during vibration was therefore greater with the easier, zero-order task.

Allen, Jex and Magdaleno (1973) compared the effect of z-axis vibration at 2, 6 and 10 Hz on performance with two sets of dynamics of different complexity. The simpler first-order dynamics required the subjects to act only as a pure gain, while the more complex second-order dynamics required some lead generation; ie., subjects had to respond to the rate of change of the error as well as its absolute magnitude. With the first-order task, total error, input-correlated error and remnant were unaffected by 2 Hz vibration, but increased with frequency from 6 to 10 Hz. With the second-order dynamics, input-correlated error was relatively unaffected by vibration while total-error increased due to increased remnant at all vibration frequencies. There was a gradual increase in error from 2 to 10 Hz. The task demanding more complex behaviour from the subjects therefore appeared more sensitive to vibration than the first-order task, but showed less frequency dependence. With the first-order task, subjects could respond at higher tracking frequencies without vibration, but 10 Hz vibration reduced the performance bandwidth.

3.3 Displays

Variables associated with the display have only been investigated in three studies. Two of these looked at physical parameters and the third looked at the way in which the task is presented.

Hall (1980) used displays which were either close to the subjects and moved with them, or 3 m from the subjects and did not move. In the latter condition, subjects viewed the display through an eye piece. Hall presented z-axis, broad-band random motion (1-20 Hz) with superimposed 125 msec impacts. Results were confounded in a number of ways, many of which the author reports. With the stationary display subjects were unable to maintain effective contact with the eye piece.

Wilson (1974) looked at the effect of collimating the display during z-axis vibration at frequencies from 2 to 10 Hz.

Displacement was constant at all frequencies resulting in extremely high acceleration magnitudes at the higher frequencies. Without collimation, all frequencies degraded performance and the decrement was proportional to the vibration frequency. Collimating the lens reduced the disruption significantly at 4 and 6 Hz. However, even with display collimation significant disruption remained at all vibration frequencies.

Finally, Lewis (1980) compared performance with pursuit and compensatory tracking displays during z-axis vibration at frequencies between 2 and 12.5 Hz. Results were very similar for both types of display. A slight reduction in sensitivity occurred with the compensatory display during 5 Hz vibration. This was attributed to the different subject populations used with each type of display.

3.4 Task Difficulty

A number of authors have speculated that the effect of vibration on task performance may depend upon the workload imposed on the subject in performing the task. However, the way in which 'workload' has been defined, and the methods used to vary it have differed. Besco (1961) and Weisz et al (1965) varied the frequency content of the tracking task performed. Both studies found that higher frequency tracking tasks produced more error without vibration, and Besco found that as the tracking task became more difficult, the effect of vibration became more pronounced. The result may not be directly due to operator workload however, as the higher frequency task required higher frequency control activity. As in the study by Allen et al (section 3.2), vibration may cause a reduction in the bandwidth of tracking performance for some tasks, (ie., in the ability to perform at high frequencies).

In a second experiment, Weisz et al (1965) varied the workload on the subjects by asking them to perform secondary visual and auditory monitoring tasks. Without vibration, adding the secondary task impaired performance. With vibration, decrements were greater with the secondary task than without, and the difference was greater as the acceleration magnitude increased. Chaney and Parks (1964) also used secondary task and found they caused greater error without vibration. However, vibration seriously impaired performance without the secondary tasks, but had little effect with the secondary task, probably because performance was already so poor. The difference between these two studies may be due either to the different levels of workload used or the different sensitivity of each task to vibration.

In summary, the effect of vibration may depend upon the difficulty of the task performed (more difficult tasks being more affected) as well as on the other variables which have been discussed. However, when a task is very sensitive to vibration-induced disruption, task difficulty may make little difference.

3.5 Adaptive Systems

Three studies have attempted to minimise the disruptive influence of vibration by some form of adaptive technique. Dimasi, Allen and Calcaterra (1972) demonstrated that effects could be largely removed by active isolation of the human, control and display from the vibration. An Active Vibration Isolation System (AVIS) compensated for platform motions centred at 4.2 Hz. Subjects remained approximately stationary during platform vibrations. However performance was not improved if the display was not isolated from the platform motion.

Velgar, Gronwald and Merhar (1982) used an adaptive filtering technique to cancel vibration breakthrough in the control output. They demonstrated that for a particular set of aircraft dynamics having a bending mode at 2.5 Hz, substantial pilot-induced oscillations of the airframe due to vibration breakthrough could be produced through the use of high gain isometric controls. Adaptive filtering of the control output removed this effect. However, the technique depends upon being able to clearly separate, in the frequency domain, intentional control activity from vibration breakthrough. In many systems in which vibration occurs below 2 Hz this may not be possible. Repperger (1983) has proposed the use of 'smart stick' controls to minimise the effects of acceleration, among other variables, on system performance. These controls use digital computers to adaptively change their parameters as a function of specified conditions. This technique has not yet been adequately evaluated and may only be of practical use when vibration breakthrough is a significant factor in overall system disruption.

4.0 Mechanisms

The literature reviewed in Sections 1, 2 and 3 has described effects on performance observed during vibration exposure. The reasons why vibration might affect performance have not been discussed. Until these mechanisms are fully explained, the effects of vibration will not properly be understood; they will simply be described. Understanding the mechanisms involved is therefore central to studying the effects of vibration on manual control performance, and is a major theme of this thesis. This section reviews those mechanisms which have been suggested to occur, and examines the experimental evidence for each.

Few authors have provided any empirical evidence indicating the mechanisms which may be involved in disrupting manual control performance during vibration exposure. Seven studies have used cross-spectral analysis techniques to divide tracking error into a component due to direct vibration breakthrough (vibration-correlated error), a component due to linear operations on the tracking input (input-correlated error) and a portion not linearly correlated with either the tracking task or vibration input (remnant). Remnant is itself composed of involuntary control activity arising from visual and neuro-muscular 'noise' as well as non-linear tracking strategies adopted by the subjects and any other source of control activity not linearly related to the tracking task. (Chapter 4 describes the theoretical basis of these spectral analyses techniques). Considerable difficulty occurs in interpreting observed changes in either input-correlated error or remnant in terms of fundamental mechanisms.

The four mechanisms by which low frequency vibration has been suggested to disrupt performance are briefly described below.

1. <u>Vibration Breakthrough</u>: Defined as motion of the controlled element on the display directly caused by, and linearly correlated with, the vibration input. In many simple tracking

systems breakthrough has been shown to make a significant contribution to tracking error.

2. <u>Visual Interference</u>: Relative motion between the subjects' eyes and the display can give rise to a blurred image of the information presented on the display, with a consequent reduction in tracking ability. Motion of the controlled element arising from vibration breakthrough can also impair visual performance.

3. <u>Neuro-muscular Interference</u>: Vibration at frequencies above about 10 Hz has been shown to interfere with neuro-muscular activity. There is also evidence that vibration below 10 Hz can induce reflex activity in mammalian muscle. Any interference with neuro-muscular control processes may interfere with tracking performance.

4. <u>Central Effects</u>: Many authors have speculated that vibration can act as a non-specific stressor affecting levels of arousal and motivation. Changes in these central factors could result in changes in performance in a number of ways; for example subjects may exert more or less effort in performing the task, they could change their control strategy to accept a lower level of performance, or they may be less able to attend to the task presented. Although precise effects are difficult to define, the possible effects on performance may be very large.

The remainder of this section will examine the experimental evidence for each of these mechanisms.

4.1 Vibration Breakthrough

Six experiments have measured both total tracking error and its components (input-correlated error, vibration-correlated error and remnant). Five of these have used simple zero-order tracking tasks (Lewis, 1980, 1981; Lewis and Griffin, 1977, 1978, 1979). In these studies, the magnitudes of increase in total tracking error were closely matched by increases in both vibration breakthrough and remnant. Input-correlated error also showed some changes. Breakthrough was a major mechanism of disruption in these experiments although other mechanisms were also involved.

Two studies used first-order tracking systems (Allen et al, 1973; Lewis, 1980). The proportion of tracking error attributed to vibration breakthrough was minimal. In each case changes in tracking error were closely matched by changes in remnant. This is consistent with the results from the zero-order studies. Theoretically, remnant incorporates both perceptual and neuro-muscular noise processes as well as the non-linear portion of subjects' tracking strategy. Considerable difficulty therefore occurs in attributing changes in remnant to any specific mechanism. The identification of the source of changes in remnant will be discussed in sections 4.2 and 4.3.

Vibration breakthrough then is clearly an important mechanism by which vibration disrupts tracking performance in simple zero-order systems. More complex systems attenuate control activity above some critical frequency. The precise relationship between frequency and attenuation will depend upon the particular system dynamics used. In the systems studied, considerable attenuation has always occurred at the lowest vibration frequencies investigated. In some systems however, control breakthrough at frequencies considerably below 1 Hz may be amplified by the system dynamics. In such cases breakthrough may be an important mechanism of performance disruption in first and higher-order systems.

A number of sophisticated biomechanical models have been developed to explain, and predict, the occurance of breakthrough at the control (eg., Allen, Jex and Magdaleno, 1973). These will be discussed in more detail in Chapter 3.

4.2 Visual Effects

Effects of vibration on vision have been, and continue to be, the subject of considerable research effort. Effects can be exceedingly complex. Vibration of the whole-body or of a target alone can produce eye motion through both voluntary pursuit tracking of the target and a compensatory reflex response to induced head motion. Becuase of the complexity of the area, only a brief overview will be presented here. The reader is referred to reviews by Griffin and Lewis (1978 b) for effects on visual acuity, and to Wells (1983) for vibration-induced eye motion.

Visual effects on tracking performance fall into two categories:

(i) Motion of the controlled element on the display arising from vibration breakthrough. This can produce perceptual confusion by masking the intentional movements of the controlled element. Subjects may also try to 'control out' the interference by responding to the breakthrough as an additional tracking input. Clearly, such interference could only arise when a significant amount of breakthrough occurs.

(ii) Motion of the subjects' eyes relative to the display can give rise to a blurred image of the displayed information. Subjects may be less able to quickly and accurately perceive changes in the motion of the target relative to the controlled element and to see the consequences of control actions.

Only one study directly bears on the latter category with respect to tracking performance, although a large amount of research, referred to above, relates to it. Three studies are relevant to the first category. These will be considered first.

Huddleston (1970) asked subjects to perform a compensatory tracking task with induced 'apparent' vibration of the target at frequencies from 1 to 10 Hz. Subjects were not vibrated. All frequencies of target vibration disrupted performance, with greatest disruption occurring at frequencies between 3 and 6 Hz. Below 3 Hz subjects were apparently able to visually pursue the vibrating target. Above 6 Hz subjects made use of 'nodal images' formed at the points of sine wave reversal (ie., zero velocity, maximum displacement). Huddleston suggested that at some frequency between 3 and 6 Hz, a changeover in viewing strategy occurred with a consequent impairment in tracking performance.

In an attempt to explain the increases in remnant observed to accompany vibration breakthrough, Lewis and Griffin (1979) compared vibration of the man-and-control with vibration of the control only at 4 and 16 Hz. They also induced apparent vibration of the target at 4 Hz while subjects were not vibrated to simulate the effect of breakthrough-induced target motions. Results showed that artificially induced target vibration produced similar increases in remnant to the two 4 Hz vibration conditions. The observed increases in remnant with vibration were therefore attributed to perceptual confusion arising from vibration-induced motion of the target.

Lewis (1980) used a similar technique to investigate differences in the mechanisms producing disruption in zero and first-order tasks. Although increases in total tracking error were similar with the two systems, zero-order tasks showed more breakthrough, as expected, and first-order tasks showed greater increases in remnant. The first-order task was shown to be very much more sensitive to the breakthrough which did occur; with an induced 5 mm rms disturbance of the target at frequencies from 2.5 Hz to 12.5 Hz, while subjects were not vibrated, the first-order tasks showed greater increases in remnant than the zero-order tasks. This increased sensitivity to display disturbances was not sufficient to explain the total increase in error observed during whole-body vibration however. Other mechanisms were therefore involved.

The second type of visual effect is caused by relative movement between the subjects' eyes and the display. Translational motion of the subjects' seat can give rise to motion at the head in any of the six translational and rotational axes (Griffin, 1981). During rotational head movements, the vestibulo-ocular reflex (VOR), induced by stimulation of the semi-circular canals, combined with voluntary, compensatory eye movements can exactly compensate for induced rotational eye movements at frequencies up to at least 5 Hz and probably up to around 14 Hz (Benson and Barnes, 1978; Wells, 1983). Wells measured compensatory eye movements in response to head pitching at frequencies up to 20 Hz. He suggests that the compensation above 14 Hz may have been caused by mechanical isolation of the eye from the head motion. The eye may therefore be expected to be stable in space during rotational head motion at frequencies up to at least 14 Hz.

During translational head motion, the eye may be assumed to be fixed in the head and to translate with the same magnitude, and in phase with, the head. However, subjects may be able to compensate for low frequency translational head movements (below about 2 Hz) by voluntarily tracking the target.

There is some evidence that translational head motion can induce rotational eye movements through stimulation of the otoliths (which are sensitive to linear accelerations). For example, Tokita et al (1981) found light dependent compensatory eye movements induced by translational z-axis seat motion at frequencies up to 5.0 Hz. Barnes (1980), however, points out that for such eye movements to be successful in compensating for translational motion between the head and a viewed object, the magnitude of the induced eye movement would have to depend upon the viewing distance. If the magnitude of induced eye movements were not distance dependent, they may serve to impair visual ability during translational motion. The precise details of this otolith-ocular reflex response are not known and therefore the extent to which it contributes to visual performing during vibration exposure is not clear.

The displacement of an image on the retina during translational eye movements is inversely proportional to the viewing distance. For rotational eye movements, the image displacement is independent of viewing distance. Griffin (1976) demonstrated that the minimum magnitude of whole-body vibration above 7 Hz which produced visual blur is independent of viewing distance for distances greater than 1.2 m. He therefore concluded that at vibration frequencies above 7 Hz, decrements in visual acuity are mainly caused by rotational eye movements. He suggested that translational eye movements may be more important at lower frequencies and shorter viewing distances. This suggests that, in the study by Griffin (1976), the VOR was not perfectly compensating for head rotation at frequencies above 7 Hz.

A convex lens positioned at its focal length in front of an object will place the image of the object, viewed through the lens, at optical infinity. A collimating lens should therefore remove visual impairment arising from translational eye motion but not due to rotational eye motion. Wilson (1974) demonstrated a significant improvement in tracking performance with a collimating lens during vertical vibration at 4 and 6 Hz. There was no significant improvement at 2, 8 and 10 Hz, and with collimation a decrement remained at all frequencies. This remaining error may have been caused either by rotational eye movements not compensated by the VOR, particularly at 8 and 10 Hz (Griffin, 1976), or by other non-visual mechanisms.

4.3 Neuro-muscular Interference

Results from physiological studies have shown that vibration applied to muscles of the arm and leg can produce illusions of limb movement. These effects have been attributed to muscle spindle activity and depend upon the amplitude and frequency content of the vibration (Brown et al, 1967; Eklund, 1972). Lewis and Griffin (1979) noted subjective reports of 'sluggishness' and 'numbness' in the tracking arm during 6.4 Hz vibration and at high magnitudes of vibration at 16 Hz. These effects were attributed to interference with neuro-muscular actuation mechanisms. Dimasi, Allen and Calcaterra (1972) also noted 'muscle tingling and a numb feeling' during random vertical vibration with frequencies up to 25 Hz.

Recent research has demonstrated that vibration of the whole-body or of isolated limbs or muscles can either inhibit or induce reflex muscle activity. For example, Martin, Roll and Gauthier (1984) demonstrated reduced motor neuron activity in response to 18 Hz vibration of the legs of a seated subject. Greatest inhibition occurred at frequencies between 15 and 20 Hz, although considerable inhibition also occurred at 10 Hz. Gauthier, Roll, Martin and Horley (1981) demonstrated that whole-body vibration at 18 Hz could impair sensory motor performance on tasks involving positioning and tracking with arms and feet as well as the production of constant torques with the feet. Results were interpreted as showing direct interference with the proprioceptive receptors in the neurological networks of the body.

A number of studies have indicated that sinusoidal stretching of mammalian muscle at frequencies as low as 2 Hz can induce a stretch reflex in the muscle causing it to resist the applied force (Rack, 1966; Jansen and Rack, 1966; Rack and Ross, 1974; Rack, Ross and Walters, 1979). These studies have also measured electrical activity correlated with the sinusoidal motion.

In two experiments, Lewis and Griffin (1976, 1979) tested hypotheses concerning effects of vibration on muscle activity. These two studies provide the only direct experimental investigation of mechanisms in the literature. It is therefore worth discussing them in some detail. In the first study, Lewis and Griffin (1976) compared performance with different levels of control stiffness during z-axis vibration having components at 3, 5 and 8 Hz. They argued that muscle spindles, which provide feedback of changes in muscle length and velocity and are therefore important in control with isotonic sticks, would be more sensitive to disruption than golgi tendon organs. Golgi organs give feedback of muscle tension and are more important in performance using isometric sticks. Lewis and Griffin therefore argued that changes in the effect of vibration with isotonic and isometric controls may be attributable to effects on the different sense organs: isotonic sticks were expected to be more affected than isometric sticks. Results showed that increasing the control stiffness reduced the effect of vibration. A large amount of error occurred at frequencies above the highest forcing function frequency, but below the lowest vibration frequency. The authors attributed error at these frequencies to differential effects on muscle feedback activity. Their results however do not necessarily support this conclusion for two main reasons.

First, although the experiment compared controls described as 'isotonic' and 'isometric', these terms appear only to reflect the physical parameters the controls responded to (respectively, displacement and force). In the highest stiffness condition (0.016 kg mm^{-1}) subjects would have been able to move the control through substantial displacements with little effort. (No details are provided of the sensitivity of each control, so it is unclear whether movement actually occurred). The hypothesis depends upon subjects actually using the sources of feedback assumed: muscle spindles or golgi organs. The conclusion of differential effects upon each type of sense organ must therefore be open to question. Second, and as is clear from various other studies (see section 3.1.3) increasing the stiffness of the control reduces the amount of vibration breakthrough. It has already been noted that increases in remnant error have been found to accompany vibration breakthrough due to perceptual confusion arising from induced target motion. This may therefore provide a more plausible explanation of the results, and one more consistent with data from other studies.

In the second study, Lewis and Griffin (1979), presented vibration only at the control, in order to remove effects due to visual or central effects. However, in the discussion of the results, they suggest that the effects observed may have been due to perceptual confusion arising from the vibration-induced motion of the controlled element. A second experiment, reported in the same paper, suggests that this was the case. The results of the first study (Lewis and Griffin, 1976) seem likely to be explained by the same mechanism, particularly as the equipment and tasks were the same in both cases.

No other studies have tried to experimentally test the possibility of neuro-muscular interference disrupting tracking performance at vibration frequencies below about 10 Hz. Allen, Jex and Magdaleno (1973), suggest that an observed increase in the high frequency phase lag of the human operator describing function during 10 Hz vertical vibration may have been caused by a direct effect on the neuro-muscular system. This suggestion appears to be based upon comments from one subject of 'increased neuro-muscular sluggishness' during 10 Hz vibration. They also report comments of visual blurring at the same frequency, and suggest this may have caused the observed increases in remnant. It seems likely that visual blurring would lead to an increased phase lag if subjects were unable to clearly see the target.

It was noted in section 3.1.3 that, with a moving control during y-axis vibration (Allen, Jex and Magdaleno, 1973), large amplitudes of vibration-induced stick motion occurred. Subjects commented that, in this case, they were unsure of the central, or null, position of the control. Tracking error was substantially increased. Lewis and Griffin (1979) have suggested that such perceptual confusion may be more disruptive in first-order systems than zero-order systems due to the greater dependence on kinaesthetic feedback cues.

In various papers, Levison and his co-authors have consistently attributed effects of vibration to increases in neuro-muscular noise. Initially, Levison (1974) performed a limited analysis of a part of the data from one subject from the study by Allen et al (1973). For some vibration conditions he found that the best prediction of the effect of vibration was obtained by increasing the proportion of operator-generated motor noise. In three further studies using the same model parameter matching technique, Levison (1976), Levison and Houck (1975) and Levis and Harrah (1977) have attributed effects to increase in 'motor related sources of randomness' (Levison and Harrah, 1977), and increases in pilots' phase lags. Visual effects were considered to be of minor importance. None of these studies provides any indication of the type of motor processes which may be affected. (It should be noted that increases in motor activity through adaptive changes in strategy, including non-linear behaviour, would be included in 'motor noise').

In summary, the assumption of interference with neuro-muscular processes has been found to be useful in modelling the effects of low frequency vibration on manual control performance. There is evidence that high frequency vibration can induce numbness in a controlling limb and can cause illusions of limb movement. In some conditions of direct stimulation, vibration can induce a stretch reflex in muscle at frequencies as low as 2 Hz. However, there has been no direct demonstration that effects on tracking performance were caused by neuro-muscular interference. The interference which has been cited can often be explained through other mechanisms.

4.4 Central Effects

The most commonly suggested central effect is a change in the operators' arousal level. Lewis and Griffin (1979), found consistent, although statistically non-significant reductions in operators response lags with whole-body vibration, vibration of the control only and artifically-induced 'breakthrough' on the display with no true vibration. The authors suggest that this result may indicate a selective arousal mechanism, focussing subjects' attention on different parts of the task. Catterson, Hoover and Ashe (1962) found significant improvements in performance with z-axis vibration from 2 to 11 Hz at rms displacement of 0.58 mm, although all frequencies disrupted performance at a magnitude of 1.17 mm rms. The improvement in performance at the lower magnitude may have been due to increased arousal.

A second central effect which has been suggested is that vibration could increase the workload performed by the subjects. For example, subjects may have to expend more effort in detecting target movements in the presence of visual blurring. Alternatively, they may try to 'control out' vibration-induced limb motions which could produce breakthrough. The increases in high frequency (1.3 Hz) remnant observed by Lewis and Griffin (1976; 1979) as a result of breakthrough-induced perceptual confusion suggest that subjects altered their tracking strategy to try to overcome the disruption. Performing at high frequencies can be assumed to be more demanding than performing at low frequencies. It is therefore likely that, in those studies, subjects experienced greater workloads during vibration exposure. Indeed, the reduced response lags observed by Lewis and Griffin (1979) could have arisen as a consequence of subjects trying harder.

Even if vibration increased the operators' workload, performance would not necessarily be disrupted. Overall system disruption would only occur if subjects are either unable to adapt to the increased workload, or if they can only perform the more complex task by accepting a poorer standard of performance. Vibration may also cause disruption through this mechanism when the task itself induces a high level of workload.

A third possible central mechanism is that vibration could interfere with fundamental psychological processes involved in the performance of complex skills, such as manual control. There is little experimental support for such a mechanism. Huddleston (1976, 1965) investigated a rolling arithmetic task involving both recall from short-term memory and mental arithmetic. Although the task was considered to be insensitive, there was evidence of an impairment in performance with vertical vibration. The effect was independent of vibration frequency and may therefore have been caused by a non-specific central effect, such as apprehension. Shoenberger (1973) investigated performance on a 'memory-reaction-time' task. Subjects compared visually presented single letters against a previously given set of one, two or four letters and determined, as quickly as they could, whether the probe was a member of the target set. This task has been demonstrated to measure both simple reaction time and the time to process each letter. Results showed no effect of vibration not attributable to visual interference.

In summary, various authors have speculated that vibration can affect psychological processes in a number of distinct ways. There is no direct experimental evidence to support these speculations. However, indirect evident suggests that central factors could be important, although the conditions under which they are involved may be complex. Although they are difficult either to define or measure, central effects could be of considerable significance in the performance of complex control tasks in real life.

4.5 Summary of Mechanisms

The mechanisms of vibration-induced performance disruption depend upon the nature of the system being controlled. It is clear that vibration-breakthrough and visual interference are important mechanisms in many systems. In addition, neuromuscular interference and effects on cognitive processes have been suggested, although there is little direct experimental evidence to indicate that these possibilities are important.

Table 2.2 summarises each of the mechanisms which have been suggested. The table summarises the frequency range in which each mechanism has been implicated and identifies the factors which determine the influence of each on overall system disruption. The table indicates the section of the review discussing each mechanism.

5.0 Exposure Duration

It is widely believed that, for some tasks at least, the effect of vibration on performance depends upon the exposure duration. Indeed, a time dependence for performance effects is explicitly incorporated in the current International Standards Organisation guide to the effects of vibration on humans (ISO 2631, 1985).

Time dependent effects of vibration may depend upon the nature of the task performed. The lack of general agreement

Table 2.2 Summary of Mechanisms

Mechanism	Description	Frequency range for z-axis Vibration	Influencing Factors	Section of Review
Breakthrough	Vibration transmitted to the arm directly induces activity of the controlled element on the display. Can have two effects: - vibration-correlated tracking error, - perceptual confusion through induced motion of controlled element.	Greatest in region of whole-body resonance (3 to 8 Hz). Dependent on frequency response of system dynamics.	- sensitive axis of control relative to axis of vibration - control sensitivity - control stiffness - control damping - system dynamics - arm supports - other factors affecting transmission to hand (eg. seats).	
Visual effects	Visual blurring due to relative motion between eye and display. May be caused by translational or rotational head motion.	1) Translation greatest in region of whole-body resonance (3 to 8 Hz). 2) Rotation: 2-14 Hz compensated by VOR; 0-2 Hz compensated by voluntary eye tracking.	1) Any factor influencing transmission to head (eg. seats) 2) - alcohol, drugs - central effects possibly.	
Neuromuscular effects	Inhibition or excitation of spinal and muscular reflexes. Interference with kinaesthetic feedbacks. Direct stimulation of muscle activity	Generally, 10 Hz to 100 Hz. Stimulation of stretch reflex may occur down to 2 Hz.	Muscle tension. Possibly duration. Source of stimulation.	

Table 2.2 (continued)

Mechanism	Description	Frequency range for z-axis Vibration	Influencing Factors	Section of Review
Central effects	Changes in tracking strategy to compensate for perceptual confusion. Increased workload. Changes in arousal.	Not determined. Could alter tracking strategy below about 2 Hz.	Task difficulty Task duration Motivation Training Instructions	

in the literature may be partly due to differences in the tasks investigated: for example, whether a task is sensitive to disruption by short duration vibration exposures, (less than about 5 minutes) and whether it was performed continuously throught the exposure, could be important. Observed effects may also depend on the nature of the performance measures taken as well as the nature of training given to the subjects. Further, in order to conclude that a time dependent change in performance was caused, or altered, by vibration, it is necessary to demonstrate that for the same duration, performance is different either with no vibration or with a different vibration exposure.

This section reviews twenty-one studies which have looked for duration dependent effects of vibration on performance. Four of these did not investigate effects on tracking performance but are considered to be relevant. The studies are divided into three sub-sections: those showing clear time-dependent effects of vibration (section 5.1), those which did not show clear effects but where there was at least a suggestion of a vibration effect (section 5.2), and those in which vibration had no effect (section 5.3). Exposures of between 20 minutes and 1 hour were presented in nine studies, exposures of between 1 and 2 hours in four studies, of between 2 and 4 hours in seven studies, and exposures of longer than 4 hours in six studies.

5.1 Studies showing clear time-dependent effects

Six studies provide good evidence of time dependent effects of vibration. All of these compared performance during vibration with performance over the same duration but with no vibration. Glukharev et al (1973) investigated compensatory tracking performed for 2 out of every 15 minutes up to 2 or 4 hours with z-axis vibration at frequencies between 3 and 8 Hz and at acceleration magnitudes up to 4 ms^{-2} rms. Subjects received separate exposures in each frequency by magnitude condition. Although full details and results were not presented, the effect of duration depended upon both the frequency and the magnitude of the vibration. The greatest effect occurred at frequencies between 4.5 and 4.75 Hz at 4 ms^{-2} rms. After 4 hours, this exposure produced an after effect on performance of 45% of the pre-exposure performance. At a magnitude of 2.65 ms^{-2} rms, the after-effect was 6%. The effect was therefore dependent on the vibration condition.

Wilkinson and Gray (1974), found an interaction between the effect of 3 hour exposures and 5 Hz sinusoidal z-axis vibration at 1.2 ms^{-2} rms on performance of an auditory vigilance task. The effect depended upon whether or not subjects were given feedback of performance on previous sessions. Subjects were exposed for the full 3 hours either with or without vibration on four separate occasions (ie., two with vibration, two without). When no feedback was given, vibration removed the decrement in performance observed in the latter part of the duration without vibration. When feedback was provided, vibration impaired performance compared to the no vibration condition. A feedback dependent interaction was also observed in compensatory tracking performance, although it was not statistically significant. Wilkinson and Gray concluded that vibration impaired performance when conditions were motivating, but may be beneficial by arousing the subject when motivation is low.

Results from studies by Khalil and Ayoub (1970) and Dudek et al (1973) also suggest that vibration may improve performance through arousal when conditions are unmotivating. Both studies investigated the effect of various work/rest schedules on zero-order compensatory tracking performance with or without exposure to 5 Hz sinusoidal z-axis vibration at 1.4 ms^{-2} rms. Khalil and Ayoub used work/rest cycles of 5/5 (5 minutes work, 5 minutes rest), 10/10 and 15/15. Dudek et al extended the cycles to 30/30, 40/40 and 60/60. Vibration was presented respectively for 1 hour and 2 hours. In both studies the same pattern of results emerged. With the shortest durations, vibration impaired performance. The difference between performance with and without vibration reduced as the work/rest cycles lengthened until, with the 60/60 cycle, performance was better with vibration than without. This effect was attributed to boredom occurring without vibration being partially alleviated by the vibration. The study by Dudek et al also showed more rapid recovery after vibration exposure, possibly due to the novelty of the interruption of vibration.

The other two studies to have demonstrated effects were performed by Bastek et al (1977) and by Seidel et al (1980) in the same laboratory. Both studies investigated effects on visual and acoustic target identification tasks which had previously been demonstrated to be unaffected by short duration exposures to whole-body vibration. Bastek et al exposed subjects to z-axis sinusoidal, and octave-band random vibration centred at 2, 4 and 8 Hz at two acceleration magnitudes. Each condition was presented for 30 minutes, on separate occasions, and was preceded by 20 minutes performance without vibration. The effect of duration depended upon the acceleration magnitude but not upon the frequency; higher magnitudes produced both an increase in response times and a greater number of errors.

Seidel et al presented 4 and 8 Hz z-axis sinusoidal vibration at 1 ms^{-2} rms for 3 hours. Subjects received each frequency and a no-vibration condition 4 times (ie., 12 exposures per subject). Without vibration, there was no effect of exposure duration. With both vibration frequencies performance deteriorated with time: as in the study by Bastek et al, the main effect was on response times. Because the effect was not frequency dependent, the disruption was attributed to a non-specific stress induced by the vibration. Seidel et al also found that the effect of duration reduced with repeated exposures. The greatest improvement occurred in the first 100 minutes. For both tasks this adaptation continued until the fourth replication, although the rate of adaptation was slower for the more difficult acoustic task than for the visual task. Subjects ratings indicated that the vibration exposures were felt to be more stressful than the exposures without vibration, and that repeated exposures reduced the stress.

In summary, vibration dependent effects of duration have been demonstrated on manual tracking performance and visual and auditory target detection tasks. Glukharev et al found the effect on manual tracking to be frequency dependent, while Bastek et al and Seidel et al found no frequency dependence on target detection tasks. Any frequency dependence may therefore depend upon whether the task involves control of a limb and is sensitive to disruption by mechanical interference. Glukharev et al and Bastek et al both found the effect to increase with increasing acceleration magnitude. The studies by Wilkinson and Gray, Khalil and Ayoub and Dudek et al suggested that vibration may reduce time dependent effects in unmotivating tasks through an arousal mechanism. Finally, Seidel et al demonstrated that subjects can adapt to performance over extended durations.

5.2 Studies suggesting time-dependent effects

Four studies have indicated that vibration may have altered duration effects, but without providing clear evidence. Jackson (1956) analysed heading and altitude recordings of an aircraft during four, fifteen hour flights. In each flight, pilots performed four, two hour watches with manual control being performed for at least 1 hour within each watch. Jackson also recorded turbulence-induced motion of the cockpit and correlated cockpit motion with the performance indices. Results showed deterioration in flying accuracy over the first 40 minutes within a watch and between watches 1 to 3. Correlations with cockpit motions showed that in the first two watches performance was better in turbulent air, while in the last 2 watches turbulence was associated with poorer performance. Jackson concluded that the general deterioration was not caused by turbulence although results suggested an interaction between turbulence and performance over the extended duration.

Hornick (1962) and Lewis and Griffin (1979) investigated effects of sinusoidal vibration on manual tracking performance in the laboratory. Hornick found a time dependent effect of 30 minutes exposure to y-axis vibration. The effect extended into a post-vibration period. However, full details are not provided and there was no control condition without vibration. The result may be due to simple fatigue and may not have been caused by the vibration. Lewis and Griffin exposed subjects to 4 Hz z-axis sinusoidal vibration at 1.2 ms^{-2} rms for 60 minutes. Although performance was disrupted with time, there was no overall effect of vibration compared to an equivalent period without vibration. However, there were large differences between subjects, and, for individual subjects, there were significant tendencies for error variance to increase more rapidly over time with vibration than without.

Guignard et al (1976) studied a range of tasks including foot tracking, visual detection and manual dexterity during exposure to z-axis sinusoidal vibration between 2 and 16 Hz at acceleration magnitudes equivalent to the ISO 2631 (1974) 'fatigue-decreased-proficiency' boundary. Durations ranged from 16 minutes to 8 hours. For durations greater than 2.5 hours, subjects were allowed to rest from performance for at least 5 minutes in every 30 minutes. Performance deteriorated in all conditions although there was no effect of any vibration environment. However, subjects felt that the tasks were more difficult during vibration. It is possible that subjects were able to compensate for vibration effects by increasing their effort, thereby showing no overall performance disruption.

5.3 Studies showing no time-dependent effect

The remaining eleven studies found no effect of vibration on performance of a variety of tasks over extended durations (Bennett et al (1974), Catterson et al (1962), Coermann (1940), Holland (1967), Hornick and Lefritz (1966), Mcleod et al (1977), Schmitz (1959), Shoenberger (1973), Stave, (1977, 1979)). Tasks studied have included manual tracking, visual and auditory monitoring, simple and choice reaction times, visual acuity, foot pressure constancy and 'flying' helicopter simulators. Durations have ranged from 20 minutes (Catterson et al, 1962; Weisz et al, 1965) to 8 hours (Stave, 1979; Coermann, 1940) and a variety of vibration conditions have been presented, mainly covering the frequency range from 0.17 Hz (McLeod et al) to 17 Hz (Stave), although Coermann (1940) presented sinusoidal vibration at 300 Hz. Five of these studies compared performance against equivalent exposures without vibration and four made comparisons against pre- and post-vibration exposures.

5.4 Summary

While there are clear differences between most of the studies reviewed in this Section, it is not clear why some tasks showed vibration related time dependencies and others did not. Appendix B2 summarises the studies reviewed. Where possible the table indicates the relationship between the vibration exposures presented and the ISO 2631 (1985) 'fatigue-decreased-proficiency' boundary. The table also identifies the 'vibration dose value' of the exposures as defined in the current British Standard (BSI, 1986).

There appears to be no simple factor which determines whether a task will be sensitive to time-dependent effects of vibration. Effects are likely to be dependent upon the task presented, including such factors as its difficulty and the motivation and experience of the subjects. The tasks which have been shown to be affected by vibration involved durations of between 30 minutes and 3 hours. From the data available, it is not possible to define a simple quantitative relationship between duration and performance effects. However, two studies demonstrated that the effect at a given frequency was dependent upon the acceleration magnitude.

The only factor common to the tasks affected appears to be their dependence upon attention and cognitive processes. It seems likely that the mechanism occurred at a fundamental level upon which more complex and specific mental processes depend: the mechanism may depend upon fatigue and arousal.

6.0 Summary of the Literature Review

The literature demonstrates that the effect of vibration on manual control performance depends upon the vibration environment, the nature of the system involved and the task performed, and may depend upon the duration of the vibration exposure. There are large differences between effects on individual subjects.

The means by which vibration exerts its effect are not clearly understood. The mechanisms which have been implicated were discussed in Section 4. A major aim of this thesis is to investigate the mechanisms by which low frequency whole-body vibration can disrupt the performance of a complex manual control system. The intention is to clarify the effects that have been suggested, and to investigate the frequency range over which each mechanism may be important.

The literature also indicates that there is little information on the effects of vibration at frequencies below about 2 Hz. Experiments described in this thesis will extend the frequency range to 0.5 Hz.

This Chapter has not reviewed the various models which have been proposed to explain and predict vibration effects on manual control. These will be reviewed in the next Chapter.

CHAPTER THREE

MODELLING THE EFFECTS OF VIBRATION ON MANUAL CONTROL PERFORMANCE

1.0 Introduction

This chapter has two main aims. The first is to review some attempts at modelling the effects of vibration on manual control performance. The second is to provide a framework for the experimental investigation which forms the central part of this thesis. The chapter is in three sections:

- Section 3.1 provides some general background to modelling manual control performance.

- Section 3.2 reviews and discusses three existing models of the effects of vibration on manual control performance.

- Section 3.3 presents a behavioural model summarising the processes involved in performing a manual control task, and indicating the mechanisms by which vibration has been suggested to impair performance. Sections 3.1 and 3.2 should help to put the behavioural model into perspective with respect to existing models.

1.1 Adaptation and Strategies

The ability to adapt is one of the most important properties of humans as system components. Indeed, it may be this ability alone which ensures the continuing role for humans in many control systems. Figure 3.1, taken from Moray (1978) indicates some of the most important categories of adaptive behaviour. The aims of most models of manual control behaviour are to describe and predict the ways in which humans adapt to different tasks, systems or environmental conditions.

The way a particular task is performed depends upon the strategy the operator adopts. The strategy may determine the form of any adaptation which occurs, and it may itself be changed in the process of adapting to changes in the task. The ability to adapt and the adoption of strategies are fundamental to understanding the ways in which humans perform manual control tasks. (Kelley, 1972, emphasises the importance of adaptation in manual control performance and Moray, 1978, discusses the importance of strategies in information processing).

Laboratory experiments aim to control as many variables as possible in order to study the effect of controlled changes in experimental variables on some measure of performance. To achieve this control in manual tracking tasks, it is normally necessary to train and instruct subjects to perform the task in a prescribed manner. The extent to which adaptive changes in task performance are successfully controlled in the laboratory is not known.

Techniques from control theory have been extensively applied both to the study and modelling of manual control behaviour in the laboratory, and to the design and evaluation of manual control tasks in both commercial and military settings. Most of this work is beyond the scope of this thesis. Consideration of some of these approaches however will provide a reference for the model presented in section 3.3.

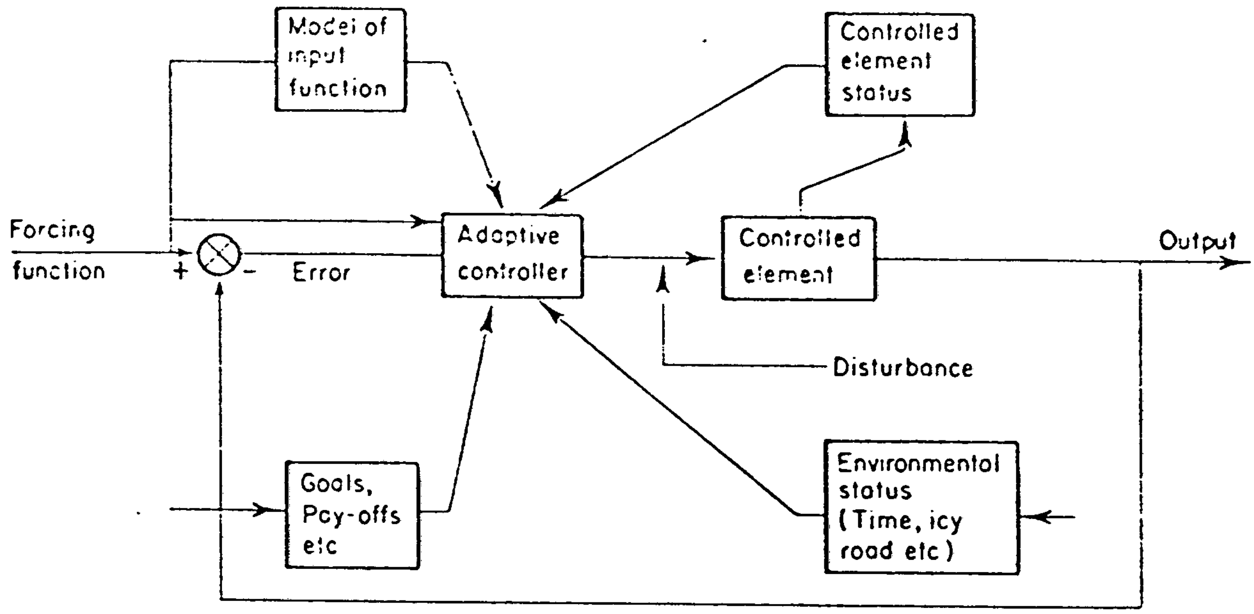


Figure 3.1 The human as an adaptive manual controller (from Moray, 1978, after Young, 1969).

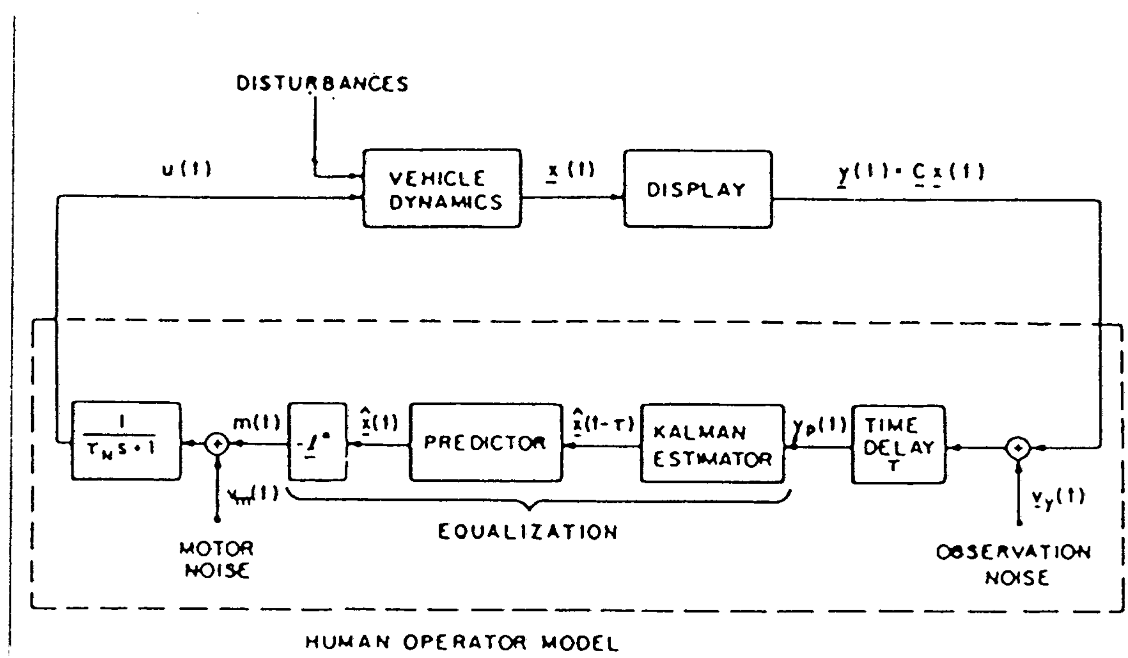


Figure 3.2 Optimal Control model of human control behaviour (from Kleinman, Baron and Levison, 1971).

2.0 Models of Manual Control Performance

2.1 The Optimal Control Model

Kleinman, Baron and Levison (1971) used modern control and estimation theory to develop a model incorporating the inherent limitations of the human as an information processor. The model assumes that the well trained controller adapts his behaviour to compensate for his limitations. He therefore performs optimally. Figure 3.2 illustrates the model. The human is assumed to observe information about the state of the system presented continuously on a visual display. The operator may act upon one or more types of displayed information (such as target position and error), and their time derivatives. 'Observation noise' is added to each display parameter, accounting for errors in observing information on the display. A single parameter, τ, accounts for all time delays involved in the neuromotor conduction pathways and central information processing.

The operators' adaptation is modelled as a combination of a Kalman filter or estimator, a least mean-squares predictor and a set of optimal feedback gains. The Kalman estimator yields an optimal estimate of the state of the system based upon the noisy signal, $\underline{y}_p(t)$. The predictor compensates for the inherent time delays of the human, and the optimal gains minimise some pre-determined cost-function expressing task requirements. The optimal gains explicitly incorporate the operators' control objectives by specifying cost weightings associated with each source of display information used. A second noise process, $U_m(t)$, representing imperfect execution of central commands, and a first-order lag, τ_H, accounting for physiological restrictions on the neuromuscular actuation system, complete the human operator model.

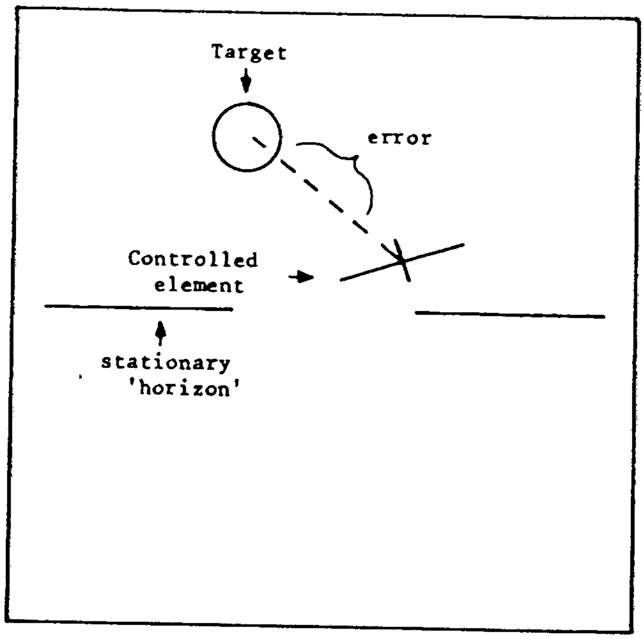
The observation and motor noise processes are approximated by Gaussian white noise scaled according to the signal with which it is associated (respectively, $\underline{y}(t)$ and $m(t)$). Both of these processes may be sensitive to system and environmental factors, such as the quality of the display, sensitivity of the control or exposure to vibration.

The Optimal Control model does not attempt to describe the mental or physiological processes involved in control behaviour. Time-varying changes in the operators' linear response as well as the adoption of non-linear strategies - both of which may be important in voluntary adaptive behaviour, particularly during stress - are indistinguishable from the noise processes included in the model. An application of this model to predicting effects of vibration will be discussed in section 3.2.2.

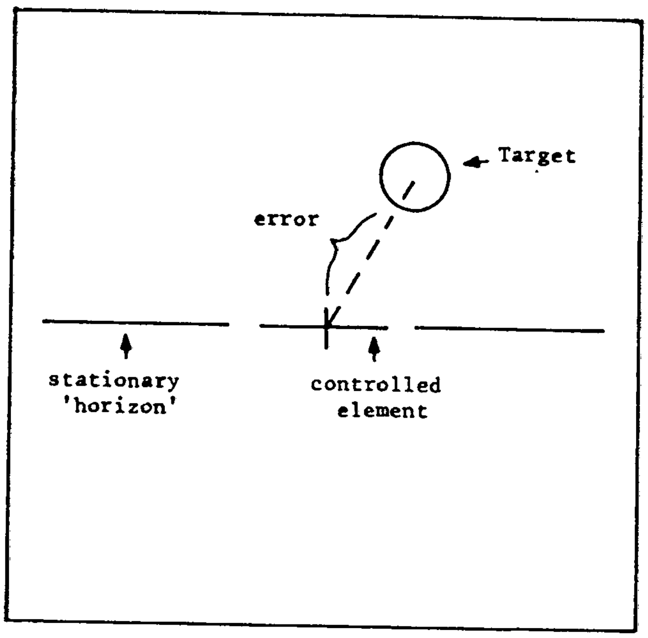
2.2. <u>Pursuit Tracking</u>

Figure 3.3a shows a representation of the pursuit tracking display used in the experimental part of this thesis. Subjects controlled the position of the cross (controlled element) on the display. The target moved around the screen in a random manner. The main task was to keep the cross inside the target at all times. (In these experiments subjects also performed a secondary task. Details of the tasks, forcing functions and analysis procedures are presented in chapter 4).

With a compensatory display, only the controlled element moves. The controller sees only the instantaneous error between the forcing function and the system response, although he may derive error rate information. Figure 3.3b shows a compensatory version of the display.



a) Pursuit



b) Compensatory

Figure 3.3 Representations of (a) Pursuit and (b) Compensatory tracking displays.

The performance of compensatory systems is often described using the 'Crossover' model. The background, justifications and assumptions of this model are described in detail in McRuer and Krendel, 1974. According to the Crossover model, the controller adapts his behaviour to maintain consistent overall system performance under a wide range of conditions by adjusting his internal gains and his effective time delay. (The term 'Crossover' refers to the frequency range over which the model applies). This model is closely related to the Optimal Control model. As with the Optimal Control model, the Crossover model has been found to be extremely useful in describing and studying both laboratory and real-life tasks.

Because of the additional sources of information available compared with a compensatory display, pursuit tracking behaviour is more difficult to describe or analyse. As well as the directly displayed target, controlled element and error information, the operator may derive the first, and possibly higher, time derivates of each. However, all of this information is not necessarily used. Figure 3.4 shows the model of pursuit tracking proposed by Hess (1981). Target position and controlled element rate information were not included and good fits to experimental data were still obtained.

The model of pursuit tracking developed by Hess (1981) incorporates a switch representing the distribution of attention between the various information sources (see Figure 3.4). The switch is controlled by pre-determined parameters giving the probabilities of each source being used. With a human controller, the input attended to at any instant will depend upon a complex decision process incorporating the aims of the task and the strategy adopted. (McRuer and Krendel (1974) explicitly incorporate a decision process in a model of complex control behaviour).

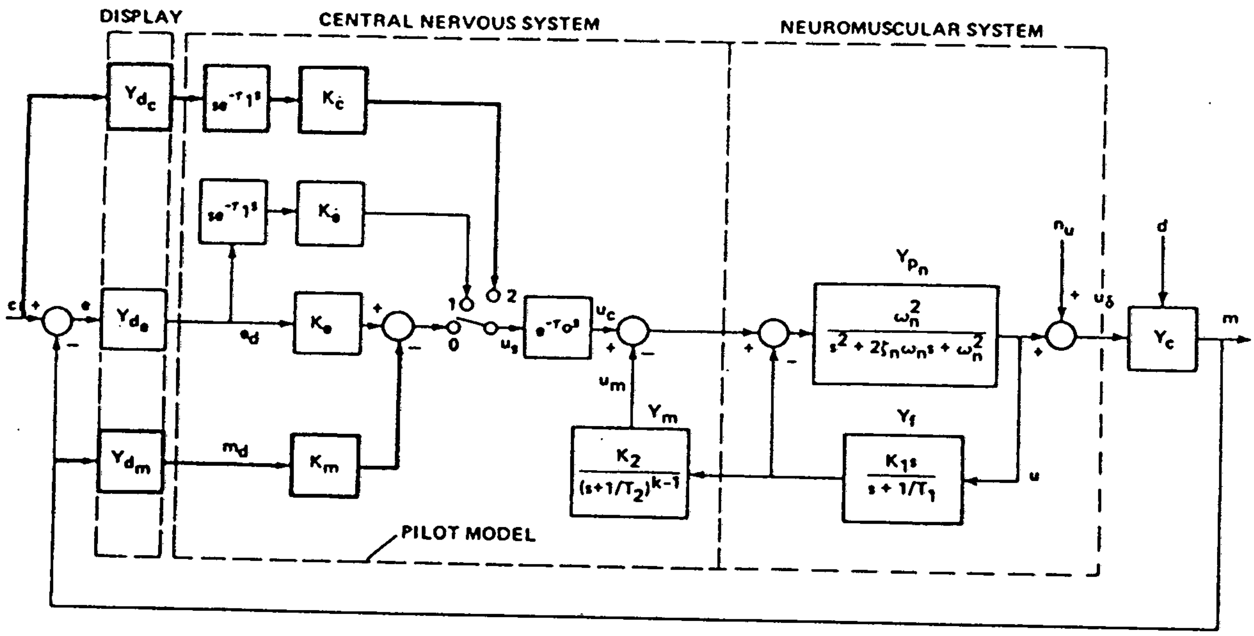


Figure 3.4 Model of Pursuit tracking behaviour (from Hess, 1981)

Pursuit displays do not necessarily produce pursuit behaviour. As Hess (1981) points out "When faced with (a pursuit display) the pilot may simply ignore all but the explicit error information and effectively adopt compensatory behaviour". (p.264). Alternatively, if the controller is able to predict the future path of the target even for short periods of time, he may ignore all visual feedback and perform in an open-loop 'pre-cognitive' manner. The Successive Organisation of Perception (SOP) theory (McRuer and Krendel, 1974), describes how, as skills are developed, the operator progresses from simple, compensatory error correcting through a pursuit stage using visual and proprioceptive feedback, to a pre-cognitive phase in which stored repertoires of responses are 'released' and run their course in an open-loop manner. In performing a given task, the skilled operator will switch between pursuit and pre-cognitive behaviour depending upon the difficulty of the task, the predictability of the target motion and the goals and response criteria - ie., the strategy that the operator adopts.

The models discussed so far incorporate the assumption of quasi-linearity of operator behaviour. This assumption accepts that the human is not a purely linear operator: the human has thresholds determining, for example, the minimum error which can be detected, and the minimum output which he can exert, he may be distracted by extraneous factors and he has, potentially, an extremely large repertoir of non-linear behaviour which he may adopt. Indeed, human subjects could stop performing at will should they wish.

Quasi-linearity assumes that the highly skilled, highly motivated subject constrained to perform a well defined task and to achieve a defined goal can be described as if he were a linear system. Any response not linearly related to the movement of the target is modelled as 'noise'. As well as including true operator-generated 'noise' arising from input and output inaccuracies and such things as muscular tremor, the added ' noise' component includes all of the humans' intentional behaviour not linearly related to movements of the target. Furthermore the added 'noise' includes components due to time-dependent changes in the operators' linear response. Non-linear behaviour and time dependent changes in linear parameters could arise through the effects of fatigue or through changes in strategy: the operator may be able to switch from one, linear or non-linear, response mode to another depending on the goals of the task, the performance achieved, the instantaneous demands of the task and the performance criteria adopted.

3.0 Models of the Effects of Vibration on Manual Control Performance

In this section three approaches to modelling effects of vibration on manual control performance will be reviewed and discussed. The three approaches are very different in their aims, the form they take and the generality of their application.

3.1 A Taxonomic Model

Lewis and Griffin, (1976) described a taxonomic model of the processes which may be involved when a human performs a manual control task. The model, shown on Figure 3.5, amounts to a simple description of some general sensory, perceptual, cognitive

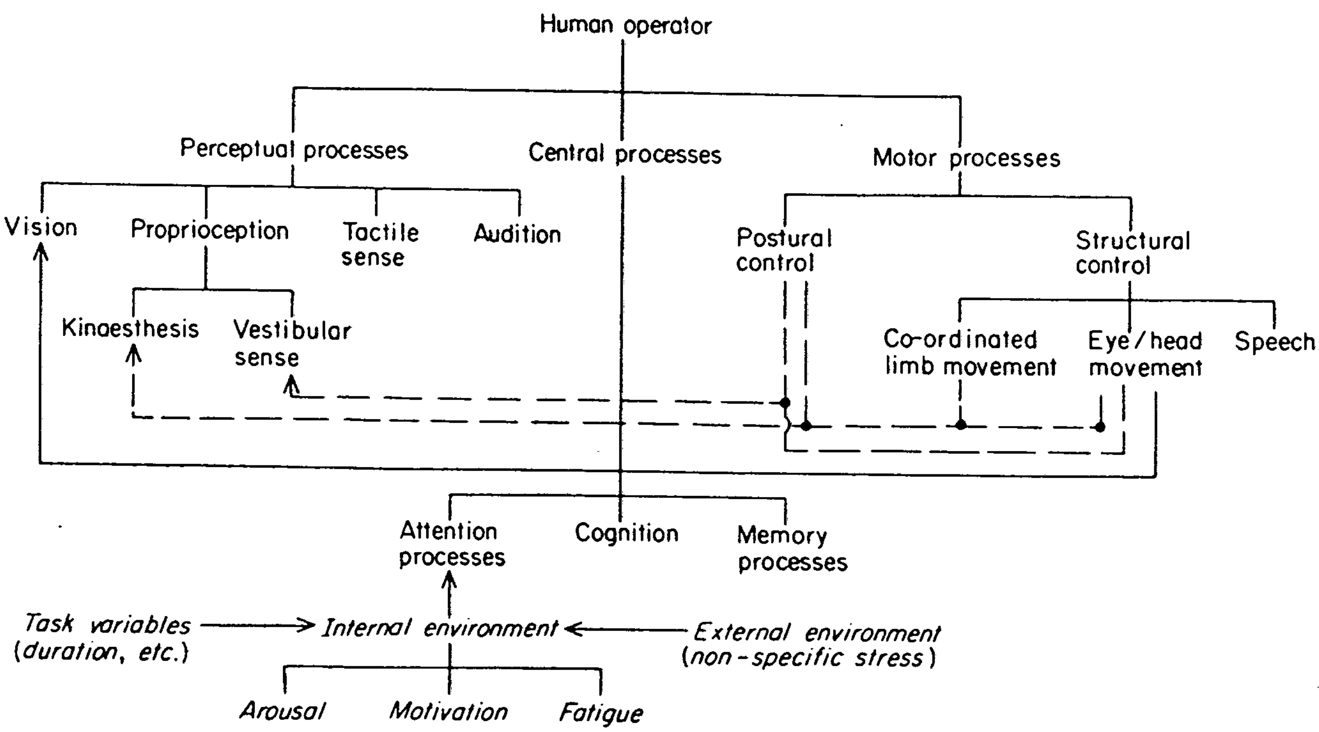


Figure 3.5 A taxonomic model of human operator processes contributing to performance with vibration (from Lewis and Griffin, 1978).

- - -→, Fundamental feedback pathways;
——→ interactive effects

and motor functions. Lewis and Griffin proposed that if effects of vibration on isolated functions could be determined, effects on task performance could be predicted by combining effects on identified component processes. They suggested that, while the model was not intended to be rigorous, it may have application in both identifying weaknesses in planned systems and in guiding research.

Although the general approach of the taxonomic model may be useful (ie., predicting gross effects from a knowledge of effects on component processes), the application of the model has not been demonstrated. Three general shortcomings can be identified.

First, the processes identified are relatively arbitrary, and there is no indication of the relationships between them. For example, recent models from experimental psychology include cognitive processing as a central component of memory, rather than as a distinct process, (Baddeley, 1976). The distinction between perceptual processes and central processes is also not clear. Second, there is no indication of the way in which effects of vibration on individual processes might combine to affect overall task performance. This problem is not unique to this particular model, however. Indeed, it is common throughout Human Factors. Third, for the model to be useful as an approach, or technique, for identifying weaknesses in a system it would be necessary to provide some detailed guidance on the procedure for identifying the processes involved in any given task.

In principal, the taxonomic model proposed by Lewis and Griffin may help in predicting whether a particular task is likely to be disrupted by vibration. However, a great deal of research would be required before anything more than simple statements of possibility could be made.

3.2 Biodynamic Models

Jex and Magdaleno (1978) provide a general overview of an extensive programme, carried out mainly in the United States, aimed at producing mathematical models of the effects of vibration on aircrew performance. The overall objective was to specify the model in sufficient detail that a computer programme, supplied with appropriate system information, could predict both visual and tracking performance for a wide range of systems under a wide range of vibration conditions. The model could therefore be used as a tool providing quantitative guidance to designers.

This model is applied in three stages. The first stage involves defining a functional model describing the particular task of interest and specifying the properties of each of its components; this task model is generated from a more general model of performance, illustrated on Figure 3.6. The function of this stage is to identify those components of task performance which vibration may disrupt. The second step is to calculate the vibration transmitted to such things as the seat, head, eyes and control, depending upon the components of the task model. Where the task includes a visual component, this stage also estimates the relative motion between the eye and the image on the display, taking account of the effects of both the vestibulo-ocular reflex and voluntary eye tracking, both of which act to compensate for induced image motion.

The third stage relates biodynamic response to task performance. The authors acknowledge that this is the weakest link in the model and, for visual performance, depends largely upon empirical relationships between induced motion and performance decrements. To predict effects on manual control performance, a further model, proposed by Levison (1977), is used. Levison's model, illustrated on Figure 3.7, is an application of the Optimal Control model (described in section 3.1.2). Effects of vibration

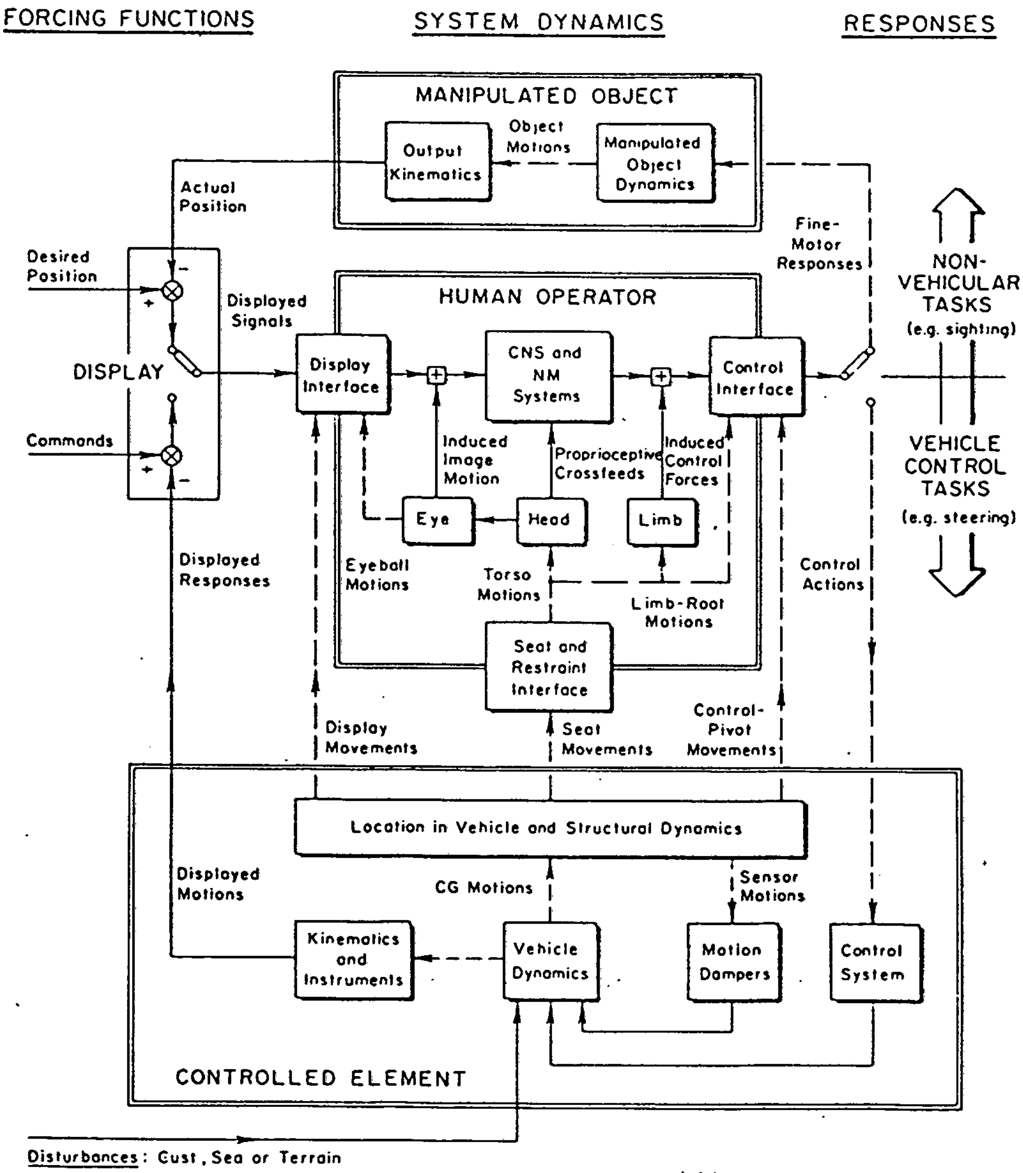


Figure 3.6 Overall model structure for evaluating biodynamic interference with task performance (from Jex and Magdaleno, 1978).

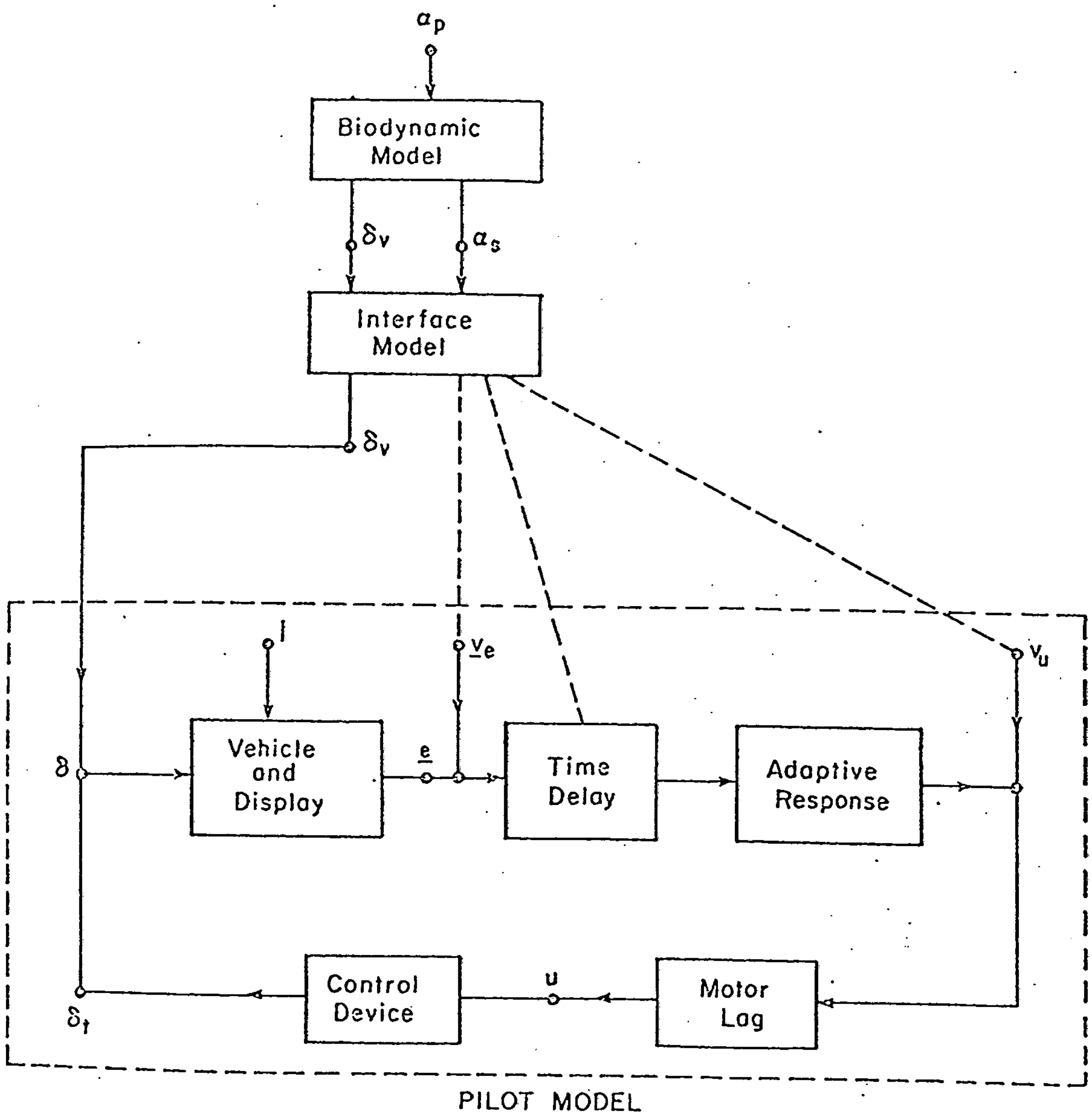


Figure 3.7 An Application of the Optimal Control model to predicting effects of vibration on manual control performance (from Levison, 1977).

are accounted for by a combination of direct vibration breakthrough to the control, and changes in the adaptive parameters of the basic operator model; specifically, increases in pilot-induced motor noise and processing time delays. This model has been found to provide reasonable agreement between predicted and measured rms control activity and rms tracking error across a range of vibration environments and with a variety of systems.

The biodynamic modelling programme summarised by Jex and Magdaleno represents a major effort in modelling the effects of vibration on performance. The models are extremely detailed in their description of both active and passive mechanisms affecting the relative motion between the body and relevant parts of the immediate environment (such as displays and controls). Such detailed descriptions are useful both in indicating the location of vibration effects and in providing a framework to guide further research. In addition, the fact that reasonable predictions have been obtained suggests that the model may be of use in 'real-world' applications.

Despite these advantages however, such biodynamic models have considerable limitations. First, in order to implement them to evaluate even a relatively simple system, it is necessary to provide quantitative estimates of a great many parameters. Many of these, such as most of the 21 parameters needed to define the dynamic response of the neuro-muscular system, cannot readily be measured.

Second, even when all of these parameters are defined, relating the predicted biodynamic response to effects on performance remains the weakest part of the model. The predictive ability even of the complex model developed by Levison (1978) is limited and for many applications may be wholly inadequate: for example, predictions of tracking error in Levison's model are calculated as the average rms error. In many systems, average rms tracking error would not be useful as a measure of performance. As Lewis and

Griffin, (1978) point out, it is often not sufficient to know the response of the 'average' person: it is the response of an individual in a particular setting which may define whether or not the performance of a system is acceptable. It may often be important to quantify, at least, the variability in the effect with different individuals as well as the average effect.

These criticisms should not detract from the contribution which these models make. The models are complex because the nature of the system and the effects of vibration are complex and in many instances poorly understood. The generality of the models is also restricted by the complexity of the effects which can occur: effects can depend upon both the task and control system involved, as well as the nature of the vibration environment. Furthermore, the fundamental mechanisms by which vibration can disrupt performance are not well understood.

Even for a relatively obvious form of interference, such as vibration-correlated activity of the controlled element on the display (vibration breakthrough), the precise mechanism by which performance is disrupted is not clear. Lewis and Griffin (1979) have shown that breakthrough appearing on the display can produce perceptual confusion leading to an increased proportion of control activity not linearly related to the target motion (ie., remnant). This increase in remnant reflects a change in the way the task is performed in the presence of vibration breakthrough; however, the nature of the change has not been determined.

To adequately predict the effects of vibration on performance, it will be necessary to fully understand both the mechanisms by which vibration interferes with the processes involved in task performance, and the ways in which humans change or adapt their performance in response to the interference.

4.0 A Behavioural Model

This section presents a behavioural model of the effects of whole-body vibration on manual control performance. The intention is to summarise the mechanisms which have been demonstrated, or suggested, to be important in producing the vibration effects, and to emphasise the adaptive nature of human performance. The model is not intended to be a complete description of the ways in which humans perform manual control tasks: the processes involved can be extremely complex and in many cases are themselves poorly understood. The processes described allow the suggested mechanisms of disruption by vibration to be indicated.

Assumptions made will be indicated where appropriate. The fundamental assumption underlying the model, however, is that human control performance can be considered as though the human was generating discrete responses to instantaneous observations about the system status.

4.1 Description of the Model

4.1.1 Without Vibration

The model is shown on Figure 3.8. The key to the model is given on Table 3.1. The basic model summarising the processes involved in manual control performance will first be described. Mechanisms by which vibration has been suggested to interfere with these processes, and adaptive changes in performance which may result, will then be considered.

Three stages of information processing, roughly

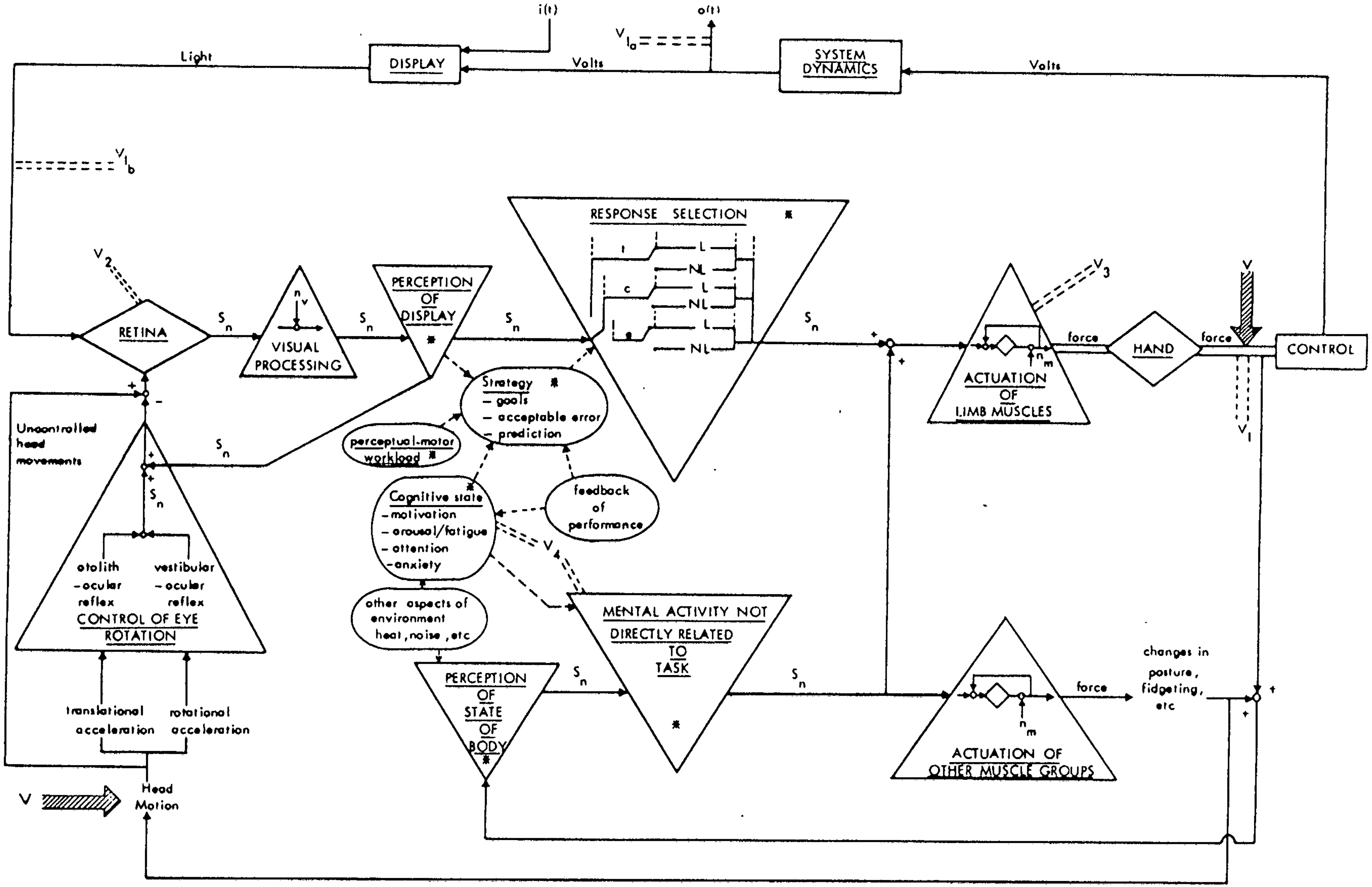


Figure 3.8 A behavioural model of manual control performance during exposure to whole-body vibration. (See Table 3.1 for Key).

Table 3.1 Key to Figure 3.8

◇	=	Physiologicol location
△	=	Physiologicol process
▽	=	Psychological process
○	=	Factor influencing psychological processes
□	=	System hardware
═══	=	Physical link
⟶	=	Direction of flow of information
- - - →	=	'can influence'
V ⇨	=	Location of vibration-induced activity
V_X =====	=	Location of interferance by vibration mechanism x
✱	=	Location of secondary effect of vibration
S_n	=	Neural signal
N_m	=	Neuro-musculor 'noise'
N_v	=	Visual 'noise'
t	=	Response to target position, velocity, etc
c	=	Response to controlled element position, velocity, etc
e	=	Response to error position, velocity, etc
L	=	Linear response mode
NL	=	Non-linear response mode
i(t)	=	Position of target of time (t)
o(t)	=	Position of controlled element at time (t)

corresponding to identifiable psychological and physiological processes are indicated; an input (or visual processing) stage, a central (or cognitive processing) stage, and an output (or muscular actuation) stage.

Visual Processing Stage

The controller (ie., the human) is assumed to obtain information about the state of the system by observing a visual display. The vestibular system (including the semi-circular canals, which are sensitive to rotational acceleration of the head, and the otoliths, which are sensitive to linear acceleration of the head) compensate for movements of the head by producing rotational eye movements. This compensation attempts to keep the image of the display elements on the same area of the retina at all times. The pattern of light on the retina is processed, principally in the visual cortex, and gives rise to a perception of the displayed information. The controller can induce voluntary eye movements to bring any part of the visual field onto the fovea of the retina.

Cognitive Processing Stage

The controller uses the perceived information to select an appropriate response based on the instantaneous state of the system and the strategy which is adopted: the strategy depends, for example, on the acceptable error (which is defined by the system objectives), and the extent to which prediction is possible. Strategy depends onthe cognitive state of the controller, such as his motivation and level of fatigue or arousal. The cognitive state may itself be influenced by a variety of factors, including the controllers' perception of his performance, and other environmental or personal factors. The difficulty of the task, in terms of the perceptual-motor workload involved, can also influence the strategy adopted.

Three assumptions are made in the cognitive stage of the model. First, that the controller responds to a single item of displayed information at any instant of time. Second, that there are a large number of modes of responding potentially available, and third, that the controller can switch between different modes of responding depending upon the instantaneous state of the system, the demands of the task, and the strategy adopted. A time-history of the controllers' response would therefore be composed of the accumulation over time of the results of the various modes of responding used.

As indicated earlier, in most tasks more than one type of information is available from the display. In pursuit tracking, movements of the target, of the controlled element, and of the difference between them (ie., the instantaneous error) could all potentially be used as the basis of a response. Furthermore, the controller could respond to the displacement of each, or its first or higher time derivatives. On the model, the process of 'Response Selection' indicates some of the types of information available. For simplicity, the model does not indicate first or higher time derivates, although it is assumed that these could be used as the basis of a response.

Manual control performance has been shown to be adequately modelled for many purposes by assuming that the highly trained controller operates essentially as a constant parameter linear system; ie., a system which can be described by linear differential equations, (eg., Licklider, 1964; McRuer and Krendel, 1974). During vibration exposure however, a number of experiments have shown an increase in the proportion of tracking error not linearly related to movements of the target (Allan et al, 1973; Levison and Harrah, 1977; Lewis and Griffin, 1977, 1978, 1979). These results suggest that the assumption of quasi-linearity may not be sufficient to understand the ways in which vibration can affect manual control performance. Indeed, the use of these models can restrict the interpretation of the underlying mechanisms. In his application of the Optimal Control model to predict vibration effects, Levison (1977) accounts for the effects of vibration by assuming interference with 'motor related sources of randomness'. This can include both interference with neuro-muscular processes and changes in the way the task is performed; specifically, the adoption of tracking strategies not linearly related to the motion of the target.

The behavioural model assumes that humans can intentionally adopt response strategies which are both linearly and non-linearly related to movements of the target. It also emphasises the ability of humans to instantaneously switch between these different response modes. The behaviour underlying 'linear' and 'non-linear' responses is likely to be a great deal more complex than these simple descriptions might suggest. Nevertheless, because of the widespread use of spectral analysis techniques, and because of their relative amenity to measurement, the process of 'Response Selection' on the model separates the responses which may be adopted into these two general categories. The output from the Response Selection process is a neural signal inducing activity in muscle groups involved in producing forces at the hand.

As well as Response Selection, the cognitive stage of the model also contains a process indicating cognitive activity not directly involved in task performance. This may produce general awareness of the physical state of the body (such as muscular fatigue, or the position of limbs, etc), as well as its psychological state (for example, the experience of discomfort or boredom). This process can also produce neural signals which may, either intentionally or unintentionally, induce muscular activity. Part of this muscle activity will cause movements of body parts not involved in task performance; for example, movement of the torso to alleviate discomfort. A component could also give rise to muscle activity producing forces at the hand.

In summary, the Cognitive Processing stage produces neural signals inducing muscle activity. The muscle activity which arises is of two types; that producing forces at the hand, and that producing forces at other parts of the body. Forces at the hand are further considered to be of two types; those intended to produce activity of the controlled element, and those arising from cognitive activity not related to task performance, such as attempts to alleviate discomfort at the hand.

Muscular Actuation Stage

In the Muscular Actuation stage, the neural signals from the Cognitive stage induce muscle activity. The neuro-muscular system is exceedingly complex. The model does not attempt to describe it. The model merely separates those muscle groups involved in producing forces at the hand to effect the required changes in the state of the system from those producing forces in other parts of the body. In both cases, muscles are modelled as being under feedback control. A noise source is indicated accounting for spontaneous muscle activity, such as tremor. (Jex, 1974, describes a linear model indicating the complex processes and feedback mechanisms involved in muscular actuation).

Actuation of limb muscles produces forces at the hand which, in turn, induce forces or displacements on the control. Actuation of other muscle groups can produce changes in posture or general fidgeting. Movement of the body, and of the hand on the control are fed back to the cognitive stage and produce a perception of the state of the body. Movements of the head are sensed in the vestibular system and can produce a perception of head position.

The activity induced at the control is fed through the system dynamics. The resulting system response is indicated by movement of the controlled element on the display. Depending on the type of task, the controller obtains visual feedback of his response either directly (in a pursuit task), or combined with the new target position (in a compensatory task).

This completes the description of the basic model of manual control performance. The next section considers the mechanisms by which vibration could interfere with this basic model.

4.1.2 Effects of Vibration

Vibration is assumed to interact with the basic model at two principal points; it can produce movement of the head, and can directly induce forces at the hand. The extent of interference at both of these points will depend upon the transmission of vibration through the body to each location. This will depend upon the vibration frequency as well as the nature of the seat and seat restraints, and whether an arm support is provided. Other factors, such as the posture adopted and whether a helmet is worn can also be important.

The model indicates four principal mechanisms by which vibration could interfere with performance of a continuous manual control task (the experimental evidence for these mechanisms is reviewed in greater detail in the Literature Review in chapter 2).

(i) Vibration Breakthrough: vibration-induced activity at the control can be transmitted through the system dynamics to produce activity of the controlled element on the display at the vibration frequency. This is termed 'vibration breakthrough' or 'feedthrough'. The extent to which vibration breakthrough is important in disrupting performance will depend upon the sensitivity of the control and the frequency response of the system dynamics at the vibration frequency; first-order dynamics, for example, attenuate control activity by one half for each doubling in frequency of control activity. Breakthrough is therefore less important in a first-order system than in a zero-order system, which transmits all frequencies with the same gain (Lewis, 1980). On the model, vibration breakthrough is indicated by V1.

Vibration breakthrough can increase tracking error in two ways; first, by directly increasing the displacement of the controlled element relative to the target (V1a) and, second, by increasing the uncertainty of the precise position of the controlled element (V1b, Lewis and Griffin, 1979).

(ii) Visual Impairment: Vibration-induced movement between the eye and the display can cause the image of the display elements to be spread over a larger area of the retina than when there is no relative movement. This can give rise to a blurred image of the display elements, producing increased uncertainty of the precise position of the target and controlled element. The extent to which visual blurring is important will partly depend upon the ability of the vestibular system to compensate for induced head accelerations: the vestibular-ocular reflex can compensate for rotational head accelerations to produce a space-stable eye at frequencies up to at least 5 Hz (Benson and Barnes, 1978). The human can also induce pursuit eye movements to compensate for relative movement between the head and the display at low frequencies (below 2 Hz).

(iii) Neuro-muscular interference: a number of authors have suggested that vibration directly interferes with neuro-muscular processes (Allan et al, 1973; Levison, 1977; Lewis and Griffin, 1976). Such interference would increase the signal-to-noise ratio between intentional, task related muscle activity and unintentional or random activity, and may lead to perceptual confusion about the forces generated in the controlling limb. It is known that direct stimulation of muscle at vibration frequencies above about 20 Hz can induce reflex muscle contraction (eg., Gail et al, 1966). This has been termed the Tonic Vibration Reflex (TVR). A stretch reflex has also been observed during direct muscle stimulation at frequencies as low as 2 Hz (Rack, 1979).

There is little evidence of direct muscle stimulation caused by exposure to whole-body vibration at frequencies below about 18 Hz. Furthermore, there is no evidence that such interference could directly impair tracking performance. However, Gauthier et al (1981) demonstrated that 18 Hz vibration applied directly to calf muscles in humans could impair foot tracking performance and the production of constant torques at the foot. Neuro-muscular interference is indicated by V3 on the model.

(iv) Central Effects: it has been suggested that vibration could directly interfere with cognitive processes: specifically, that vibration could increase the level of arousal of the controller, or that it could induce fatigue (although this may be as a consequence of effects on muscular activity). There is little direct evidence of such interference. Increases in arousal could produce improvements in performance during vibration; an improvement in performance compared to a static environment was observed with low magnitudes of vibration by Catterson et al, 1962. Lewis and Griffin (1979) suggested that reductions in the phase lag of human operator transfer functions may have been due to an increased level of arousal. Effects on arousal and fatigue are most likely to influence performance over extended durations. This mechanism is indicated by V4 on the model.

As well as these principal mechanisms, the model indicates four secondary effects which could arise as a consequence of the mechanisms described above. These effects are indicated on the model by *. There is no clear evidence of precisely the type of secondary effects which can occur, although there are many possibilities. These include:

(i) Increased workload : if the controller is unable to see the elements on the display clearly, or if there is uncertainty of the force exerted on the control, the controller may have to exert greater effort (in the sense of concentration or attention) to detect the information required.

(ii) Changes in strategy : the adoption of different modes of responding may depend upon the instantaneous error between the positions of the target and the controlled element. If the amount of error increases, the controller could, for example, increasingly respond in a non-linear manner (such as producing ballistic type movements to compensate for delays in detecting error). Increases in workload could also lead to a change in strategy, such as accepting increased error in order to reduce the workload. There are a great many possible ways in which the controller could adapt his strategy.

(iii) Active compensation: if the controller perceives vibration-induced activity at the hand, he may attempt to actively control it out by inducing compensating muscular activity. This could lead to both an increase in the workload performed and a reduction in the attention paid to the principal task. The controller could also change posture or voluntarily increase muscular tension in various parts of the body to try to minimise discomfort or otherwise reduce the experience of motion in the body. Any of these, or other effects, could distract the controller from performing the task, and may increase activity in the controlling limb not related to performance of the task.

5.0 Summary

This chapter has described some current models of manual control performance. Three attempts at modelling the effects of vibration on tracking performance have also been reviewed. The extent to which these models predict effects of vibration is limited both by the complexity of the effects which can occur and the lack of understanding of the mechanisms producing the effects.

A behavioural model was presented summarising the processes involved in manual control performance, and indicating the mechanisms by which vibration has been suggested to interfere with these processes. The model emphasises the adaptive nature of human performance.

In the remainder of the thesis a series of experiments investigating manual control performance during exposure to low frequency, z-axis, whole-body vibration are reported. This work attempts to experimentally determine the mechanisms by which vibration disrupts performance of the particular task studied. The results are interpreted by referring to the behavioural model.

CHAPTER FOUR

INTRODUCTION TO EXPERIMENTATION

This Chapter provides details of the equipment, systems, task performance measures and subjects used in the experimental work described in Chapters 5 to 10. The Chapter is in four sections: section one describes the systems and task studies, section two describes the vibrators, accelerometers and signal conditioning equipment, section three describes the signal processing, data analysis and performance measures taken and section four gives details of the subjects used.

4.1 Tasks and Control System

This thesis set out to study performance of a complex manual control task during exposure to whole-body vibration. However, in order to study the mechanisms which may be involved in producing the effects of vibration on performance, the details of the system and tasks were altered according to the aims of each experiment. The ways in which each of the components of the system was altered between studies are briefly summarised below. The reasons for each change will be indicated in the following sub-sections.

Tasks – The principal task studies was a combined continuous and discrete pursuit tracking task. In two studies however, the target (ie., the element on the display which the subjects tried to track) did not move. In these studies, the task was to hold the controlled element (ie., the element on the display which was under the subjects' control) stationary in the centre of the display.

<u>Forcing Functions</u> - The time histories used to move the target around the display are known as 'forcing functions'. In the studies in which the target moved, the frequency content of the forcing functions was altered depending on the system dynamics, the sensitivity of the control and the duration of the task.

<u>Viewing Conditions</u> - The same display was used to present the target and controlled element in all studies. However, subjects viewed the display either directly or through a collimating lens. In two studies, both direct viewing and collimation were used.

<u>Control</u> - The same side-arm, force-operated control was used in all experiments. The sensitivity, or gain, of the control (defined as the output of the control for each unit of force applied) was varied depending on the forcing functions, system dynamics, task duration and objectives of each study.

Arm Support - In two studies the subjects' controlling arm was supported and data was collected both with and without the arm support.

System Dynamics - The first experiments investigated effects on a complex, cross-coupled control task involving a simulation of aircraft dynamics in 3 axes. These dynamics were simplified in later studies to produce a task allowing independent control in the 2 axes of the display (horizontal and vertical).

The remainder of this section describes each of these variables and describes the changes made in each case.

4.1.1 Tasks

In four of the experiments, subjects performed a combined continuous and discrete pursuit tracking task. A circle subtending approximately 32 minutes of arc of viewing angle represented a target and moved around the display in an apparently random manner. The target was moved independently in the horizontal and vertical axes of the display. (Details of the forcing functions and viewing conditions are given in sections 4.1.2 and 4.1.3 respectively). Subjects moved a cross on the display (controlled element) by operating a control with their right hand. The relationship between the output of the control and the resulting movement of the controlled element is defined by the system dynamics. (The control and system dynamics are described in sections 4.1.4 and 4.1.5 respectively). The aim of the continuous tracking task was to keep the controlled element inside the area defined by the target at all times. Figure 4.1 shows the target and controlled element as they appeared on the display.

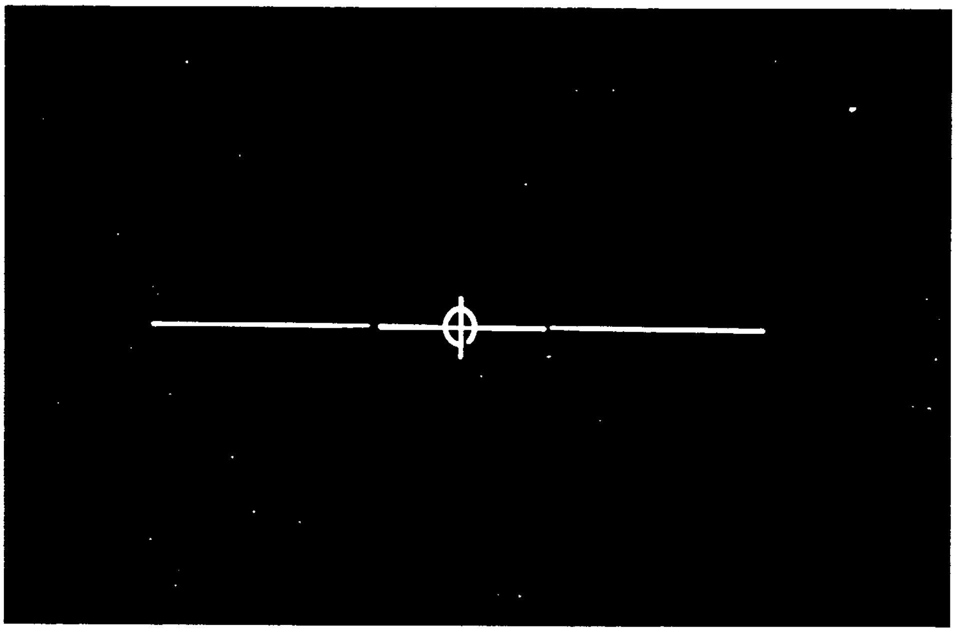


Figure 4.1 The display elements as they appeared in experiments 1, 2, 3, 4 and 6.

In the discrete task, subjects were required to press a button on the control whenever the controlled element entered the target, and to keep the button pressed as long as they were 'on' target (ie., inside the area of the target). As soon as the controlled element came out of the target the subject was to release the button. Subjects therefore performed a discrete task which depended upon performance of the continuous task. They were asked to 'hit' the target (ie., press the button while 'on' target) as often as possible, but to make as few error - 'misses' (not pressing the button while on target) and 'false alarms' (pressing the button while off target) - as possible. In some of the experiments a reward structure was introduced in which subjects earned points for each instant 'on' and 'hitting' the target, but were penalised for each instant 'off' target and making a 'false alarm'. They were paid according to the points they accumulated.

In the other two experiments, subjects did not perform the complex tracking task. In these studies subjects simply tried to keep the controlled element stationary in the centre of the display. The target did not move in either case.

4.1.2. Forcing Functions

The time histories used to move the target around the display are termed 'forcing functions'. The forcing functions used in the thesis were originally designed to meet two criteria:

(i) they were to be random in appearance.
A number of different forcing functions

were used to prevent subjects learning the time course of any one; and

(ii) their frequency content should produce a task near the limits of controllability. This was achieved by testing two trained subjects with a number of forcing functions having differing upper cut-off frequencies and spectral shapes. Forcing functions were selected based upon both tracking performance and subjective estimates of tracking difficulty.

The original forcing functions were created by low-pass filtering digitally generated random time histories at 0.1 Hz with attenuation of 24 dB per octave thereafter. However, after two experiments, and after results obtained by Wells (1984), it was felt that the non-constant rms displacements in the original forcing functions may have contributed to the variability in the results by producing differences in the difficulty of each task. It was also felt that the tasks would be less predictable if their low frequency content was increased: this would increase the proportion of time the target spent in the periphery of the display, thereby increasing the likelihood of subjects following the target at all times rather than, for example, simply waiting for it to return from a brief excursion to the limits of the display.

For the later studies, therefore, the random time-histories were first integrated over time to increase their low frequency content. They were then band-pass filtered with a lower cut-off frequency of 0.01 Hz (to avoid excessive displacements) and an upper cut-off frequency of 0.2 Hz, with attenuation of 12 dB per octave outside this region. The upper cut-off frequency was increased to produce performance at the highest frequencies which could be achieved and to maintain the difficulty of the task after changes in the system dynamics and control gains. (The reason for introducing these changes will be described in Chapter 7).

4.1.3. Viewing Conditions

The target and controlled element as well as a stationary 'artificial horizon' were presented on a 9" (228 mm) diagonal Cathode ray display (Kikusui Model 5091 alignmentscope). Subjects either viewed the display directly or through a collimating lens. Without the collimating lens, subjects sat with their eyes approximately 750 mm from the display. The display was located at head height directly in front of the subject.

Collimation was achieved by placing a convex lens at its focal length (310 mm) directly in front of the display. The distance from the subjects' eyes to the lens was approximately 750 mm. The size of the images on the display were adjusted to ensure that the angles subtended at the subjects eyes were the same in both display conditions. To avoid visual distortion which may occur at the edges of the lens, the display elements were at all times viewed through the central part of the lens. Table 4.1 summarises the viewing conditions. When the display was vibrated with the subjects, both the display and the lens were rigidly attached to the vibration platform. All experiments were carried out in a semi-darkened laboratory.

4.1.4. Control and Arm Support

In all experiments subjects operated on isometric (force) side-arm control similar in shape to that installed in the F16 aircraft. The control was mounted on a rigid steel shaft to which semi-conductor type strain guages were attached. Subjects operated the control with their, preferred, right hand. The control is shown on Figure 4.2. A miniature switch was mounted in the position of the weapon release button on the control. This switch could easily, and comfortably, be reached by the thumb. The lower left hand

TABLE 4.1: Summary of Viewing Conditions

Without Collimation

Viewing distance	=	750 mm
Target diameter	=	7 mm
Angle subtended by target at eye	=	32 minutes 5 seconds of arc
Maximum target displacement (+/-)	=	60 mm
Maximum angular target displacement (+/-)	=	4^{o}34 minutes 26 seconds of arc

With Collimation

Diameter of lens	=	110 mm
Focal length of lens	=	310 mm
Viewing distance to lens	=	750 mm
Target diameter	=	2.9 mm
Angle subtended by target at eye*	=	32 minutes 9 seconds of arc
Maximum target displacement (+/-)	=	25 mm
Maximum angular target displacement (+/-)*	=	4^{o}36 minutes 38 seconds of arc

$$\text{* Magnification of lens} = \frac{\text{Viewing distance}}{\text{focal length}} = \frac{750}{310} = 2.42$$

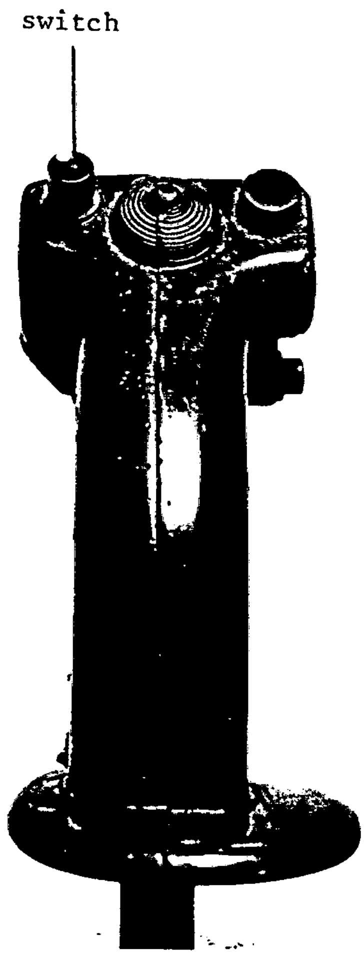


Figure 4.2 The Isometric side-arm control.

edge of the top of the control was approximately 250 mm to the right of the longitudinal centre line of the seat pan and 530 mm forward along a horizontal line projecting from a point on the right hand margin of the seat back, 300 mm up the back rest from the seat surface.

The control gain was linear; ie., the force applied (F) was related to the voltage produced (V) by the simple relationship V = K.F, where K is a constant formed from the gain of the bridge amplifiers fed by the strain gauges and the sensitivity of the gauges themselves. As with the forcing functions, the control gains used were determined by evaluating the performance and subjective impressions of two trained subjects. The optimum gain is a compromise between speed of response, operator generated noise, vibration breakthrough and the physical effort demanded of the subject. The control gain used in each experiment depended upon the system dynamics used, the frequency content of the forcing functions, the duration of the task and the aims of the particular study. The precise control gains in each case are therefore described in each Chapter.

Arm Support

Two experiments investigated the effect of providing an arm support on induced activity at the control during vibration exposure. The arm support was constructed from 3 mm steel tubing with an inside diameter of 18 mm, and was rigidly attached to the frame supporting the control. The arm support consisted of a 180 x 110 mm platform mounted on a 400 mm shaft. When lying horizontally, the front edge of the support was 120 mm from the back edge of the control. The support could be adjusted through 180 mm in the vertical axis, in 10 mm steps, and could be rotated through greater than 60^{o} about the x- and y-axes through the body.

However, the support was fixed about the z-axis, to ensure that the arm always lay in the fore-and-aft axis of the control. The support was adjusted for each subject such that the arm was comfortably supported but without changing the grip on the control or otherwise interferring with the position of the hand on the control. Once adjusted, the support was secured in that position. The front edge of the support lay approximately 7 cms from the projection of the ulna at the wrist.

4.1.5. System Dynamics

The relationship between the voltage produced at the control in response to the applied force and the resulting motion of the controlled element on the display is defined by the system dynamics. The first two performance studies used cross-coupled system dynamics approximately representative of modern high performance fighter aircraft. Those were implemented on VIDAC 1224 and VIDAC 333 analogue computers. The 'aircraft' model defined angular rotations of the 'airframe' in roll, pitch and yaw in response to stick commands in two axes (fore-and-aft and side-to-side). Roll, pitch and yaw feedbacks were used to augment and linearise the performance of the basic 'aircraft'. Rudder inputs and the aircraft trim system were not included. These dynamics were basically first-order. Figure 4.3 shows the moduli of the transfer functions of these system dynamics in roll, pitch and yaw. Airframe rotations were resolved with respect to a fixed 'ground' reference. (Full details of the system dynamics, including the analogue computer patch diagrams are given in Appendix C).

The major apparent difference between these cross-coupled dynamics and the independent axis tasks used in previous studies (and in later studies in this thesis), was the lack of a direct

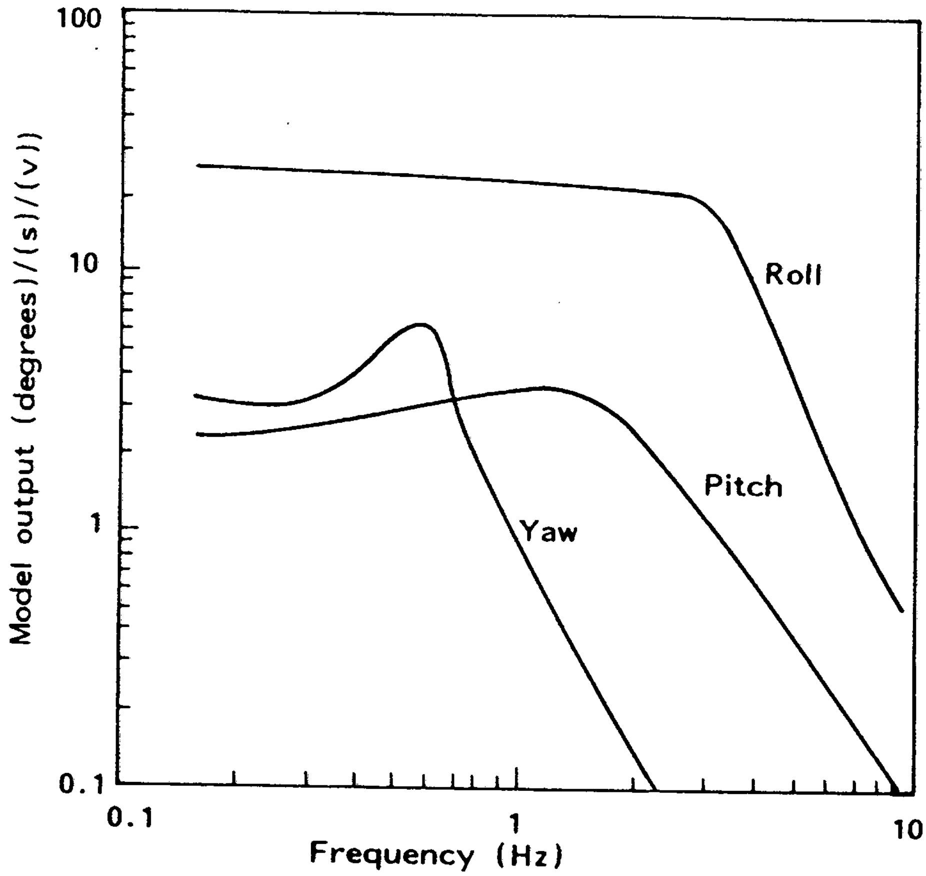


Figure 4.3 The Moduli of the transfer functions of the System Dynamics in Roll, Pitch and Yaw axes.

relationship between side-to-side forces at the control and horizontal motion of the controlled element. To move the controlled element in the horizontal axis of the display with the cross-coupled dynamics, subjects had to induce an appropriate roll angle and then induce motion in pitch. The controlled element would pitch in the axis normal to the 'airframe', inducing motion simultaneously in the horizontal and vertical axes of the display (for roll angles not equal to 0 or 90 degrees).

To further investigate the mechanisms contributing to performance disruption during vibration, the system dynamics were simplified in four experiments. These simplified dynamics used the original dynamics in the pitch and roll axes, but removed the cross-coupling between them. With this system, the dynamics in the roll axis moved the controlled element in a linear, rather than an angular manner: side-to-side forces on the control produced controlled element motion in the horizontal axis of the display. Fore-and-aft forces on the control produced motion in the vertical display axis according to the pitch axis dynamics. Again, the reasons for simplifying the dynamics will be explained in Chapter 7.

Table 4.2 summarises the tasks and systems used in each of the experiments. This table provides a brief comparison of the main differences between the various studies. There were other differences, particularly in the experimental designs employed, the measures taken and the subjects used. As with the system and task parameters, the reasons for changes in the design and measures are described in each Chapter. Section 4.4 of this Chapter gives details of the subjects used in each experiment.

TABLE 4.2 Summary of the system parameters and tasks used in the experimental programme

	Experiment 1	2	3	4	5	6
Task	NT	T	T	T	NT	T
Forcing Function	None	F1	F1	F2	None	F2
Viewing Conditions	CV	DV	DV and CV	DV and CV	CV	CV
Control	FS	FS	FS	FS	FS	FS
Control gain	G4	G1	G1	G2	G4	G3
Arm Support	NS and S	NS	NS	NS	NS and S	NS
Dynamics	SD	CD	CD	SD	SD	SD

Key:

T = Combined continuous and pursuit tracking
NT = No tracking task

F1 = -24 dB/octave attenuation above 0.1 Hz
F2 = -12 dB/octave attenuation above 0.2 and below 0.01 Hz

DV = Direct viewing
CV = Collimated display

FS = Force-type, side-arm control

G1 = Least sensitive control
G4 = Most sensitive control, etc., (see experiment for details)

NS = No arm support
S = Arm support used

CD = Full cross-coupled system dynamics
SD = Simplified, independent axes system dynamics

4.2 Vibrators, Seating and Signal Conditioning Equipment

Two different vibrators were used to generate the vibration conditions. These were:

(i) a 1-metre stroke (+/- 500 mm) electro-hydraulic vibrator, on which the display, control and subjects' seat were mounted; and

(ii) a 1-inch stroke (+/- 0.5 inch) electro-dynamic vibrator (Derritron type VP180LS) on which only the subjects' seat and the control were mounted, ie., the subjects' feet and the display were stationary.

Both of these vibrators were constrained to move in the vertical (z-) axis only. Table 4.3 compares the total harmonic distortion with each of these vibrators over the frequency range covered by the experimental programme. Figure 4.4 shows the layout of equipment and the position of the subject on the 1-metre stroke electro-hydraulic vibrator. Both vibrators were located in the Human Factors Research Unit at the Institute of Sound and Vibration Research.

Subjects sat on a hard wooden seat, with a backrest, which was geometrically similar to that in a Westland Sea-King helicopter. (Full details of the geometrey of the seat are given in Furness, 1981). The seat showed unity transmissibility in the z-axis for z-axis vibration up to at least 20 Hz. With a subject strapped into the seat, motion of the backrest was measured in the x-axis during sinusoidal platform vibration at frequencies from 0.5 to 10.0 Hz. The magnitude of x-axis backrest motion was greatest with vibration at 10 Hz: at this frequency, motion was measured at 0.15 ms^{-2} rms.

TABLE 4.3 Percentage harmonic distortion measured on 1-metre stroke electro-hydraulic and 1-inch stroke electro-dynamic vibrators

Vibration Frequency (Hz)

	0.5	1.0	2.0	4.0	8.0
Electro-hydraulic	5.2	4.1	2.1	1.3	1.0
Electro-dynamic	-	-	30.6	14.3	10.8

$$\text{Percentage distortion} = 100.\left[\frac{\int_{\sqrt{2}.fo}^{51.2} Gvv(f).\, df}{\int_{o}^{\sqrt{2}.fo} Gvv(f).\, df}\right]^{\frac{1}{2}}$$

where:

fo is the vibration frequency at which distortion is being measured; and

Gvv(f) is the Power Spectral Density (PSD) of acceleration on the vibration platform at frequency f.

Platform vibration at a magnitude of 2.0 ms^{-2} rms was produced using digitally generated sine waves with an analogue-to-digital conversion rate of 400 samples per second. The acceleration of the vibration platform was sampled at a digital-to-analogue conversion rate of 102.4 samples per second with anti-aliase filtering at 25 Hz. The PSD was calculated with a frequency resolution of 0.05 Hz.

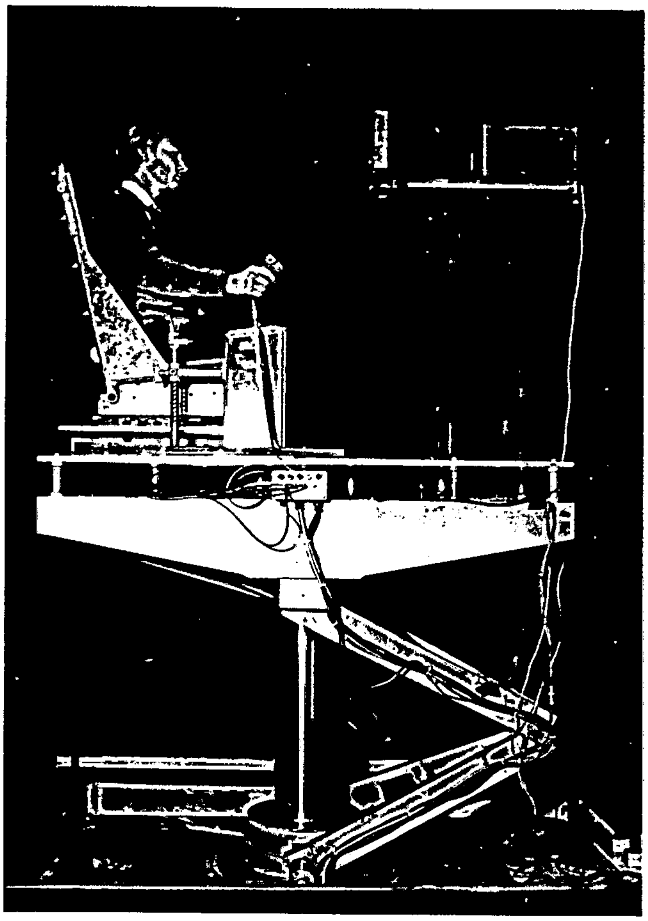


Figure 4.4 The layout of equipment and the position of the subject on the 1 m stroke electro-hydraulic vibrator.

On the 1-metre stroke vibrator, subjects' feet were supported by the vibration platform. On the electro-dynamic vibrator, subjects' feet were supported by a stationary foot-rest. In both cases, subjects' upper legs were approximately horizontal without vibration exposure. Subjects were restrained by a 5-point harness, having two shoulder straps, two lap straps and a strap between the legs, attached at the waist by a quick-release buckle. Each subject adjusted the straps to provide a tight but comfortable restraint.

In all studies, acceleration exposures were measured using a piezo-resistive accelerometer (Endevco, type 2265-20) firmly attached to the underside of the subjects' seat. Acceleration signals were pre-amplified and converted to voltages representing the acceleration magnitude.

Each of the vibration exposures were tested and calibrated prior to experimentation. During each experiment the output from the seat accelerometer was displayed on an oscilloscope (Gould OS300) and the acceleration magnitude was monitored on an rms meter having a low frequency response. Measurements of head vibration were made using translational (Endevco, type 2265-20) and rotational (Schaevitz, type ASMP 100) accelerometers attached to a bite bar. The bite bar was held firmly in the mouth by biting on a dental mould individually prepared for each subject.

Vibration signals were generated either on a PDP 11/34 digital computer or using an analogue oscillator (Wavetek, Model 171). Digitally generated signals were output using a 10-bit digital-to-analogue conversion unit.

4.3 Measurements

Two main types of measures were taken:

(i) simple measures of performance, such as the probability of being 'on' target or the root-mean-square (rms) tracking error; and

(ii) spectral measures describing, for example, the linear transformations between the acceleration occuring at the subjects' seat and that at the head, or between movements of the target and the controlled element on the display.

4.3.1. Simple Performance Measures

4.3.1.1. Probability Measures

The aim of the continuous tracking task was to keep the controlled element inside the area defined by the target at all times. For the discrete task subjects were asked to keep the button depressed as long as they were 'on' target, and to release the button as soon as they came 'off' target.

In the experiments reported in this thesis, the time-histories of the position of the target and of the controlled element were digitally sampled at equal time intervals (although the interval between samples varied between the different experiments). The probability of being 'on' target - p(on) - for sampled data can be defined as:

$$p(on) = \frac{N(on)}{N} \tag{1}$$

where;

N(on) is the total number of samples 'on' target; and
N is the total number of samples in the run.

Similarly, the probability of 'hitting' the target - p(hit) - and of making a 'false alarm' - p(FA) - can be defined, respectively, as:

$$p(hit) = \frac{N(press/on)}{N} \tag{2}$$

and

$$p(FA) = \frac{N(press/off)}{N} \tag{3}$$

where

N(press/on) is the total number of samples pressing the button while 'on' target (ie., hitting the target), and

N(press/off) is the total number of samples pressing the button while 'off' target.

The probability of 'missing' the target (ie., not pressing the button while 'on' target) - p(miss) - and of making a 'correct rejection' (ie., not pressing the button while 'off' target) - p(CR) - can be defined as:

$$p(miss) = p(on) - p(hit) \tag{4}$$

and

$$p(CR) = 1 - p(on) - p(FA) \tag{5}$$

From (4) it can be seen that p(hit) and p(miss) effectively are equivalent in the information they contain about performance. Similarly, from (5), p(CR) and p(FA) are also effectively equivalent. Because p(miss) and p(CR) do not provide any additional information not available from p(hit) and p(FA), they are not presented in the experimental Chapters.

4.3.1.2. Total Root-Mean-Square Tracking Error

The total rms tracking error in each axis of the 2-axis tracking task (e_{rms}) can be defined as:

$$e_{rms} = \left(1/_N \sum^{N} \left[o(n) - i(n)\right]^2\right)^{\frac{1}{2}} \tag{6}$$

where;

o(n) is the position of the controlled element at sample n; and
i(n) is the position of target at sample n.

For a statistically stationary random process having a mean value of zero, the rms magnitude is equivalent to the standard deviation of the distribution of samples.

4.3.2. Spectral Analysis

A number of previous studies have found that effects of vibration on tracking performance are often accompanied by increases in the proportion of operator response not linearly correlated with either the target motion or the vibration (see Chapter 2, Section 4). This section describes the theoretical basis of the techniques used to measure:

(i) the proportion of tracking error linearly correlated with the motion of the vibration platform, (vibration breakthrough);

(ii) the proportion of tracking error linearly correlated with the target motion, (input-correlated error);

(iii) the proportion of tracking error not linearly correlated with either the platform vibration or the target motion (remnant); and

(iv) the parameters (gain and phase) of the linear part of the operators' response to movements of the target.

Similar techniques were used in Experiment 1 to measure the transmission of vibration from the platform to the head. More complete theoretical treatment of this material can be found, for example, in Bendat and Piersol, (1971) and Newland, (1975).

4.3.2.1. Theory

Figure 4.5 shows a single-input, single-output system in which the output y(t) can be defined as:

$$y(t) = \left[x(t) * h(t)\right] + n(t) + v(t) \tag{7}$$

where;

x(t) and n(t) are uncorrelated, stationary random processes,

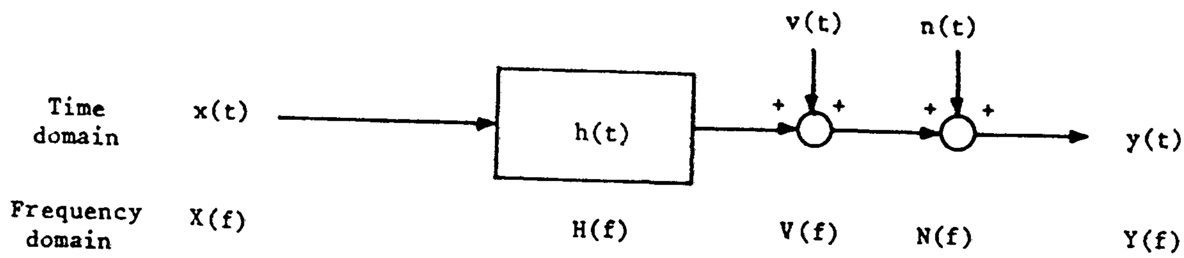


Figure 4.5   A single input, single output system.

$v(t)$ is vibration breakthrough;

$h(t)$ is the linear response of the system to a unit impulse; and

$*$ denotes convolution.

The output is formed from the response of the system to the input combined with some activity unrelated to the input and some activity due to vibration breakthrough. In the frequency domain:

$$Y(f) = \left[H(f).X(f)\right] + N(f) + V(F) \tag{8}$$

where:

$Y(f)$ is the Fourier transform of $y(t)$, etc.

$H(f)$ is known as the linear transfer function, and is a complex valued quantity. It may be written as:

$$H(f) = |H(f)|.e^{+i\phi(f)} \tag{9}$$

where;

$|H(f)|$ defines the modulus or amplification of the system and $\phi(f)$ defines the phase difference between the output of the system and its input.

Due to the presence of $N(f)$ and $V(f)$, it is not possible to estimate $H(f)$ directly from (8). However, $H(f)$ can be identified from $x(t)$ and $y(t)$ by using the cross power spectral density (CSD) between the two. The 'raw' power spectral density (PSD) of $X(f)$ can be defined as:

$$Sxx(f) = \lim_{T \to \infty} \frac{E|X(f), X^*(f)|}{T} \tag{10}$$

where;

E denotes the expected, or average value; and

$X^*(f)$ is the complex conjugate of $X(f)$.

Similarly, the cross power spectral density can be defined as:

$$Syx(f) = \lim_{T \to \infty} \frac{E\left|X(f).\ Y^*(f)\right|}{T} \tag{11}$$

substituting (8) and re-arranging;

$$Syx(f) = \lim_{T \to \infty} \frac{E\left|X(f)^2.H(f)\right|}{T} + \lim_{T \to \infty} \frac{E\left|X(f).N^*(f)\right|}{T} \tag{12}$$

$$+ \lim_{T \to \infty} \frac{E\left|X(f).V^*(f)\right|}{T}$$

So long as $X(f)$, $N(f)$ and $V(f)$ are uncorrelated

$$\lim_{T \to \infty} \frac{E\left|X(f).N(f)\right|}{T} = 0 \tag{13}$$

and;

$$\lim_{T \to \infty} \frac{E\left|X(f).V(f)\right|}{T} = 0 \tag{14}$$

and therefore;

$$Syx(f) = Sxx(f).H(f) \tag{15}$$

or

$$H(f) = \frac{Syx(f)}{Sxx(f)} \tag{16}$$

H(f), then, defines the linear transfer characteristics linking y(t) to x(t) in the frequency domain.

The proportion of y(t) accounted for by linear operations on x(t) can be quantified using the coherence function, or the squared coherence function. This is defined as;

$$\gamma^2_{yx}(f) = \frac{|Syx^2\ (f)|}{Sxx(f).Syy(f)} \qquad (17)$$

where;

$\gamma^2_{yx}(f)$ is the squared coherence between x and y at frequency f.

If x and y are entirely linearly correlated;

$$Syx^2(f) = Sxx^2(f).H^2(f) \qquad (18)$$

and;

$$Syy(f) = Sxx(f).H^2(f) \qquad (19)$$

and therefore;

$$\gamma^2 yx(f) = \frac{Sxx^2(f).H^2(f)}{Sxx(f).Sxx(f).H^2(f)} = 1 \qquad (20)$$

If however, x and y are linearly uncorrelated;

$$Syx^2(f) = 0$$

and therefore;

$$\gamma^2 yx(f) = 0$$

The squared coherence function between x and y indicates the proportion of y which can be accounted for by linear operations on x. Similarly a coherence between the input time-history and the error can be formed by substituting the power spectrum of the error, See(f), for Syy(f). The part of the error linearly correlated with the input is therefore;

$$S_{11}(f) = \gamma^2 xe(f).See(f) \tag{21}$$

$$See(f) = Syy(f) - Sxx(f) \tag{21a}$$

and the part of the error not linearly correlated with the input is;

$$S_{n1n1}(f) = \left[1-\gamma^2 xe(f)\right].See(f) \tag{22}$$

If the vibration time-history, v(t) is known, then, by measuring the coherence between y and v, $S_{ee}(f)$ can be further separated into a portion due to vibration breakthrough, $S_{bb}(f)$, and a portion not linearly related to either the task or the vibration, ie. remnant, $S_{rr}(f)$

$$S_{bb}(f) = \gamma^2 ve(f).See(f) \tag{23}$$

$$S_{rr}(f) = See(f)-S_{11}(f)-S_{bb}(f) \tag{24}$$

Power spectra describe the distribution of the average power in the signal over frequency. The total variance, or mean square value of the error time history, e(t), is:

$$\sigma_e^2 = \int_{\omega} See(f).df \tag{25}$$

where;

ω is the bandwidth of the signal.

Similarly, the variance of the input-correlated breakthrough and remnant components are:

$$\sigma_1^2 = \int_{\omega} S_{11}(f).df \tag{26}$$

$$\sigma_b^2 = \int_{\omega} S_{bb}(f).df \tag{27}$$

and

$$\sigma_r^2 = \int_{\omega} S_{rr}(f).df \tag{28}$$

The root-mean-square (rms) value of each of these components is obtained simply by taking the square root of the relevant value. In summary, the total error variance can be considered as the linear sum of these three components, ie;

$$\sigma_e^2 = \sigma_1^2 + \sigma_b^2 + \sigma_r^2 \tag{29}$$

The discussion so far has concerned estimates for the simple system shown on Figure 4.5. It is necessary to relate these measures to the more complex system being studied in this thesis. Figure 4.6 shows a simplified version of a pursuit tracking task (After Hess, 1981). Figure 4.6 shows three distinct linear response modes which the operator may adopt: he may respond either to the target, the displayed error or the controlled element. (For simplicity, the model assumes that the operator responds to the displacement alone, rather than to the velocity or higher derivatives). In performing the task, the operator is assumed to respond in one mode alone at any instant, and to switch between response modes according to the instantaneous system state, task demands and objectives. Non-linear response modes are lumped with central processing and neuromuscular 'noise' in the single non-linear term, N_2. Discrepancies between the displayed system state and the perceived system state are modelled as a single perceptual 'noise' source, N_1.

Assuming that X, N_1, N_2, and V are all linearly uncorrelated, the cross power spectral density between the output of the system, y, and the input, x, can be expressed as;

$$\begin{aligned} Sxy(f) = {} & G(f)H_1(f).Sxx(f)+G(f)H_2(f).Sxx(f) \\ & - G(f)H_2(f).Sxy(f)+G(f)H_3(f).Sxy(f) \end{aligned} \tag{30}$$

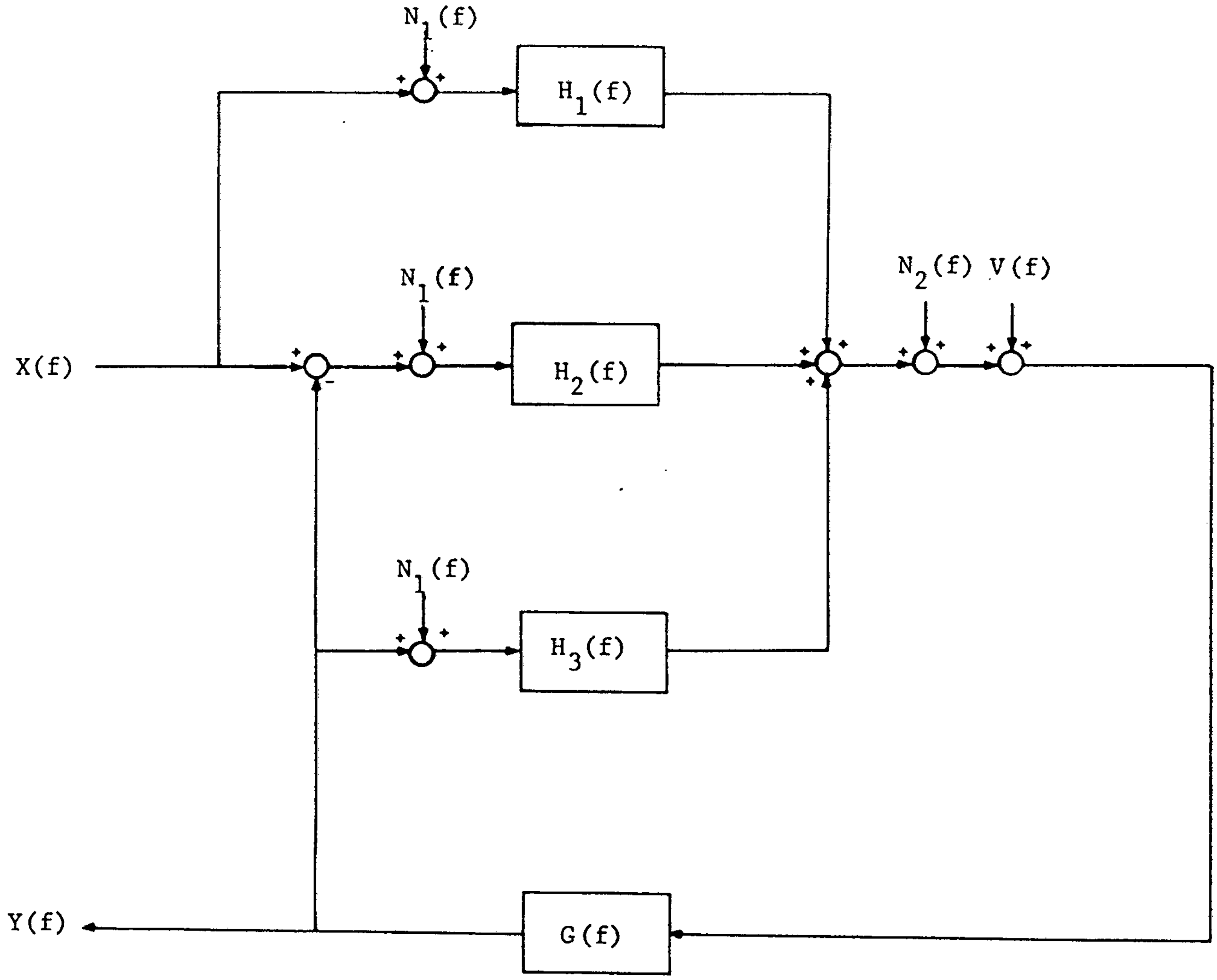


Figure 4.6 A simplified model of the human controller in a pursuit tracking task.

Dividing through by the power spectrum of the input, and re-arranging, the best linear transfer function between x and y for this system is;

$$H_s(f) = \frac{Sxy(f)}{S_{xx}(f)} = \frac{G(f)\left[H_1(f)+H_2(f)\right]}{1 - G(f)\left[H_2(f)+H_3(f)\right]} \tag{31}$$

When $H_2(f)$ and $H_3(f)$ are equal to 0, (ie., when the operator responds to the target position alone);

$$H_s(f) = G(f).H_1(f) \tag{32}$$

which equals 1 when $H_1(f) = \frac{1}{G(f)}$

When $H_1(f)$ and $H_3(f)$ are equal to 0 (ie., when the operator responds to displayed error);

$$H_s(f) = \frac{G(f).H_2(f)}{1 - G(f).H_2(f)} \tag{33}$$

which tends to 1 when $G(f).H_2(f)$ is very large.

Finally, when $H_1(f)$ and $H_2(f)$ are equal to 0, (ie., when the operator responds to the controlled element alone);

$$H_s(f) = 0 \tag{34}$$

In this case there is no response to x and, therefore, no transfer function between x and y.

The components of the total output power, Syy(f), for this system can be calculated using the same equations as for the simple system (equations 17-29). In this case the portion of Syy(f) linearly correlated with Sxx is given by:

$$\gamma^2_{yx}(f).S_{yy}(f) = \frac{|Syx|^2(f)}{S_{xx}(f).S_{yy}(f)} . S_{yy}(f) \tag{35}$$

$$= \frac{1}{1 + \dfrac{Sn_1n_1(f)\left[H_1(f)+H_2(f)+H_3(f)\right]^2+Sn_2n_2(f)+Svv(f)}{Sxx(f)\left[H_1(f)+H_2(f)\right]^2}} . S_{yy}(f)$$

Similarly, the portion of Syy linearly correlated with Svv is given by:

$$\gamma^2_{yv}(f).S_{yy}(f) = \frac{|Syv|^2(f)}{S_{vv}(f).S_{yy}(f)} . S_{yy}(f) \tag{36}$$

$$= \frac{1}{1 + S_{xx}(f)\left[H_1(f)+H_2(f)+H_3(f)\right]^2+Sn_1n_1(f)\left[H_1(f)+H_2(f)+H_3(f)\right]^2+Sn_2n_2(f)} . S_{yy}(f)$$

The portion of Syy(f) not linearly correlated with either Sxx(f) or Svv(f), (ie., the remnant power) is, therefore, given by:

$$Srr(f) = Syy(f) - \gamma^2yx(f).Syy(f) - \gamma^2yv(f).Syy^2(f) \tag{37}$$

Equations 35 to 37 define the spectral relationships between the two signals Sxx(f) and Svv(f) and the system response, Syy(f), which were measured in the experiments described in Chapters 6 to 10. The mean square error and its components are defined in the same way as for equations 25 to 29.

4.3.2.2 Measurement procedures

Data analysis was performed using a PDP 11/34 digital computer situated in the Human Factors Research Unit of the ISVR. Data were either acquired on-line to the computer during experimentation, or recorded on an FM tape recorder (RACAL, STORE 7) and acquired to the computer at a later time. In either case, data were anti-aliase filtered (Kemo Filters, type VBF17) with appropriate, manually set, cut-off frequencies and attenuation of 48 dB per octave. Each Chapter provides details of the sampling rates and anti-aliase filter settings used. Data acquisition used 10 bit digital-to-analogue conversion and the sampled data were stored on magnetic disk for subsequent analysis.

The signal from the button, (0 or 5 volts, indicating performance of the discrete task), was acquired in the same manner as for the continuous signals: this signal was also passed through the anti-aliasing filters. For continuously varying signals, the filters introduced a constant time-delay of 518 msecs. For the step response produced by the signal from the button, the time delay is dependent upon the magnitude of the step. In order to ensure that the same time delay was incurred by all channels, the threshold level for the button, (ie., the level at which the button was interpreted as being pressed or released), was set such that the maximum error introduced by the filters was less than 156 msecs, at the slowest sampling rate (6.4 samples per second) and less than 39 msecs at the fastest sampling rate used (25.641 samples per second).

Two types of computer programmes were used; those contained within the DATS 11 software package, and those purpose written by either the author or colleagues within the Human Factors Research Unit. DATS 11 is a suite of programmes developed within the Institute of Sound and Vibration Research specifically for the analysis of time series. The programmes included perform operations ranging from the manipulation of data files, through simple arithmetic operations, to the use of Fourier methods for estimating power spectral densities. There are also a series of graphics modules for displaying data and obtaining hard copy prints. DATS 11 allows the user to write 'JOBS' combining programmes from the suite, together with the users' own Fortran programmes, to perform any set of operations which may be required. Such JOBS were used extensively in this thesis.

Appendix E contains listings of the main Fortran programmes written by the author for the thesis. Numerous short programmes were also written to perform minor tasks.

4.3.2.3. Spectral Estimates

This section briefly describes some important aspects of the method of estimating spectral densities used by DATS 11. It will be clear from the theoretical discussion of Section 4.3.2. that estimates of power spectral densities (PSD) and cross-power spectral densities (CSD) were fundamental to many of the measures used in this thesis.

A sequence of data which is finite in time can be considered to be a representative sample of a sequence which is infinite in time provided it is statistically stationary. Spectral density analysis provides estimates of the distribution of energy over frequency in the infinite sequence based upon the information available in the finite sequence.

The DATS 11 programme for calculating an estimate of the power spectral density of a sequence of N data samples, calculates a number of 'raw' spectral densities using the Fast Fourier Transform. These are smoothed by averaging across adjacent frequency bands and a final estimate is obtained by ensemble averaging across these 'raw' estimates. Each of the 'raw' estimates used L data samples drawn from the N sample sequence, where;

$$L = \frac{\text{sample rate}}{\text{desired resolution}}$$

The information available from the N samples is increased by taking overlapping segments of one half of L which are assumed to be statistically independent. The number of 'raw' spectral densities calculated, K, is therefore;

$$K = \frac{2N}{L} - 1$$

and the total number of samples effectively used is:

$$N_t = K.L.$$

In order to reduce the 'leakage' of the measured quantity from one frequency band into adjacent bands, each of the L segments are extracted from the original sequence using a data window. Throughout the thesis the Hanning data window was used (Bendat and Piersol, 1971).

The resulting spectral density is therefore an estimate based upon K samples of the (theoretical) 'true' spectral density for the infinite data sequence. As with other types of estimates, the accuracy of the spectral estimates can be described statistically. Each of the 'raw' spectral density estimates can be considered to be a chi-squared random variable with 2 degrees of freedom (one each for the Fourier transform and its complex conjugate). The total number of degrees of freedom for the final estimate, therefore, is:

$$\begin{aligned} df &= 2.K \\ &= 2\left(\frac{2N}{L} - 1\right) \end{aligned}$$

The number of degrees of freedom of an estimate gives a direct indication of the accurancy of the estimate of the 'true' spectral density: specifically, as the number of degrees of freedom increases, the uncertainty about the range in which the 'true' value lies reduces. For example, with 18 degrees of freedom, it can be said with 90% confidence that the measured value lies within ± 2.5 dB of the 'true' value. With 104 degrees of freedom, it can be said with 90% confidence that the measured value lies with ± 1 dB of the 'true' value, or with 98% certainty that it lies within about ± 2 dB (Mercer, 1973).

In general, spectral estimates should be calculated with the greatest number of degrees of freedom possible. The estimates calculated in this thesis were constrained by considerations of:

(i) the number of data runs required of subjects in any one experimental session, and, therefore, the length of each run;

(ii) the sample rate, which affects the time required by the computer to store each data file; and

(iii) the desired frequency resolution.

These constraints varied between the experiments performed. Details of the spectral estimates obtained are therefore provided in each Chapter.

4.4. Subjects

A total of 24 subjects took part in the experiments described in Chapters 5 to 10. Subjects were healthy, right handed male volunteers drawn from the staff and students of the University of Southampton. All subjects had normal uncorrected vision as tested by the Keystone Visual Skills Profile. Ages ranged from 18 to 29 years with a mean of 23.1 years.

Eight subjects were originally trained and took part in the experiments using the full cross-coupled system dynamics. A separate group of subjects took part in the studies with the simplified dynamics. There were no subjects in both groups. Details of the training for each group are given in Chapter 6 (for the cross-coupled dynamics group) and Chapter 8 (for the simplified dynamics group). Training data for all 24 subjects are given in Appendix D. Table 4.4 summarises the subjects used in each of the experiments.

TABLE 4.4: Summary of subjects used in each experiment

Subject	Age	Weight (kg)	Experiment 1	2	3	4	5	6
1	28	64		x	x			
2	25	68		x	x			
3	27	82		x	x			
4	24	69		x	x			
5	23	74		x				
6	26	78		x	x			
7	27	81		x	x			
8	22	67		x				
9	28	83	x			x	x	x
10	25	68	x			x	x	x
11	22	83	x			x	x	x
12	27	64	x			x	x	x
13	23	72	x			x	x	x
14	26	72	x			x	x	x
15	20	58				x		x
16	22	63				x		x
17	27	66				x		x
18	28	65	x			x	x	x
19	26	76	x			x	x	x
20	18	61				x		x
21	21	72				x		x
22	30	74				x		x
23	32	81				x		x
24	29	88				x		x

CHAPTER FIVE

EXPERIMENT ONE: THE TRANSMISSION OF VIBRATION TO THE HEAD, CONTROL AND CONTROLLED ELEMENT

1.0 Introduction

Effects of vibration on manual control performance have been found to be closely related to the transmission of vibration through the body. (See the Literature Review in Chapter 2). The various mechanisms which may mediate effects on performance are likely to be sensitive to vibration-induced activity in different ways. The main aim of this Chapter was to measure the vibration-induced activity at the head, at the control and at the controlled element on the display, during z-axis whole-body vibration at frequencies from 0.5 to 10 Hz. The information obtained will assist in interpreting the results from later Chapters.

Performance disruption arising from visual impairment will be closely related to induced motion between subjects' eyes and the display. Both translational and rotational head motion can induce eye movements. Depending on the frequency and axis of head motion, induced eye movements may act to compensate for relative motion between the head and the display thereby minimising effects of vibration on vision. (Section 4.2 of the Literature Review discusses the visual mechanisms in greater detail).

Vibration-induced activity of the controlled element on the display (vibration breakthrough) will depend upon both the transmission of vibration to the control output and the amplification of the system dynamics at each vibration frequency: with the dynamics used in this thesis, the magnitude of breakthrough would reduce as the vibration frequency increased. Furthermore, at vibration frequencies below about 1.5 Hz, subjects may attempt to actively compensate for vibration-induced activity either sensed in the controlling limb or observed on the display. The other suggested mechanisms (neuromuscular effects and central effects) may be related to motion of the body in more complex ways.

The study also investigated the effect of providing an arm support on vibration-induced activity at the control. It has been suggested that arm supports may either improve or impair performance during vibration depending on whether they reduce or increase the transmission of vibration to the control, (eg., Shoenberger and Wilburn, 1973). However, there is no previously reported data demonstrating that arm supports can alter the vibration-induced activity occuring at the control.

Two types of motion were presented. In order to obtain an overall description of the transmission of vibration to each system location, subjects were exposed to a broad-band random motion extending from 0.25 to 12.5 Hz. Using this motion the transfer functions determining the transmission of vibration to each part of the system were calculated in two ways: (1) by dividing the power spectral density (PSD) of the activity at each location by the PSD of the platform acceleration (PSD/PSD method); (2) by dividing the cross power spectral densitities (CSD) between the activity at each location and the platform acceleration by the PSD of the platform acceleration (CSD/PSD method). (Chapter 4 describes the theoretical basis of these measures). The PSD/PSD method shows the transmissibility for the total activity at each location, while the CSD/PSD method shows the transmissibility for the total activity arising from linear operations on the platform acceleration. It was expected that differences between these measures would occur principally for activity at the control, where subjects may try to actively compensate for induced low frequency activity.

These spectral analysis techniques do not give any information of the nature of induced activity not linearly related to the platform motion. In particular, subjects could attempt to compensate for perceived motion by inducing body movements or control activity related to the platform motion non-linearly, though in a deterministic way. Any such activity would be most clearly seen during exposure to sinusoidal vibration where subjects should best be able to anticipate the motion and, therefore, optimise compensatory behaviour. Sinusoidal vibration was therefore presented at frequencies from 0.5 to 8.0 Hz in order to examine the time-histories of induced activity.

2.0 Method and Procedure

Subjects sat on a hard, flat seat with a backrest and were restrained by a 5-point harness. The seat, display and control were mounted on a 1m stroke electro-hydraulic vibrator constrained to move in the vertical axis only. Subjects held the control with their preferred right hand as if they were performing a tracking task, although the target was stationary in the centre of the display at all times. Subjects observed the display through a collimating lens and attempted to keep the controlled element stationary in the centre of the target. To accentuate vibration breakthrough and compensatory behaviour, the control gain was considerably more sensitive than that used in any of the performance studies.

The arm support was adjusted for each subject so that the controlling limb was comfortably supported, but ensuring that the position of the hand on the control was the same as without the arm rest. Figure 5.1 shows a subject on the experimental rig with the arm support in place.

Sinusoidal, whole-body vibration in the z-axis was presented at 0.5, 1.0, 2.0, 4.0 and 8.0 Hz at a magnitude of 1.8 ms^{-2} rms. The

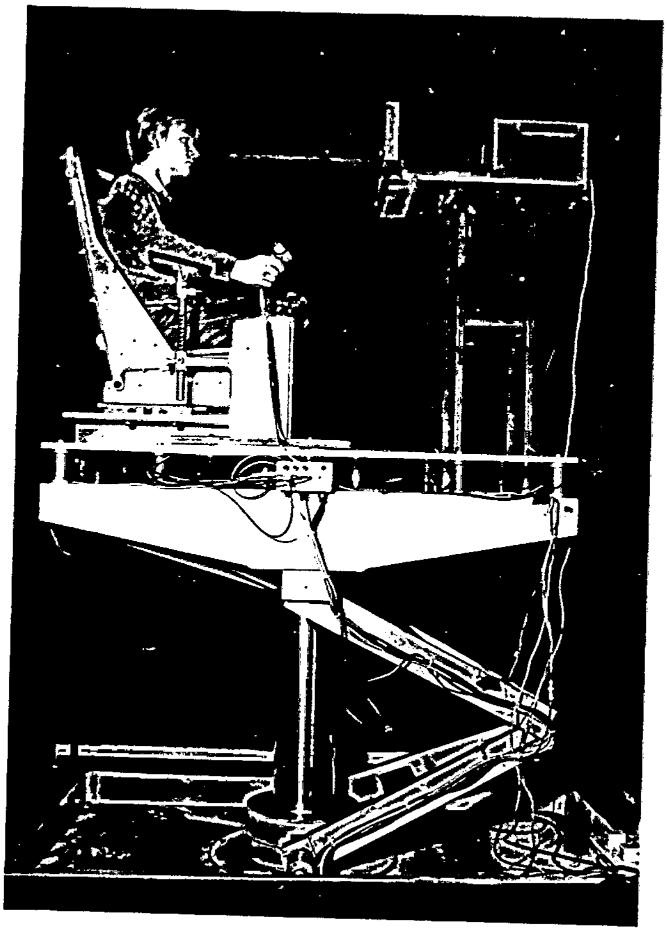


Figure 5.1 A subject on the experimental rig with the arm support in place.

first and last two seconds of each time-history were shaped using a cosine weighting to ensure smooth progressions of the platform to and from rest. An additional four seconds was allowed at the start of each exposure for subjects to adapt to the motion. The next 16 cycles provided the data used in the analysis. In the analysis, these 16 cycles were divided into successive two-cycle periods. These eight segments were then averaged to give a single two-cycle time-history at each frequency and for each subject. During this averaging, activity which is not cyclic at the vibration frequency will be progressively attenuated and activity at the vibration frequency will therefore be accentuated.

The broad-band random motion was band-pass filtered at 0.25 and 12.5 Hz with attenuation of 24 dB per octave outside this region. This motion lasted for 310 seconds and was also presented at a magnitude of 1.8 ms^{-2} rms. The first and last five seconds were shaped using a cosine weighting; these periods were excluded from the analysis. Full details of the vibration conditions presented, including the digital sampling rates and anti-alias filtering are shown on Table 5.1.

Translational acceleration was measured using translational accelerometers mounted on the platform and on a bite-bar. A rotational accelerometer, also mounted on the bite-bar, measured accelerations in the pitch axis at the head. Subjects held the bite-bar firmly in their mouth by biting on a dental mould individually prepared for each subject. Table 5.2 summarises the details of the experiment.

The experiment used a completely randomised block factorial design with all subjects being exposed to all conditions (see Kirk, 1968). All subjects had previously taken part in the studies described in Chapters 8 and 10. Subjects attended the laboratory for a single session lasting approximately 45 minutes. After making

Table 5.1: Details of Vibration Exposures and Sampling

	Frequency (Hz)	Magnitude (ms^{-2} rms)	Total Duration (secs)	Duration used in Analysis (secs)	Sample rate per second	Samples per cycle	Anti-aliase filters (Hz)
Sinusoidal	0.5	1.8	40	32	100	200	25
	1.0	1.8	24	16	100	100	25
	2.0	1.8	16	8	100	50	25
	4.0	1.8	12	4	200	50	25
	8.0	1.8	10	2	200	25	25
Random	0.25-12.5	1.8	310	300	102.4	--	25

Table 5.2 Details of Experiment 1

Independent Variables :	Vibration frequency; vibration waveform; arm support.
Dependent Variables :	Acceleration at the head; force at the hand; angular displacement of the controlled element on the display.
Subjects :	8 right-handed males.
Task :	Hold controlled element in centre of stationary target.
Forcing Function :	None.
System Dynamics :	First-order. Decoupled pitch and roll axes of aircraft model.
Control :	Isometric side-stick. With and without arm support.
Control gain :	fore-and-aft = 3.76 v/kg = 2 $^{\circ}$/s/kg (vertical) side-to-side = 0.69 v/kg = 2 $^{\circ}$/s/kg (horizontal)
Display :	Collimated. Target subtended 33 minutes of arc at the subjects' eye.
Vibrator :	1-metre stroke, electro-hydraulic. z-axis.
Seat :	Hard, flat simulated helicopter seat with backrest and 5-point harness.

Table 5.2 (continued)

Vibration Exposure	:	All whole-body exposures. 1. Sinusoidal vibration at 0.5, 1.0, 2.0, 4.0 and 8.0 Hz at 1.8 ms^{-2} rms. 16 cycles at each frequency. 2. Broad-band random vibration (0.25 to 12.5 Hz) at 1.8 ms^{-2} rms for 300 seconds. Person, control and display vibrated.
Sessions per subject	:	One.

a dental mould and completing a consent form, subjects mounted the vibrator and the various exposure conditions were explained. They then read the following instructions:

> "Please sit in a comfortable, upright posture which you can maintain throughout each vibration exposure. Please do not change your posture to try to alter your experience of the vibration. Hold the control with a comfortable grip, as if you were performing a tracking task.
>
> Do you have any questions?"

Sinusoidal vibration was then presented for 30 seconds each at 0.5 and 8.0 Hz. These exposures familiarised subjects with the range of frequencies to be presented and allowed for 'settling in'. The experimental exposures were presented in 2 blocks of 6 trials each (5 sinusoidal and 1 random). The arm support was used in the first block by 4 subjects and in the second block by the remaining 4 subjects. Within each block, the order of presentation of vibration conditions was randomised using a latin square procedure.

3.0 Results

The results will be presented in three parts. The first part shows the two-cycle responses to the sinusoidal motions and the second part shows the transfer function results obtained with the broad-band random motion. The third part compares activity at the control with and without the arm support.

3.1 Sinusoidal Vibration

The two-cycle averaged results at each part of the system are shown on Figures 5.2 to 5.8. Each figure shows the response for all 8 subjects at each vibration frequency. Figure 5.2, showing the waveforms of the platform motions, illustrates that the averaging procedure was correct and shows the quality of the waveform produced by the 1-metre stroke electro-hydraulic vibrator used in this study and in experiments 2, 4 and 5. The waveform shows a slight regular departure from a pure sinewave at 0.5 Hz. Total harmonic distortion was measured as 4.9% at 0.5 Hz and less than 4.0% above 1 Hz.

The z-axis head motion results (Figure 5.3) show that the head was effectively rigidly coupled to the platform in this axis at 0.5 and 1.0 Hz. All subjects show a marked departure from pure sinusoidal head translation at 4.0 Hz: there is a flattening of the waveform at the head at the top of the platform motion and an increased peak value at the bottom compared with the platform motion. At 8.0 Hz the waveforms are again sinusoidal and the peak accelerations are again greater than at the platform.

There was very little rotational head motion with vibration at 0.5 Hz and 1.0 Hz (Figure 5.4). At 4.0 Hz and 8.0 Hz, all subjects show head rotation periodic with the platform acceleration although there was considerable inter-subject variability in the amplitude and waveform of head rotation. The waveforms were more sinusoidal at 8.0 Hz and appear fairly complex, and show harmonic activity, with vibration at 4.0 Hz. The amplitude of induced head rotation was very much greater at 8.0 Hz than at 4.0 Hz.

The original 16 cycle time histories at the control showed vibration breakthrough at all frequencies superimposed on apparently random low frequency activity. Because of this low frequency activity, averaging these data caused the activity at the vibration frequency to be attenuated. These time-histories were therefore high-pass filtered using a zero-phase filter with a cut-off frequency one

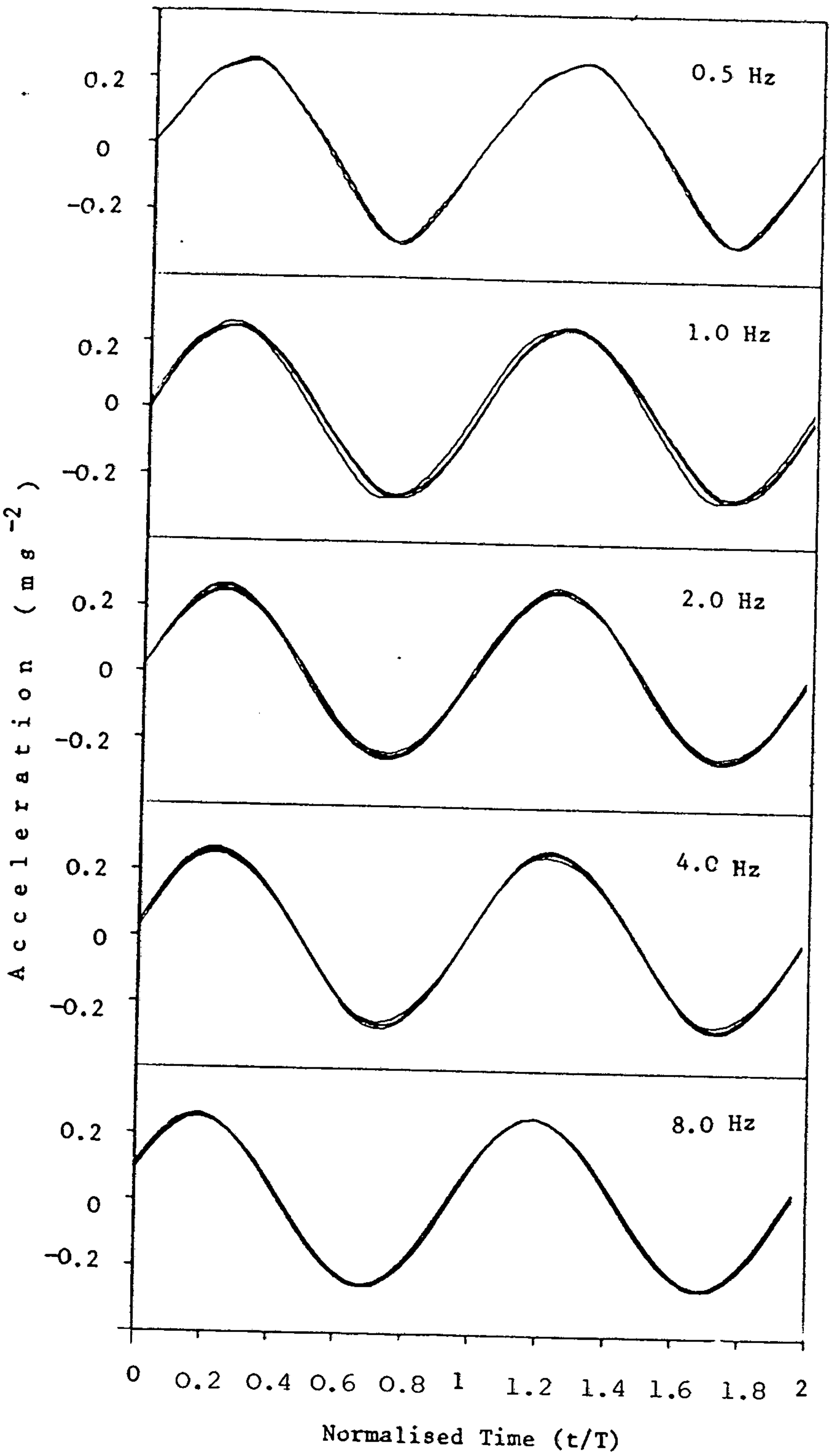


Figure 5.2 Two-cycle averaged platform acceleration time-histories at each vibration frequency. Individual data for 8 subjects.
+ve acceleration = platform moving down.

(NB. Normalised time = t/T)

t = time (seconds)
T = period of cycle (seconds)

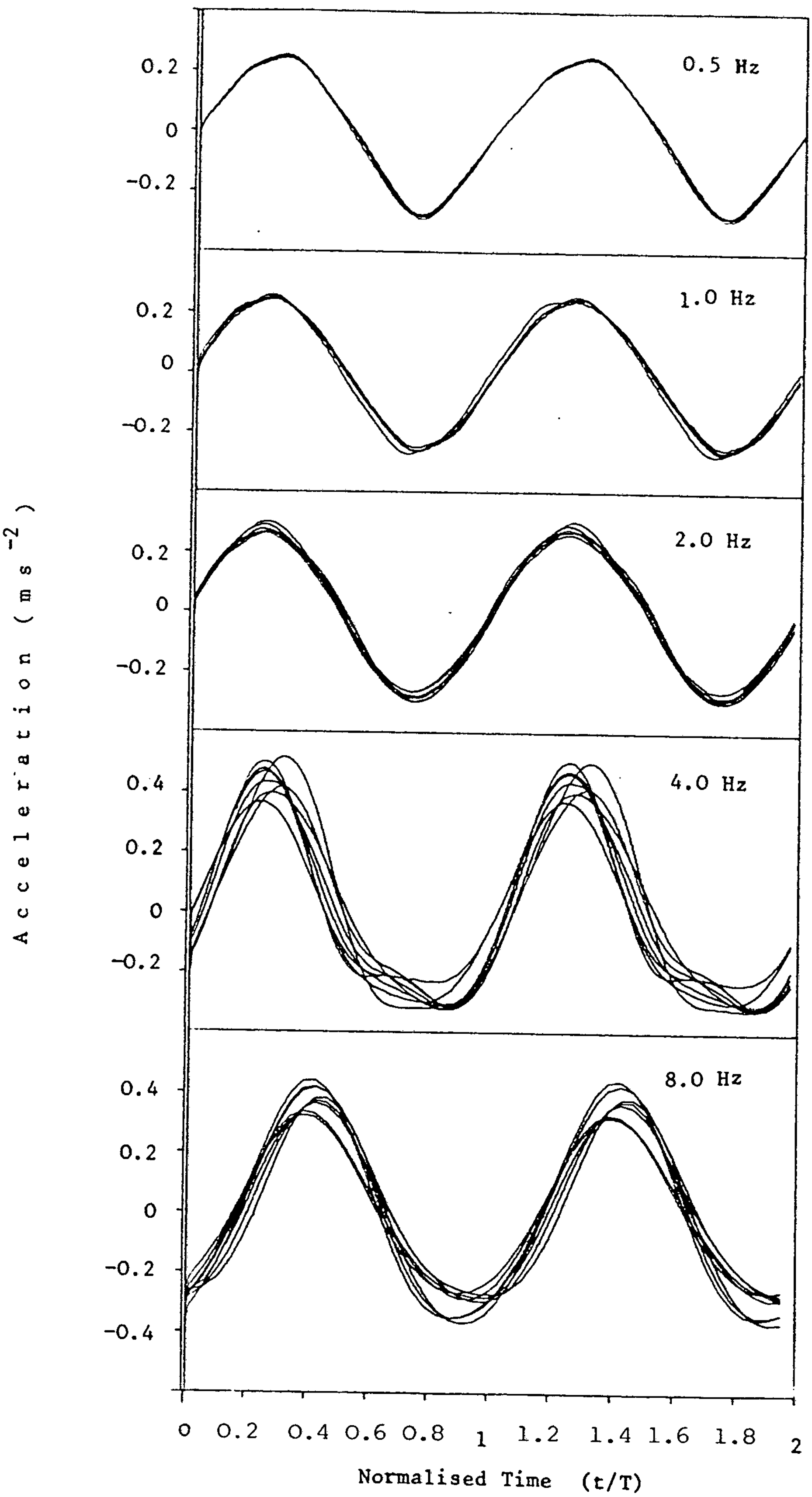


Figure 5.3 Two-cycle averaged translational acceleration time-histories of the head at each vibration frequency. Individual data for 8 subjects. +ve acceleration = head moving down.

Normalised time as for Figure 5.2

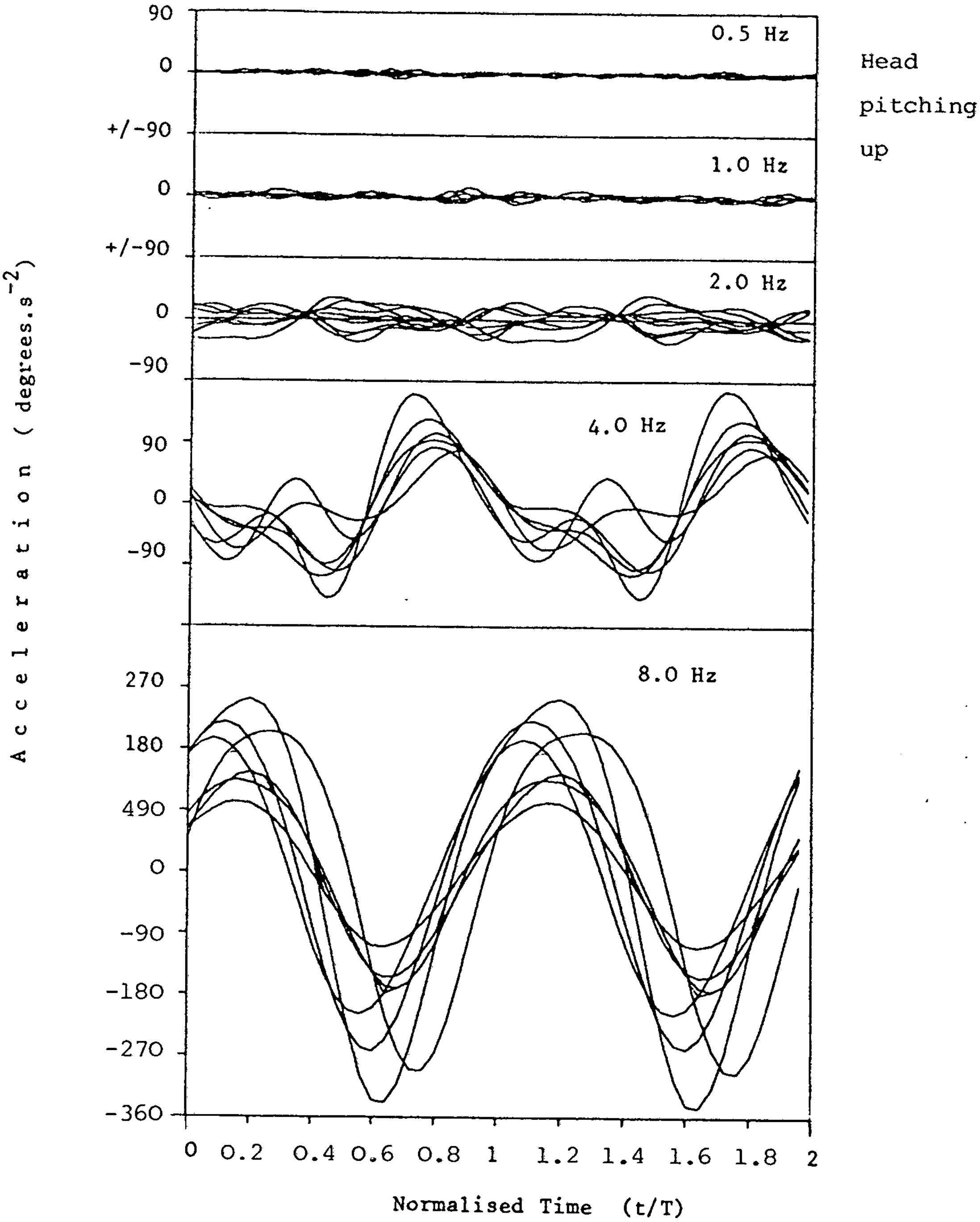


Figure 5.4 Two-cycle averaged rotational acceleration time-histories of the head at each vibration frequency. Individual data for 8 subjects. +ve acceleration = head pitching up.

Normalised time as for Figure 5.2

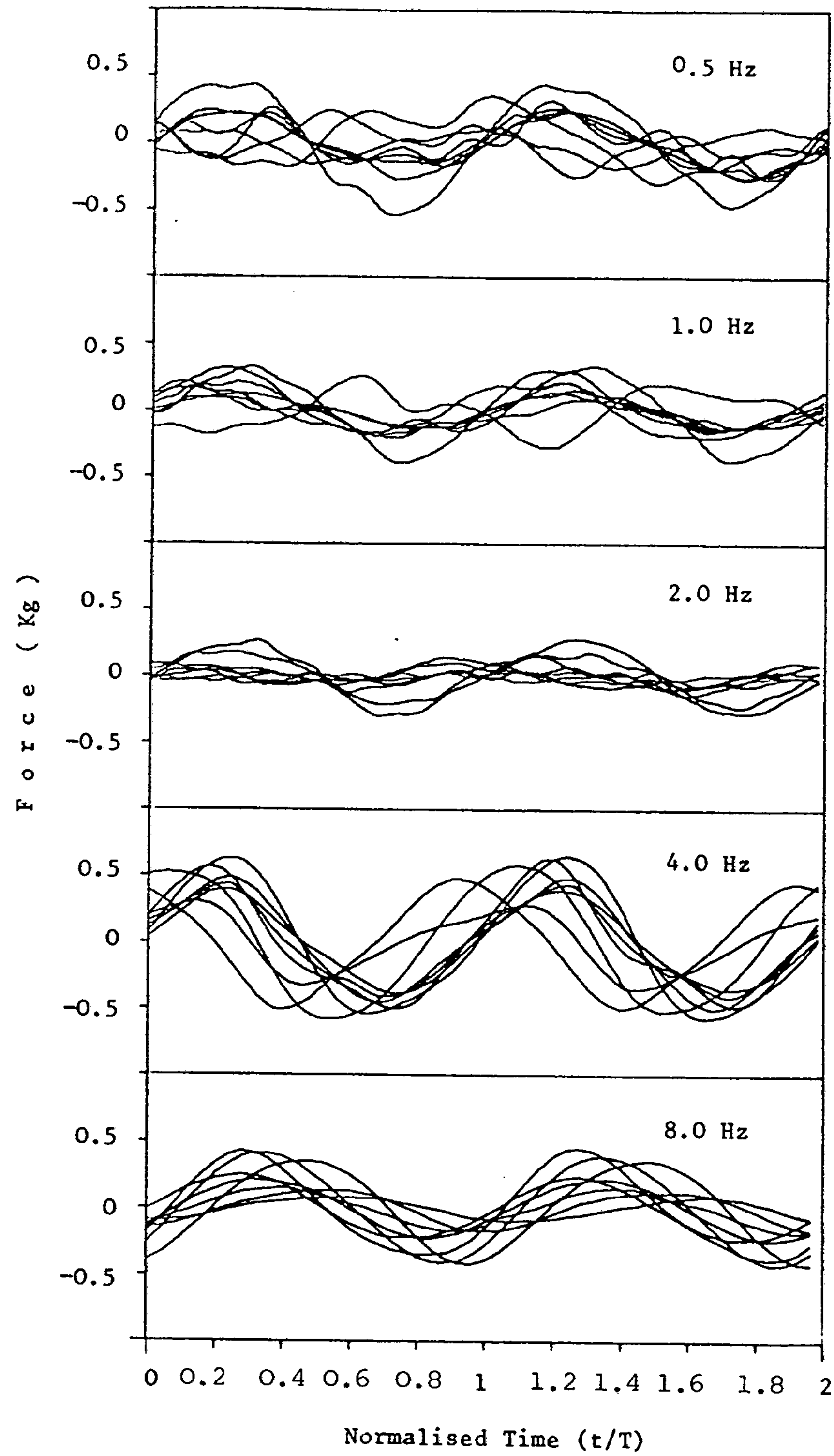


Figure 5.5 Two-cycle averaged force time-histories in the side-to-side axis of the control at each vibration frequency. Individual data for 8 subjects.
+ve force = acting to subjects' right, ie., away from centre of body.

Normalised time as for Figure 5.2

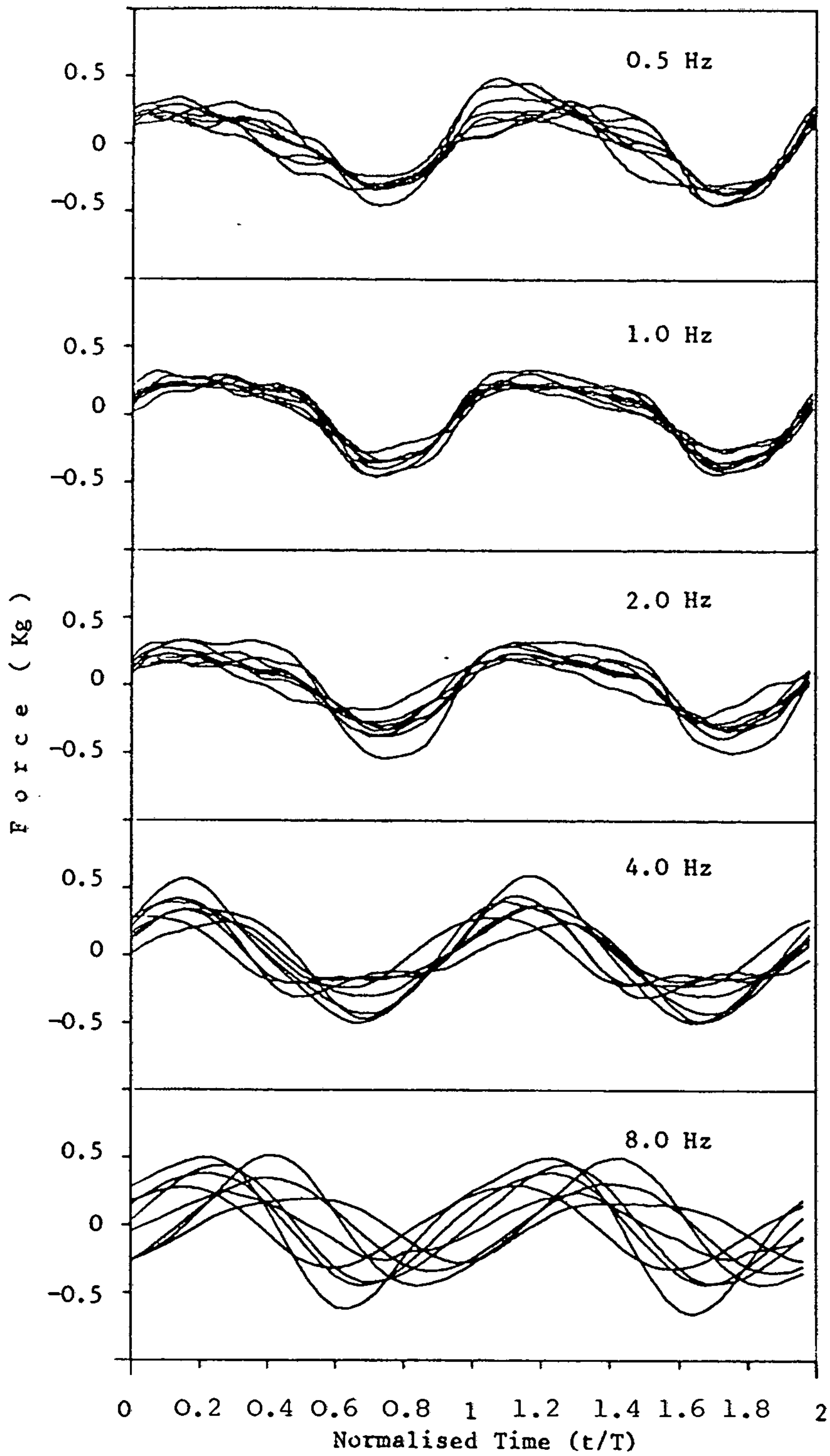


Figure 5.6 Two-cycle averaged force time-histories in the fore-and-aft axis of the control at each vibration frequency. Individual data for 8 subjects. +ve force = acting in backward (aft) direction.

Normalised time as for Figure 5.2

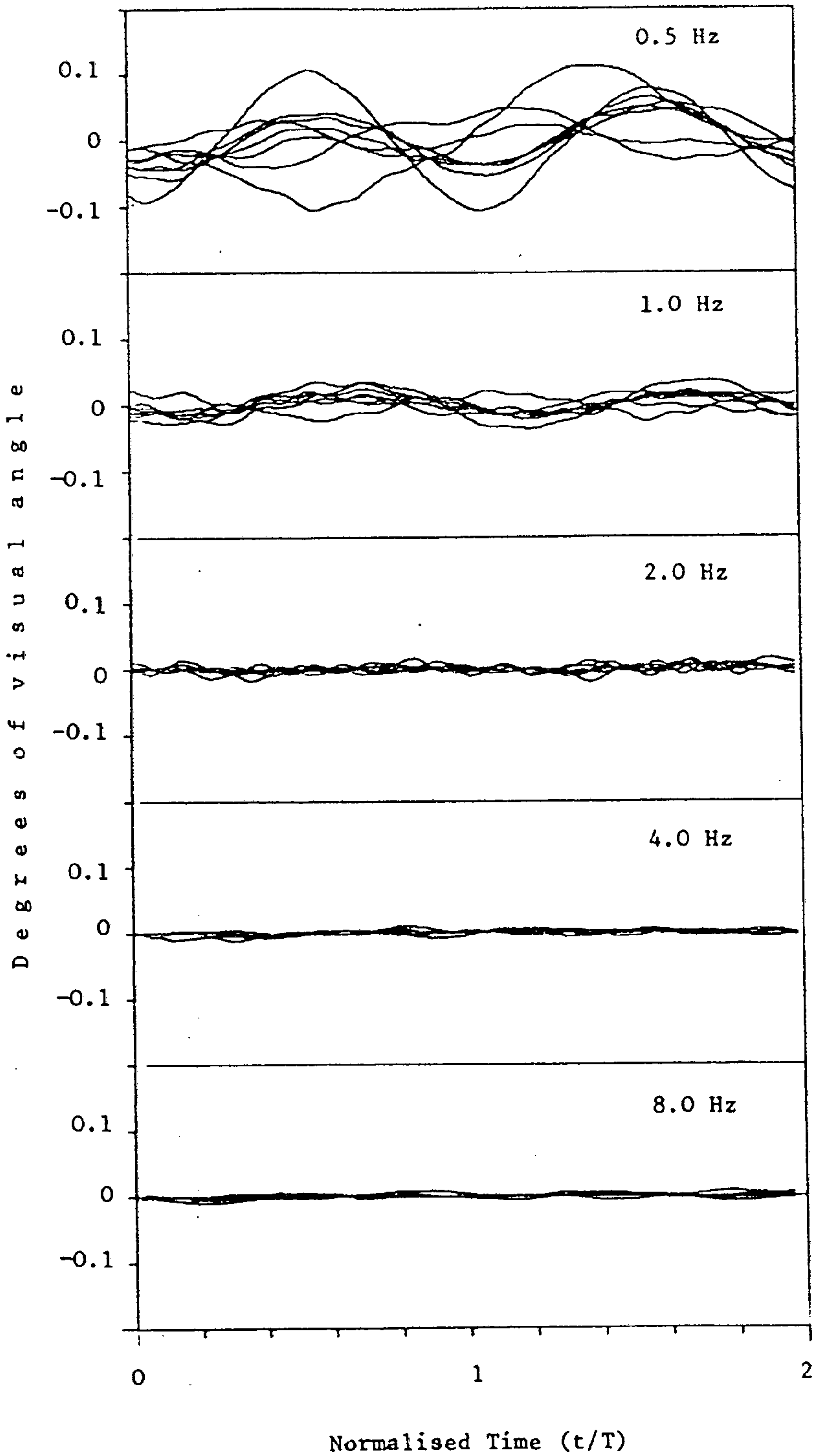


Figure 5.7 Two-cycle averaged time-histories of the controlled element displacement in the horizontal display axis at each vibration frequency. Individual data for 8 subjects. +ve angle = to subjects' right.

Normalised time as for Figure 5.2

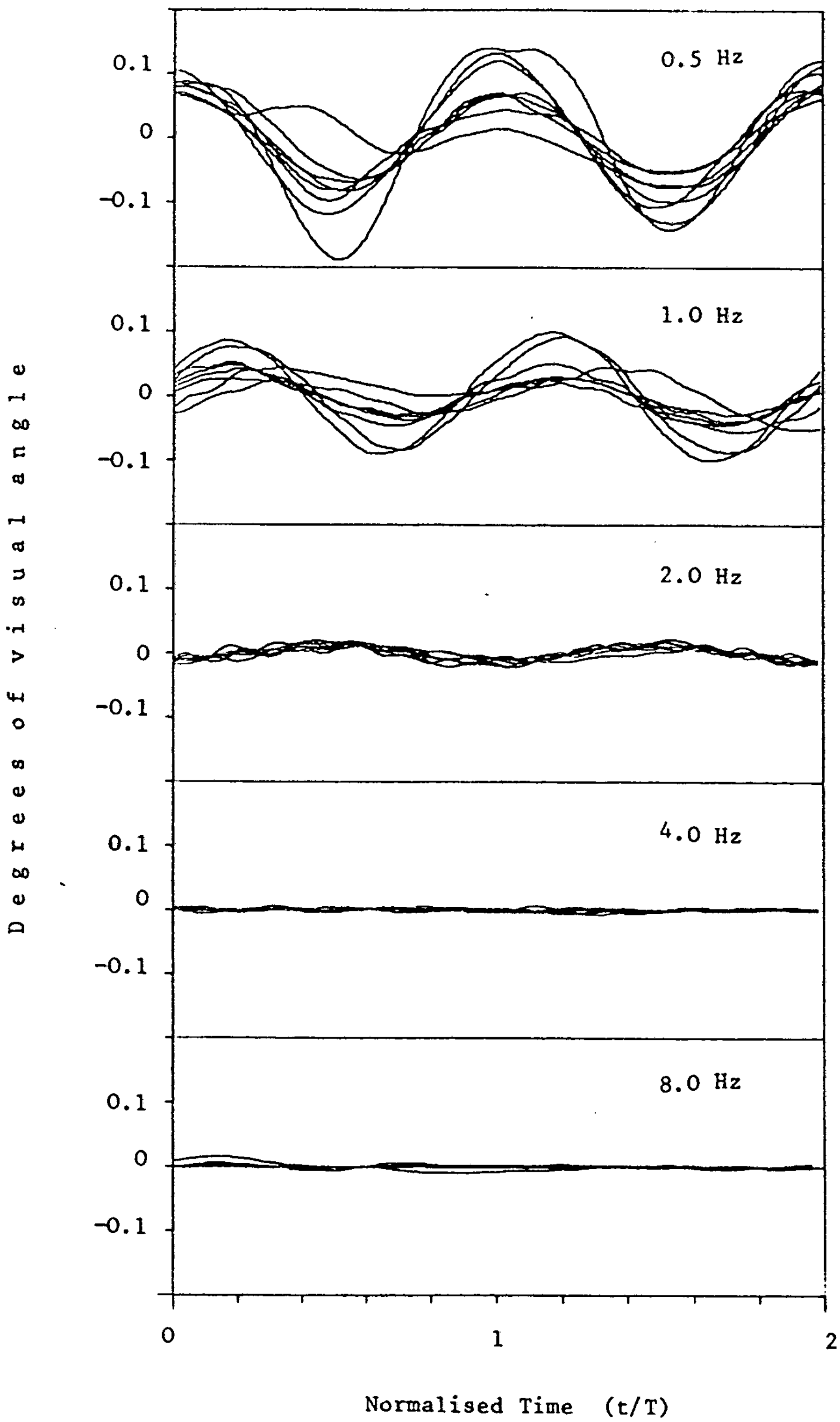


Figure 5.8 Two-cycle averaged time-histories of the controlled element displacement in the vertical display axis at each vibration frequency. Individual data for 8 subjects. +ve angle = towards top of display.

Normalised time as for Figure 5.2

octave below the vibration frequency in each case and attenuation of 24 dB per octave thereafter. The resulting control activity in the side-to-side and fore-and-aft axes is shown on Figures 5.5 and 5.6 respectively. (These data have been scaled to show the forces applied on the control in each axis. Direct comparisons can therefore be made across the two axes). Activity at the vibration frequency can be seen in all cases. In the side-to-side axis (Figure 5.5), the greatest magnitude of vibration-induced activity occurs at 4.0 Hz. In the fore-and-aft axis (Figure 5.6), control activity is more consistent across subjects and shows a consistent departure from a sinusoidal waveform at 0.5, 1.0 and 2.0 Hz.

With 4.0 Hz vibration the control activity is more sinusoidal, although 4 subjects show some flattening of the waveform in the forward direction around the bottom of the platform motion. At 8.0 Hz, inter-subject variability is greater although all subjects show more sinusoidal control activity.

Figures 5.7 and 5.8 show that effectively no vibration breakthrough appeared at the controlled element on the display in either axis with 2.0 Hz, 4.0 Hz and 8.0 Hz vibration. (These data were filtered in the same way as for the activity at the control). At 0.5 Hz and 1.0 Hz, breakthrough appeared on the display in both display axes. The median peak displacement of breakthrough was about 2 minutes of visual angle in the horizontal axis of the display and about 4 minutes in the vertical axis.

3.1.1. RMS Data

The rms magnitudes for each of the two-cycle averaged time-histories are shown on Figures 5.9 to 5.11. These data were subjected to statistical analyses. Due to the unequal variances

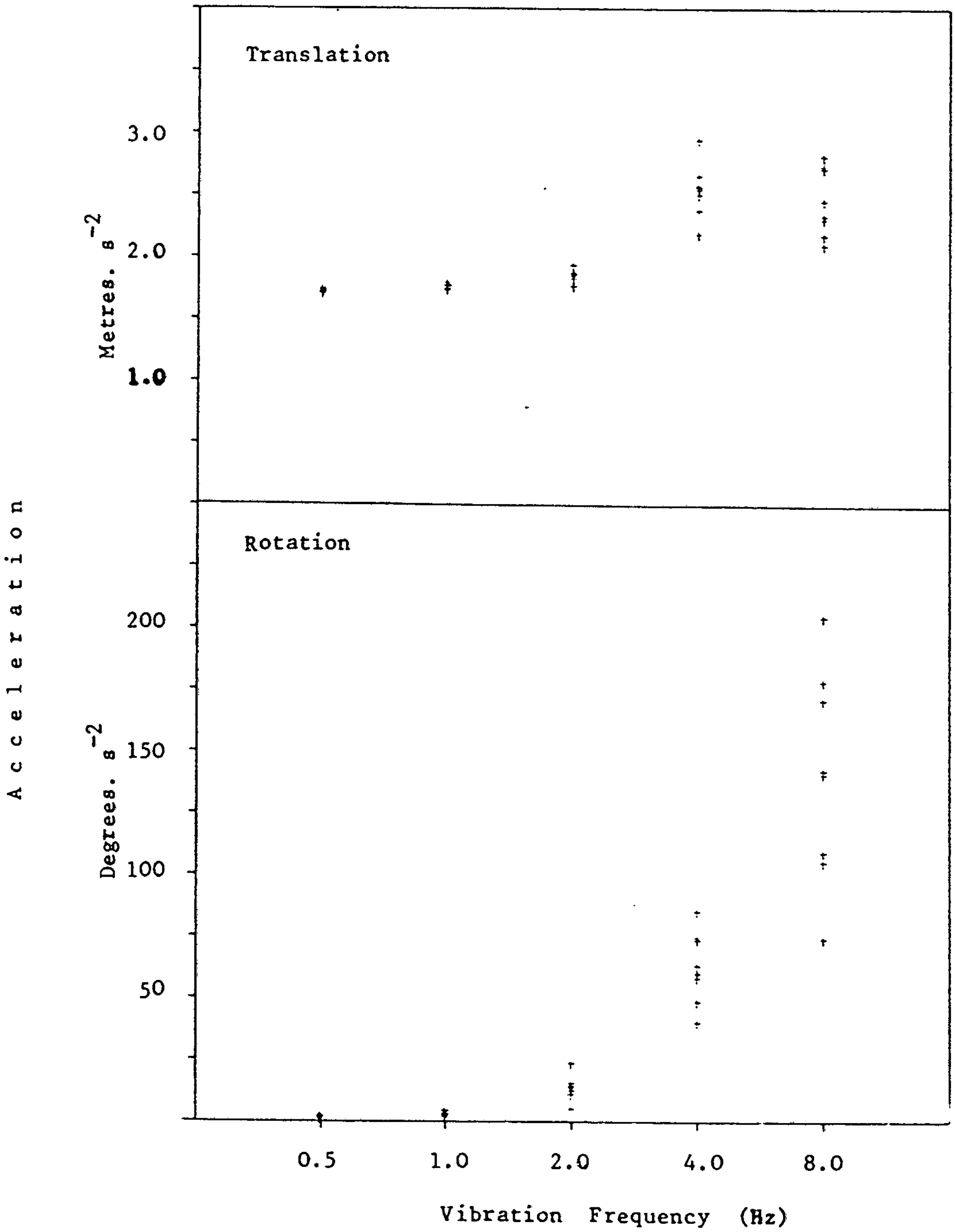


Figure 5.9 RMS magnitudes of induced activity in the translational and rotational axes at the head at each vibration frequency. Data for 8 subjects.

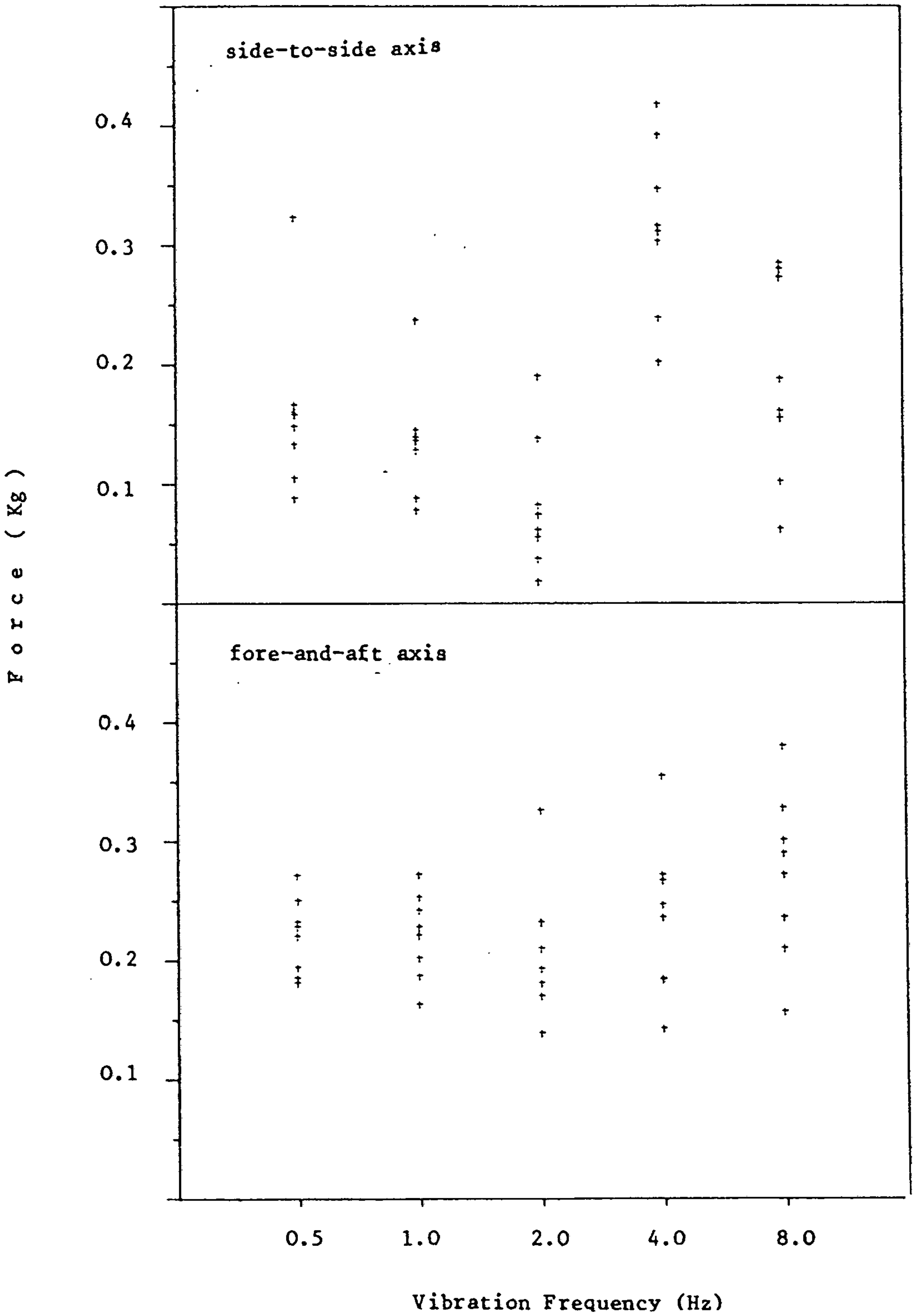


Figure 5.10 RMS magnitudes of induced activity in the side-to-side and fore-and-aft axes of the control at each vibration frequency. Data for 8 subjects.

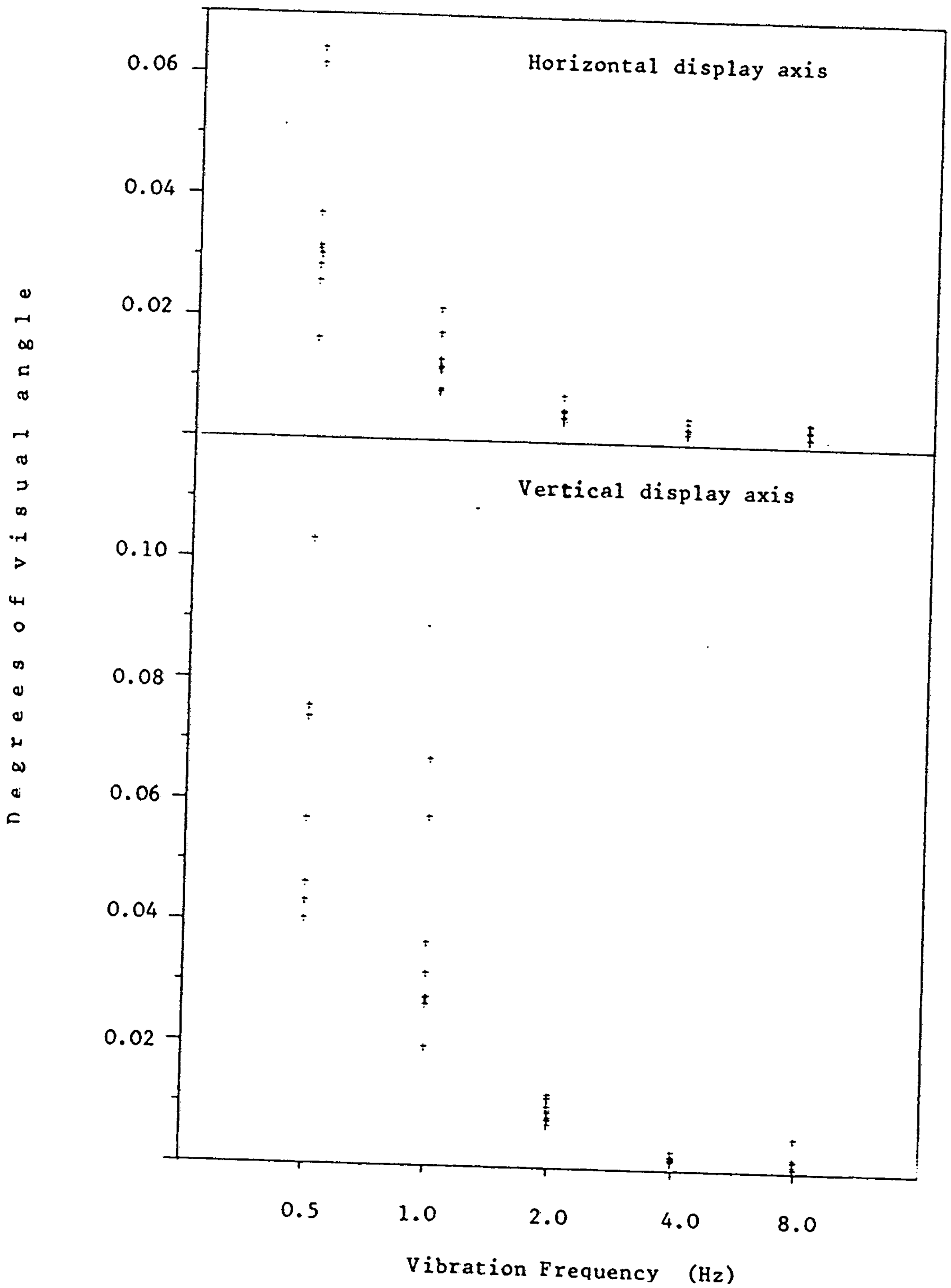


Figure 5.11 RMS magnitude of induced controlled element activity in each axis of the display at each vibration frequency. Data for 8 subjects.

and the non-normally distributed nature of much of the data, non-parametric tests were used throughout.

Friedman two-way analyses of variance by ranks were performed to test for overall effects of vibration frequency at each system location. There was no overall effect of frequency in the fore-and-aft axis of the control. Significant results occurred for all other system locations (in all cases, $p < 0.001$, df=4). Wilcoxon matched pairs signed ranks tests were then performed to test for differences between vibration frequencies at each location (except in the fore-and-aft axis at the control). Table 5.3 summarises the results of these tests.

There was no significant difference in rms z-axis head translation at 4.0 Hz and 8.0 Hz, suggesting that maximum transmissibility to the head probably occurs between these frequencies (Figure 5.9). For rotational head motion however the greatest magnitude of activity occurred with 8.0 Hz vibration. In the side-to-side control axis the effect of vibration frequency was caused both by the increase in activity at 4.0 Hz and a reduction in activity at 2.0 Hz compared with other frequencies (Figure 5.10). Figure 5.11 illustrates that, in both axes, the magnitude of breakthrough appearing on the display reduced with increasing vibration frequency from 0.5 Hz to 2.0 Hz and effectively did not occur at 4.0 and 8.0 Hz. Wilcoxon tests also showed that significantly more activity occurred in the fore-and-aft axis of the control than in the side-to-side axis at 0.5 Hz, 1.0 Hz and 2.0 Hz ($p < 0.01$).

3.2 Broad-band Random Vibration

Figures 5.12 and 5.13 show the transmissibility to the z- and pitch axes at the head for each subject during the broad-band random vibration exposures. These figures also compare the medians

Table 5.3 Results of Wilcoxon tests for differences between each vibration frequency at each location. No arm support. N=8

1. Head : z-axis

	0.5	1.0	2.0	4.0	8.0
0.5	---	***	***	***	***
1.0		---	***	***	***
2.0			---	***	***
4.0				---	NS
8.0					---

2. Head : pitch axis

	0.5	1.0	2.0	4.0	8.0
0.5	---	***	***	***	***
1.0		---	***	***	***
2.0			---	***	***
4.0				---	***
8.0					---

3. Control : side-to-side axis

	0.5	1.0	2.0	4.0	8.0
0.5	---	NS	***	***	NS
1.0		---	*	***	NS
2.0			---	***	***
4.0				---	***
8.0					---

4. Controlled Element : horizontal display axis

	0.5	1.0	2.0	4.0	8.0
0.5	---	***	***	***	***
1.0		---	***	***	***
2.0			---	***	***
4.0				---	NS
8.0					---

Table 5.3 (Continued)

5. Controlled Element : vertical display axis

	0.5	1.0	2.0	4.0	8.0
0.5	---	***	***	***	***
1.0		---	***	***	***
2.0			---	***	***
4.0				---	NS
8.0					---

Key: * = $p < 0.05$

** = $p < 0.02$

*** = $p < 0.01$

NS = Not significant

Two-tailed tests

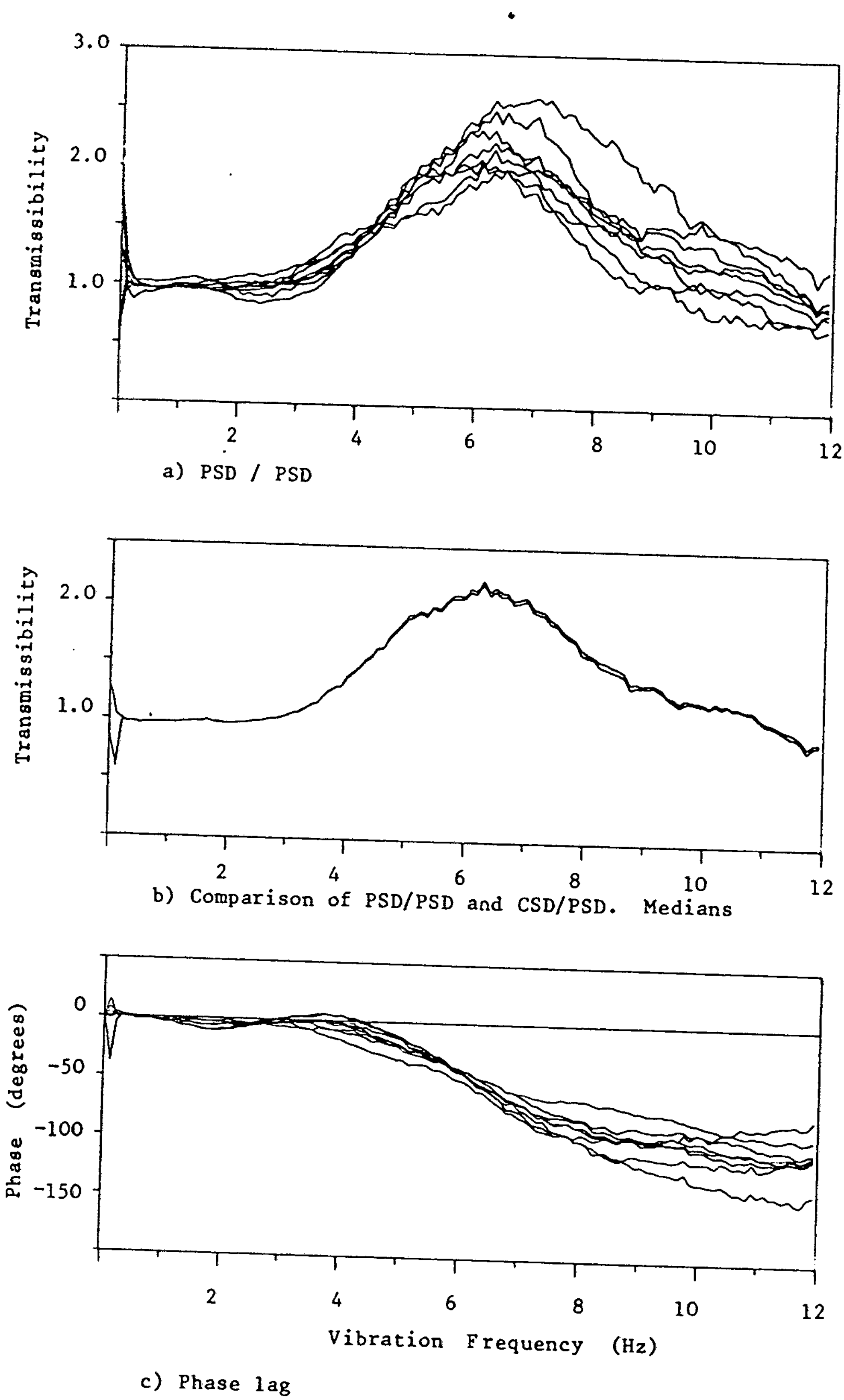


Figure 5.12 (a) Transmissibility of vibration to the head in the z-axis for 8 subjects (PSD/PSD).

(b) Comparison of median total and linear transmissibilities to the head in the z-axis.

(c) Phase lag between z-axis motion at the head and at the platform for 8 subjects.

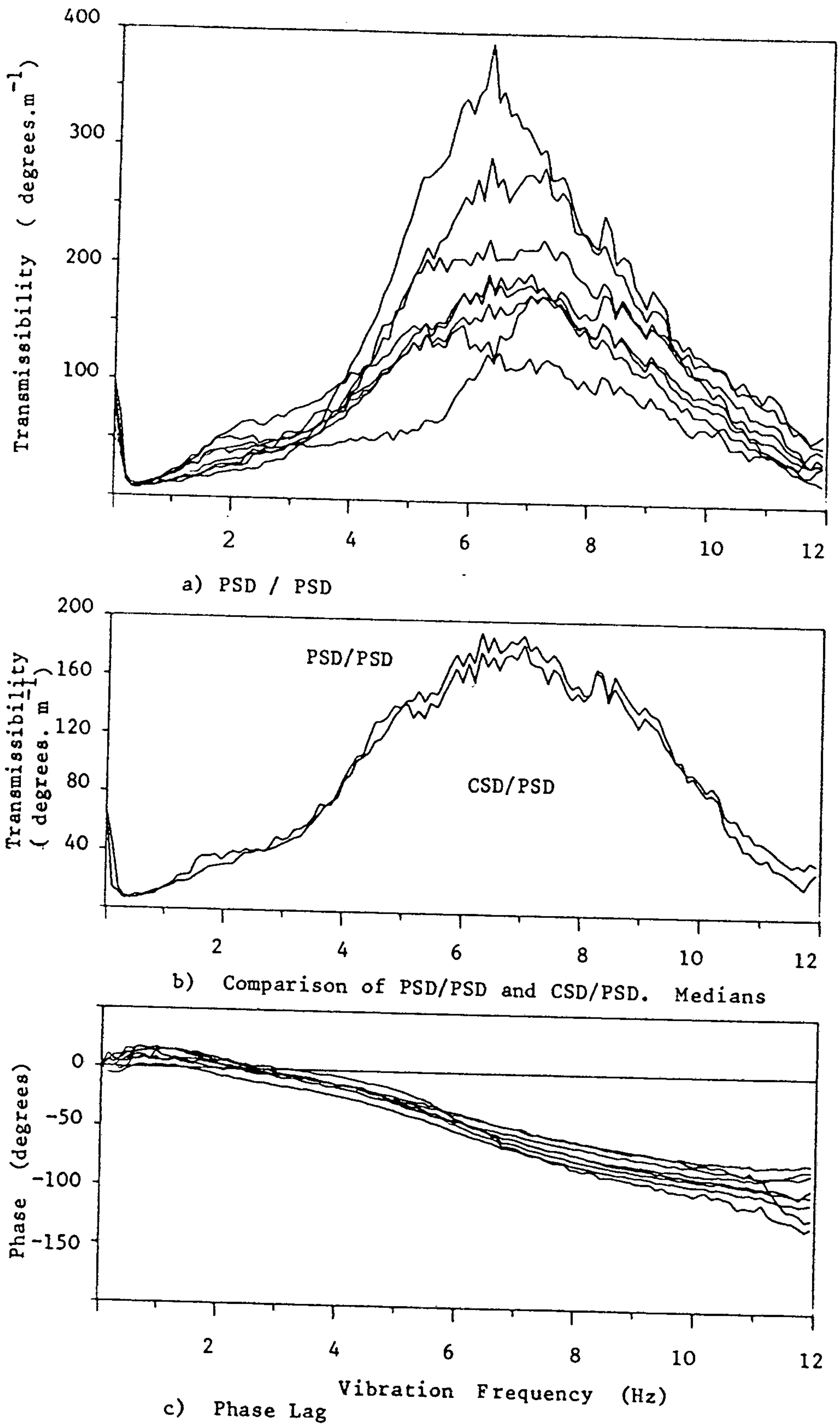


Figure 5.13 (a) Transmissibility of vibration to the head in rotation (pitch) for 8 subjects (PSD/PSD).

(b) Comparison of median total and linear transmissibilities to the head in the rotational axis.

(c) Phase lag between rotation at the head and translation at the platform for 8 subjects.

of the total transmissibility (PSD/PSD method) and the transmissibility attributed to linear operations on the platform motion (CSD/PSD method) and show the phase lag of the head relative to the display. For both translational and rotational head motion, subjects show reasonable similarity in the frequency range of maximum transmissibility: in both axes the maxima occur around 6 Hz and the region of resonance ranges from about 3 to about 12 Hz. There is considerable inter-subject variability in the absolute magnitudes of transmission. In the z-axis (Figure 5.12) transmissibility at 6 Hz ranges from about 2 to about 2.5 with a median of about 2.1. In rotation (Figure 5.13) the range is much greater - from about 100 to nearly 400 degrees m^{-1} - although two subjects show very much more rotation than the other six. The median for rotational head motion is around 180 degrees m^{-1}.

Figures 5.12b and 5.13b show that, in both axes, head motion was almost entirely attributable to the linear transmission of vibration through the body. Figures 5.12c and 5.13c show increasing phase delays between the platform motion and each axis of head motion with increasing vibration frequency. The greatest rate of increase in phase lag occurs around 6 Hz, coinciding with the frequency of greatest transmissibility.

The transmissibility to each axis of the control is shown on Figures 5.14 and 5.15. These figures also compare the total transmissibility with the proportion attributable to linear operations on the platform motion. In both axes, the dominant feature is the large transmissibility at frequencies below about 2.5 Hz, most of which does not arise from the linear transmission of platform vibration. This is attributable to control activity induced by the subjects. The apparently large transmissibility arises because of the small amount of energy in the platform motion at the lowest frequencies. In the side-to-side axis, the transmissibility was approximately constant at about 0.2 kg/ms^{-2} between about 3 and 8 Hz. In the fore-and-aft axis there was a slight drop in the magnitude of induced activity between about 5 and 7.5 Hz, although the magnitude was also about 0.2 kg rms^{-2} around this region.

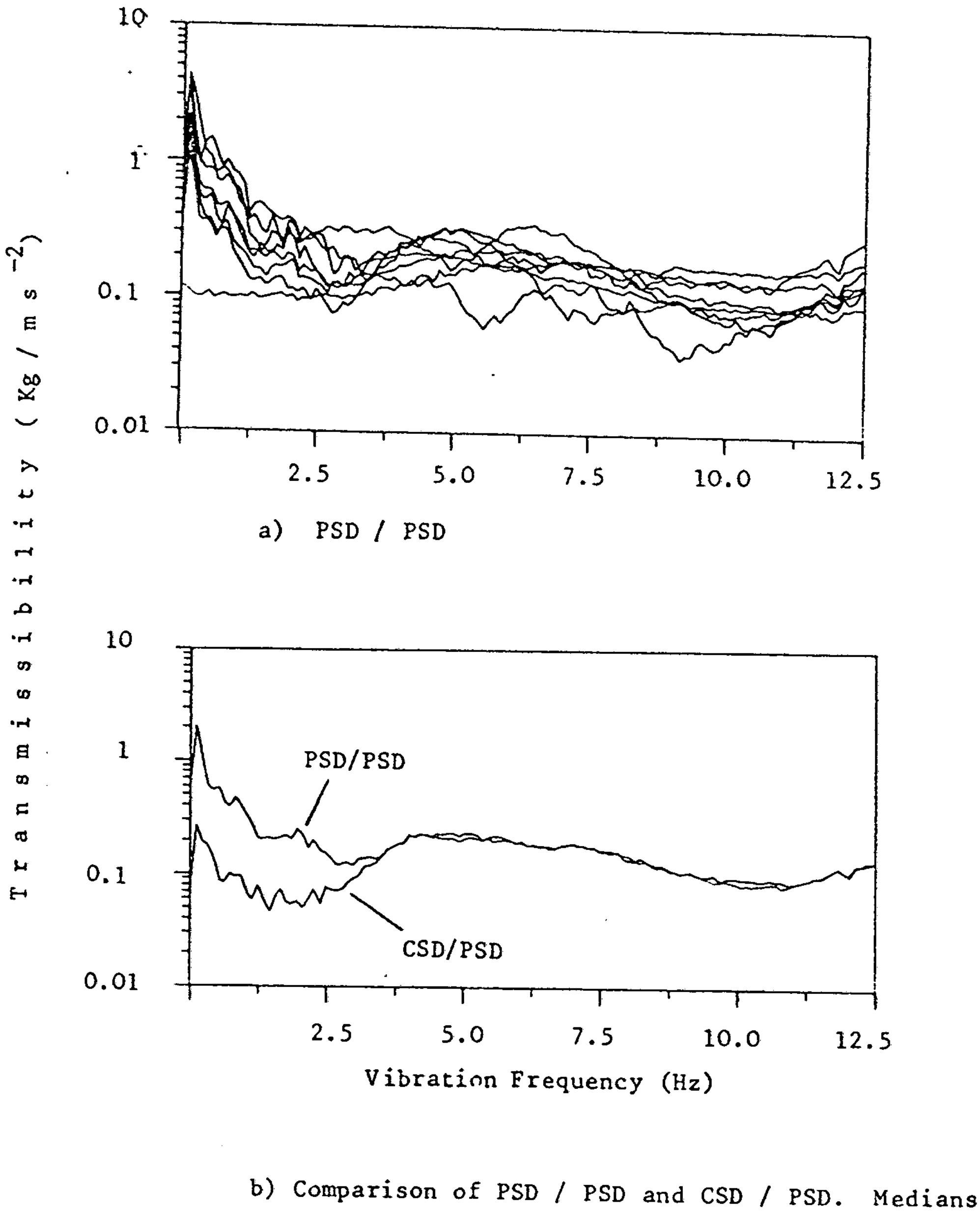
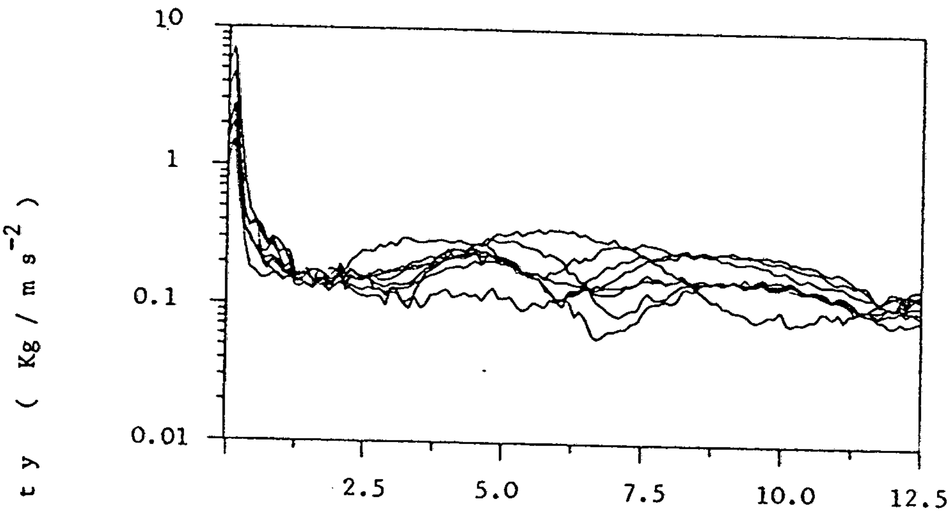
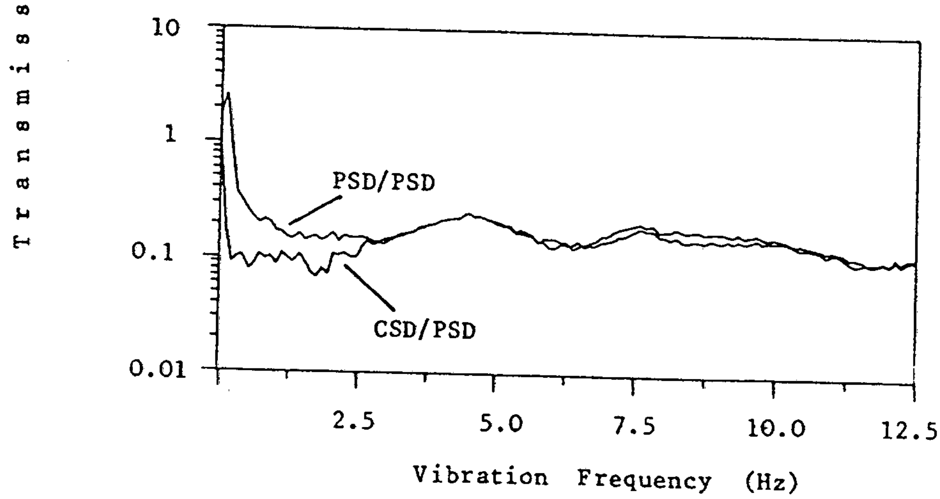


Figure 5.14 (a) Total transmissibility to the side-to-side axis of the control for 8 subjects (PSD/PSD).

(b) Comparison of median total and linear transmissibilities to the side-to-side axis of the control.



a) PSD / PSD



b) Comparison of PSD / PSD and CSD / PSD. Medians

Figure 5.15 (a) Total transmissibility to the fore-and-aft axis of the control for 8 subjects (PSD/PSD).

(b) Comparison of median total and linear transmissibilities to the fore-and-aft axis of the control.

3.3 Arm Support

Figure 5.16 compares the rms magnitude of the two-cycle averaged time-histories of control activity in response to the sinusoidal motions with and without the arm support. Friedman tests showed no significant effect of vibration frequency in either control axis with the arm support, while the figure shows a tendency for more activity to occur in the side-to-side axis without the support at 4.0 Hz than at other frequencies. Wilcoxon tests showed significantly less activity in the side-to-side control axis with the arm support during vibration at 0.5 Hz ($p < 0.05$), 1 Hz ($p < 0.01$), 4.0 Hz (p 0.01) and 8.0 Hz ($p < 0.05$) compared to the activity with the arm support. There was no significant effect of the arm support in the fore-and-aft axis.

Figure 5.17 compares the median total transmissibility to each axis of the control during the broad-band random motion with and without the arm support (PSD/PSD method). These data show that the main effect of the arm support was to reduce the vibration breakthrough in the side-to-side axis of the control. In both axes, the data with the arm support also show the large proportion of activity not linearly related to the platform motion at frequencies below about 2.0 Hz.

4.0 Discussion

The main aim of this study was to provide a description of the activity which can be expected to occur at each part of the system during exposure to z-axis translational whole-body vibration. The discussion will deal mainly with those aspects of the data which may help to explain the mechanisms underlying the effects of vibration on manual control performance. The nature of the

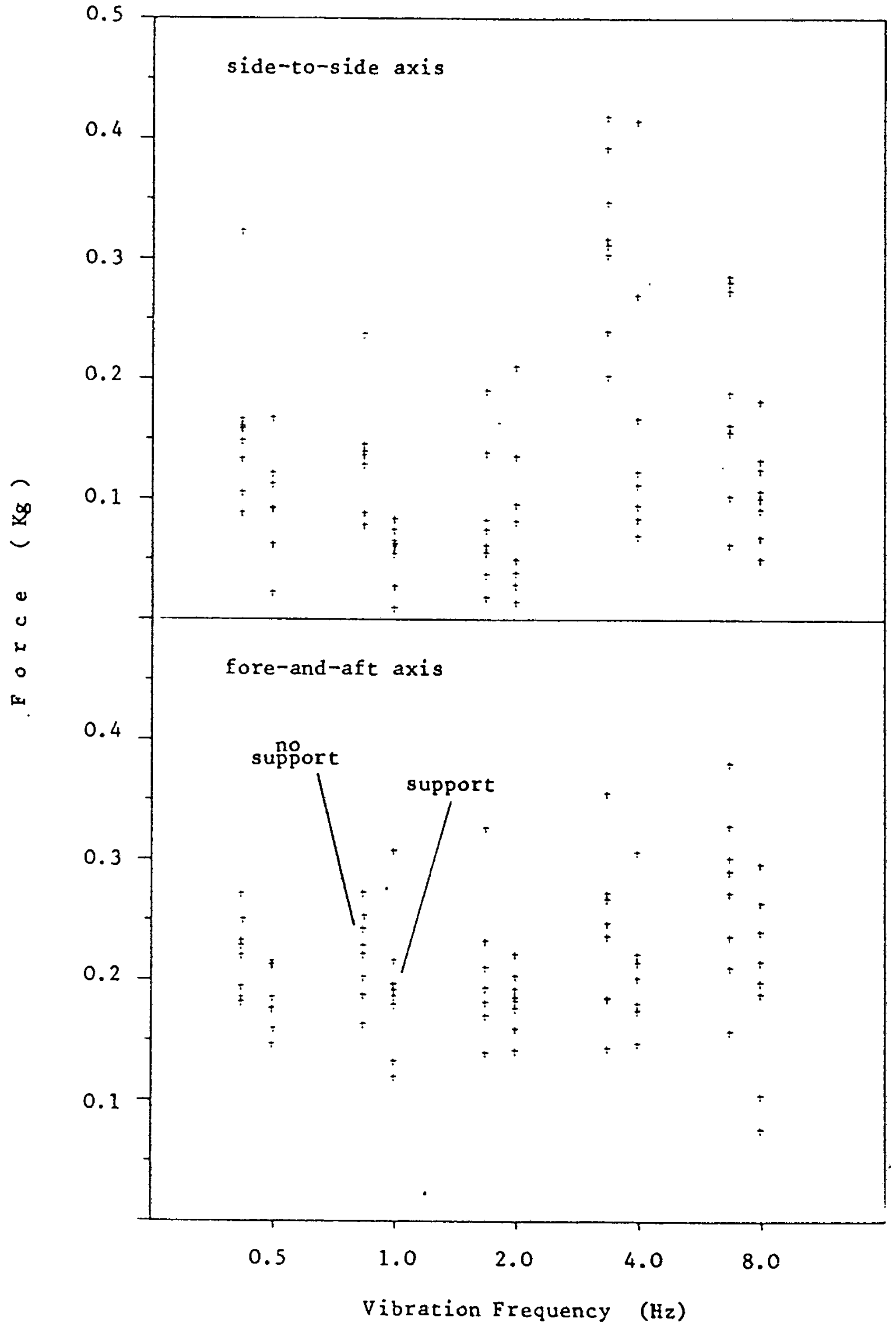


Figure 5.16 RMS magnitudes of control activity occuring with and without the arm support in each axis of the control and at each vibration frequency. Data for 8 subjects.

(NB. Data without the arm support are on the left at all frequencies).

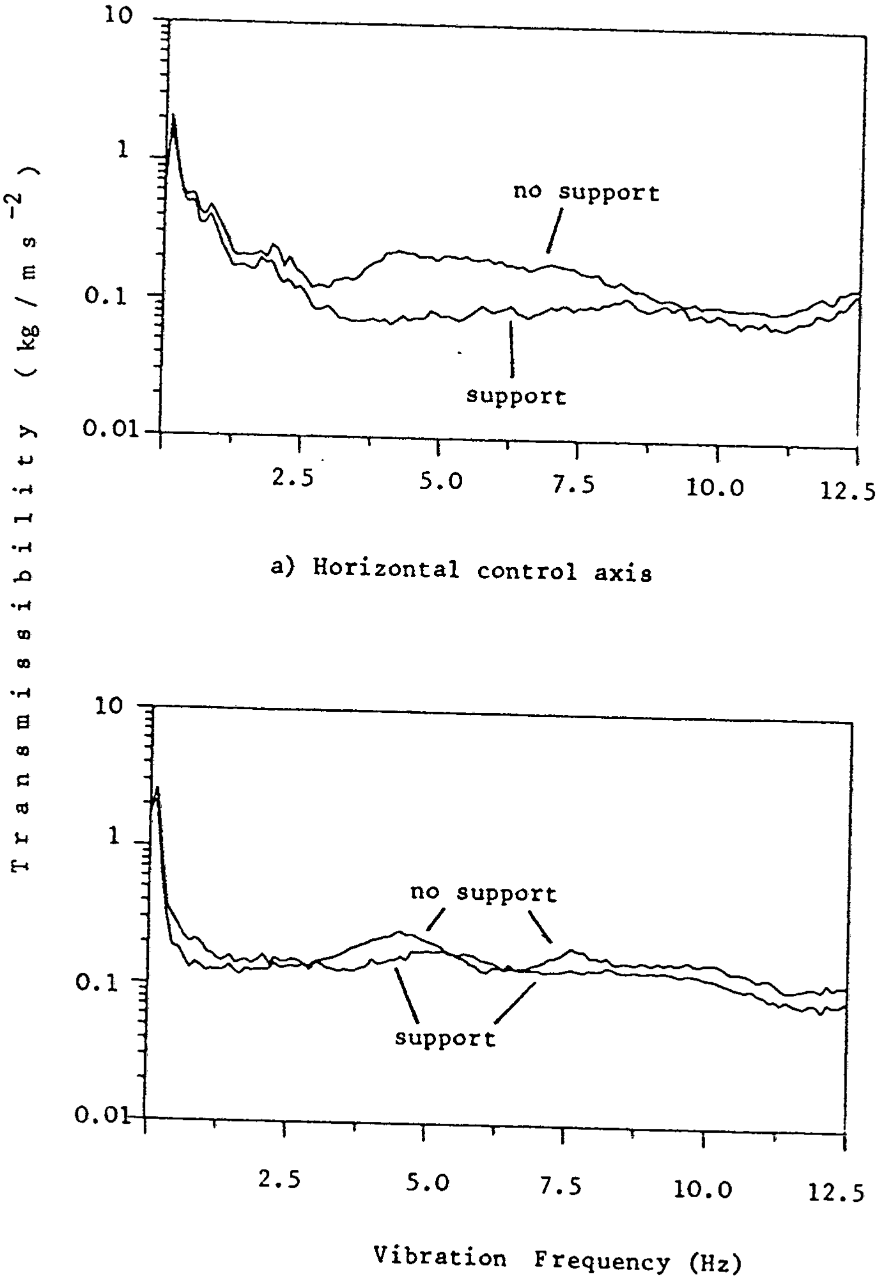


Figure 5.17 Total transmissibility to each axis of the control with and without an arm support. (PSD/PSD)

biodynamic models required to explain the results is beyond the scope of this thesis.

4.1 Activity at the Head

The data indicate that the maximum seat-to-head transmissibility for both translational and rotational head acceleration occurred around 6 to 7 Hz. Although there was considerable inter-subject variability in the absolute magnitudes of transmission, the maxima occurred in this region for all 8 subjects. Median transmissibility at 6 Hz was about 2.1 for translational and about 180 degrees m^{-1} for rotational head acceleration. The data in response to broad-band random vibration are in good agreement with results obtained by Paddan and Griffin (1986) when subjects sat with their backs supported.

These data indicate that, with the magnitude of vibration used in this thesis, significant relative acceleration between the head and the display can be expected at vibration frequencies above about 2 Hz. The magnitude of relative acceleration between the eye and the display will depend upon the extent to which the vestibular-ocular reflex, the otolith-ocular reflex and voluntary eye tracking can compensate for acceleration of the head relative to the display. These are all dependent on the vibration frequency. The effects will also depend upon the visual resolution required by the task, and effects from head translation will be dependent on the viewing distance. Furthermore, with increasing magnitudes of vibration, subjects may be able to utilise nodal images in the pattern of visual blurring to assist in detecting the displayed information, (Huddleston, 1970). It is therefore not possible to to make simple statements about the relationship between induced head acceleration and the magnitude of visual disruption. At frequencies below about 2 Hz, however, the data indicate that visual disruption arising from relative acceleration between the head and the display is not likely to be significant.

4.2 Activity at the control and controlled element

In both control axes, most of the activity at vibration frequencies above about 2.5 Hz can be directly attributed to the vibration. At lower frequencies, the proportion of activity not linearly related to the vibration increases as the frequency reduces. In the fore-and-aft axis of the control the two-cycle averaged waveforms (Figure 5.6) show a highly regular departure from sinusoidal activity at 0.5 Hz, 1.0 Hz and 2.0 Hz. This may reflect subjects intentionally inducing forces on the control to try to compensate either for perceived breakthrough or for some more general sensation of motion. In the side-to-side axis, the activity not attributable to the motion is more random-like in waveform (Figure 5.5), and is therefore less likely to reflect an active compensatory response.

Random appearing low-frequency control activity occurred in all vibration conditions and, indeed, was the reason why the time-histories of control activity were high-pass filtered. This study cannot distinguish whether this background activity was altered, or indeed induced, by the vibration conditions. (However this will be investigated in Experiment 5). The apparent trend towards reducing activity in the side-to-side axis of the control as the vibration frequency increased from 0.5 Hz to 2.0 Hz (Figure 5.10), may reflect the reducing ability of subjects to respond as the frequency increases.

4.3 Effect of the Arm Support

The arm support caused a reduction in the magnitude of vibration-induced activity in the side-to-side axis of the control. The arm support therefore provided lateral stability to the arm but had little effect in the longitudinal (ie., fore-and-aft) axis. It is difficult to generalise from the particular support used in this study to arm supports in general: the precise effects are likely to depend on the type of support provided including its dynamic characteristics. However, the results from the study suggest that an arm support may reduce the effects of vibration on performance if vibration breakthrough - in this case in the side-to-side axis - significantly contributes to the disruption.

5.0 Conclusion

Four main conclusions are drawn from the data obtained in this study.

1. At vibration frequencies between about 2 Hz and 12 Hz, both translational and rotational acceleration occurs between the head and the display: in both cases, maximum relative acceleration occurs at about 6 Hz. Because of the complexity of the visual system, and the mechanisms contributing to visual impairment, predictions of the extent of visual disruption are not possible on the basis of these data. However, with the magnitudes of vibration presented in this thesis, impairments in visual ability are not expected to significantly contribute to performance disruption at vibration frequencies below about 2 Hz.

2. Platform vibration can directly induce activity at the vibration frequency in both axes of the control across the range of frequencies presented. However, vibration breakthrough only appeared at the controlled element on the display at frequencies below about 1 Hz. The median rms magnitude of breakthrough in this study was about 2 minutes of viewing angle in the horizontal display axis, and about 4 minutes in the vertical axis. The control gain in this study was considerably more sensitive than in any of the performance studies. Vibration breakthrough is therefore not expected to be an important mechanism of performance disruption in the later studies at vibration frequencies above about 1 Hz, and is unlikely to significantly contribute to disruption at the lowest frequency presented in this thesis (0.5 Hz).

3. At vibration frequencies below about 2 Hz, the data suggest that subjects may actively induce control activity to compensate for perceived motion of the body.

4. Providing an arm support can reduce the magnitude of vibration-induced activity occuring at the control. The effect of an arm support, however, is likely to depend upon the details of the particular support provided. With the support used in the present study, the effect occurred mainly in the side-to-side axis of the control. The effect of a reduction in vibration-induced activity at the control on performance will depend upon the extent to which vibration breakthrough is an important mechanism of disruption.

CHAPTER SIX

EXPERIMENT TWO: THE EFFECT OF SINUSOIDAL VIBRATION AT FREQUENCIES FROM 0.5 TO 5.0 HZ ON PERFORMANCE OF THE COMPLEX MANUAL CONTROL TASK

1.0 Introduction

This Chapter describes the first experiment investigating performance of the combined continuous and discrete manual control task during whole-body vibration exposure. The study had two main aims. The first was to investigate whether this complex task would be sensitive to disruption by whole-body vibration. The second was to investigate whether any disruption would be frequency dependent.

In Experiment 1 relative acceleration between the head and the display was observed in both translational and rotational axes at vibration frequencies from about 2 to about 10 Hz. In both axes the greatest magnitude of relative acceleration occurred at about 6 Hz. If effects of vibration on visual ability are related to the relative acceleration between the head and the display therefore, effects would be expected to increase as the vibration frequency increased from about 2 to about 6 Hz. At vibration frequencies below about 2 Hz, impairment in vision due to relative acceleration between the head and the display would not be expected. Effects on performance arising from impaired visual ability should show a similar frequency dependence.

Experiment 1 also demonstrated that similar magnitudes of vibration breakthrough could occur at the control during sinusoidal vibration at frequencies from 0.5 to 8.0 Hz. However, the system dynamics increasingly attenuate control activity at increasing frequencies: breakthrough only appeared on the display at vibration frequencies below 1 Hz. Breakthrough at the display is therefore not likely to be a significant mechanism of performance disruption at vibration frequencies above about 1 Hz, and its effect should increase with decreasing frequency below 1 Hz. However, in order to accentuate breakthrough in Experiment 1, the control gain was considerably more sensitive than in the present study. It was therefore considered unlikely that display breakthrough would significantly contribute to performance disruption in this experiment.

In summary, from a knowledge of the transmission of vibration to the head, to the control and to the controlled element on the display, it was expected that effects of vibration on performance would arise mainly from impaired visual ability. Disruption was expected to occur at vibration frequencies above about 2 Hz, and was expected to increase due to increasing visual impairment as the frequency increased to 5 Hz. If vibration breakthrough contributed to performance disruption, its effect would increase with decreasing vibration frequency below about 1 Hz.

2.0 Method and Procedure

Subjects performed the combined continuous and discrete tracking task using the full, cross-coupled system dynamics described in Chapter 4 and Appendix C. They operated the isometric side-arm control with their preferred right hand and viewed the display directly at a distance of approximately 750 mm. Subjects sat on a hard, flat seat with a backrest and were restrained by a 5-point harness. The seat, control and display were all mounted on a 1 m stroke electro-hydraulic vibrator which was constrained to move in the vertical axis only. Figure 6.1 shows the layout of equipment on the vibrator.

Movement of the target, a circle of diameter 10 mm, was controlled on-line from a PDP 11/34 digital computer. Forcing functions were low-pass filtered at 0.1 Hz with attenuation of 24 dB/octave above this frequency. A separate random appearing forcing function moved the target in each axis of the display. Forcing functions were randomly selected for each run from a total of 36 different time-histories but ensuring that no subject received the same one twice and that no forcing function was used more than once for any vibration condition. The target always started and ended each run in the centre of the display.

Forcing functions were output to the display by 10-bit digital-to-analogue conversion at 25.64 samples per second. The forcing functions and the system response (controlled element position and button state), were acquired by analogue-to-digital conversion at 25.64 samples per second. All time-histories were passed through anti-aliasing filters with a cut-off at 6.3 Hz and attenuation of 48 dB/octave thereafter. Tracking runs lasted for 180 seconds although the first 15 seconds of each run were discarded in the analysis.

Whole-body, sinusoidal, z-axis vibration was presented at each preferred third-octave centre frequency between 0.5 Hz and 5.0 Hz at an acceleration magnitude of 2.0 ms^{-2} rms. Subjects also performed a single control run without vibration. The order of presentation of these 12 runs (11 vibration, 1 static) was randomised both within and across subjects. Further details of the equipment, vibrators and task are presented in Chapter 4. The details of this experiment are summarised on Table 6.1.

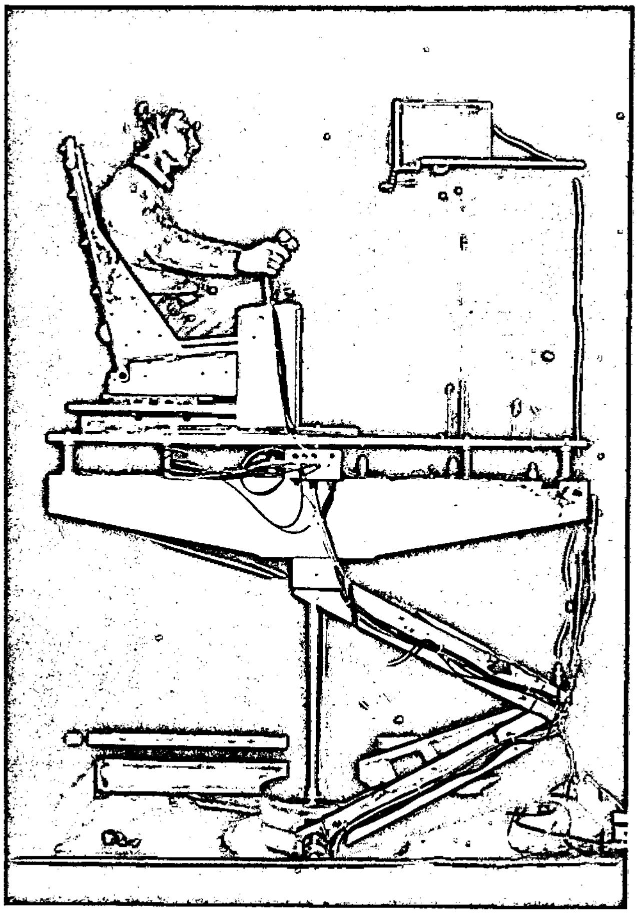


Figure 6.1 A subject on the experimental rig for experiment 2.

Table 6.1 Details of Experiment 2

Independent Variables	:	Vibration frequency; Session.
Dependent Variables	:	Simple probabilities - p(on), p(hit), etc.
Subjects	:	Session I - 10 right-handed males Sessions II and III - 8 right-handed males (6 from Session I).
Task	:	Combined continuous pursuit tracking and discrete target acquisition task. 300 seconds per run. The first 15 seconds of each run were omitted from the analysis.
Forcing Function	:	Gaussian random time-histories, low-pass filtered at 0.1 Hz with 24 dB/octave attenuation thereafter.
System Dynamics	:	First-order. Full, cross-coupled aircraft model.
Control	:	Isometric side-stick. No arm support.
Control gain	:	fore-and-aft = 1.0 v/kg = 0.53 $^{\circ}$/s/kg (pitch) side-to-side = 0.2 v/kg = 5.2 $^{\circ}$/s/kg (roll)
Display	:	Uncollimated. Viewing distance = 750 mm Target subtended 33 minutes of arc at the subjects' eye.

Table 6.1 (continued)

Vibrator	:	1-metre stroke electro-hydraulic. z-axis.
Seat	:	Hard, flat simulated helicopter seat with backrest and 5-point harness.
Vibration Exposure	:	Whole-body, sinusoidal vibration at 0.5, 0.63, 0.8, 1.0, 1.25, 1.6, 2.0, 2.5, 3.15, 4.0 and 5.0 Hz at 2.0 ms^{-2} rms. Person, control and display vibrated.
Sessions per subject	:	3 complete replications.

2.1 Training

Ten subjects were initially trained over three sessions of 10, 3 minute runs without vibration. These sessions were presented on successive days. In the fourth session, subjects performed two runs without vibration, followed by a block of twelve runs in random order; one at each of the eleven vibration frequencies and one with no vibration. The fifth session was a replication of the fourth with a different random order of presentation. This fifth session was originally planned as the experimental session, and will be referred to as Session I.

Data from Session I are presented in the results. The data were highly variable both within and across subjects and showed no overall effect of vibration. It seemed likely that the variability in the data reflected insufficient training and that this variability could have masked any systematic vibration effect. It was therefore considered necessary to further train the subjects and repeat the experiment. At this stage, four of the original subjects dropped out and two new subjects were recruited, giving a final sample size of eight. The six original subjects were given five more training sessions of 10, 3 minute runs each without vibration. The two new subjects were given 10 sessions of 10 runs each, with sessions 4 and 5 providing the same vibration exposures as the other subjects had received. Training was followed, as before, by two identical sessions under vibration. New sets of forcing functions were used for the second series of training sessions and for the final two sessions with vibration. Learning curves for these subjects are presented in Appendix D.

On the final two sessions, subjects performed 13, 3 minute runs. The first run served as a 'warm-up' and was performed without vibration. The next 12 runs included one at each vibration frequency and one without vibration. The order of presentation of these 12 runs was randomised. These two sessions will be referred to as Sessions II and III respectively.

3.0 Results and Discussion

The results will be presented in two parts; the first part deals with performance of the continuous task and the second part deals with the discrete task.

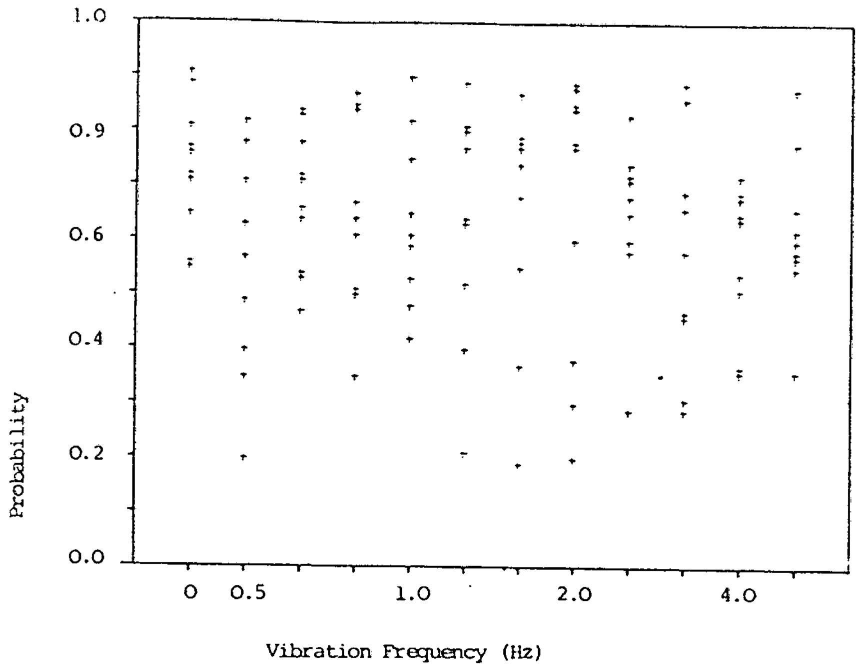
3.1 Continuous Task

Figures 6.2 to 6.4 show the distribution of the probability of being on target - p(on) - against vibration frequency for each of the three experimental sessions (ie., Sessions I, II and III). These figures also show the medians and inter-quartile ranges of the data for each session. Friedman two-way analyses of variance by ranks tests were used to test for overall effects of vibration frequency within each session. Results showed an effect of frequency for Session III only ($\chi^2 = 31.98$, 11 degrees of freedom (df), $p < 0.001$). The effect of frequency remained when the data for the no vibration run were excluded from the analysis ($\chi^2 = 23.4$, 10 df, $p < 0.01$). There were no effects of vibration on Session I.

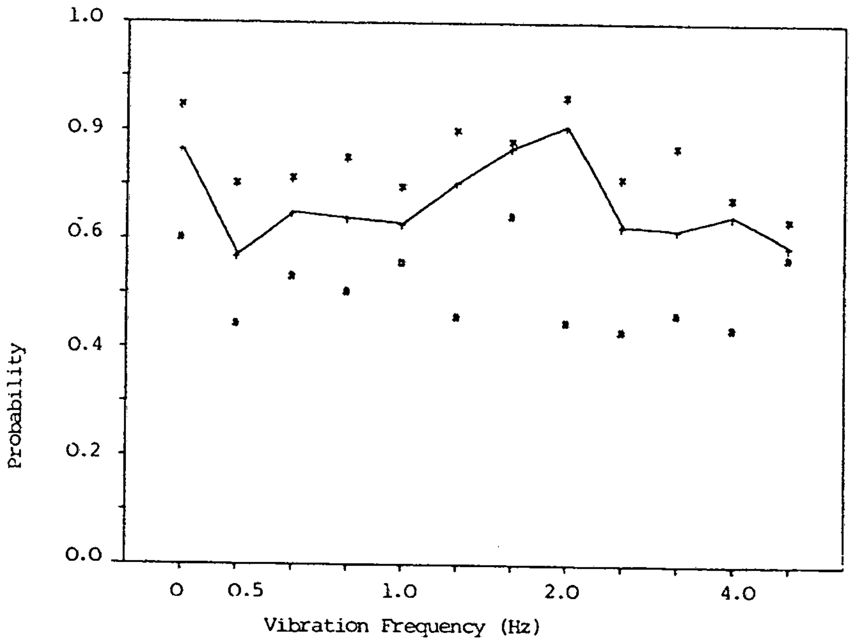
The data for Sessions II and III were transformed to show the percentage change in p(on) at each vibration frequency. The percentage change was defined as:

$$\text{Percentage change} = \frac{\text{p(on) static} - \text{p(on) vibration}}{\text{p(on) static}} \times 100$$

These data are shown on Figure 6.5 for Sessions II and III. The probability of these percentage change data having occurred by chance compared with an expected change of 0% was assessed using the sign test. These tests were significant on both sessions ($z = 5.7$ for Session II and 6.3 for Session III, $p < 0.0001$) indicating that vibration significantly disrupted performance in both cases. Wilcoxon Matched-pairs signed ranks tests were then carried out on



(a) Distribution of Data



(b) Median and Inter-quartile range

Figure 6.2 The probability of being on target - p(on) - as a function of vibration frequency on Session I.

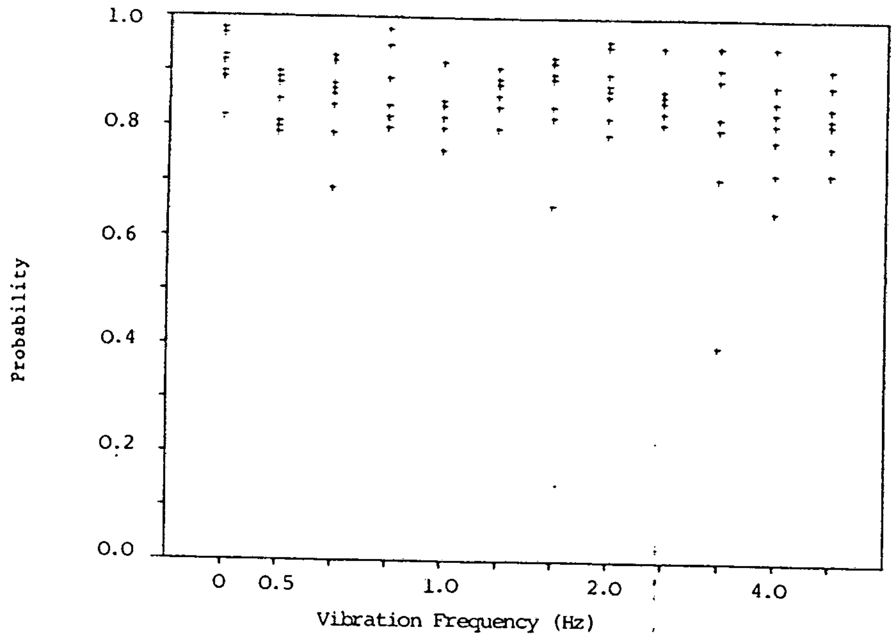
(a) Distribution of data

(b) Median and inter-quartile ranges

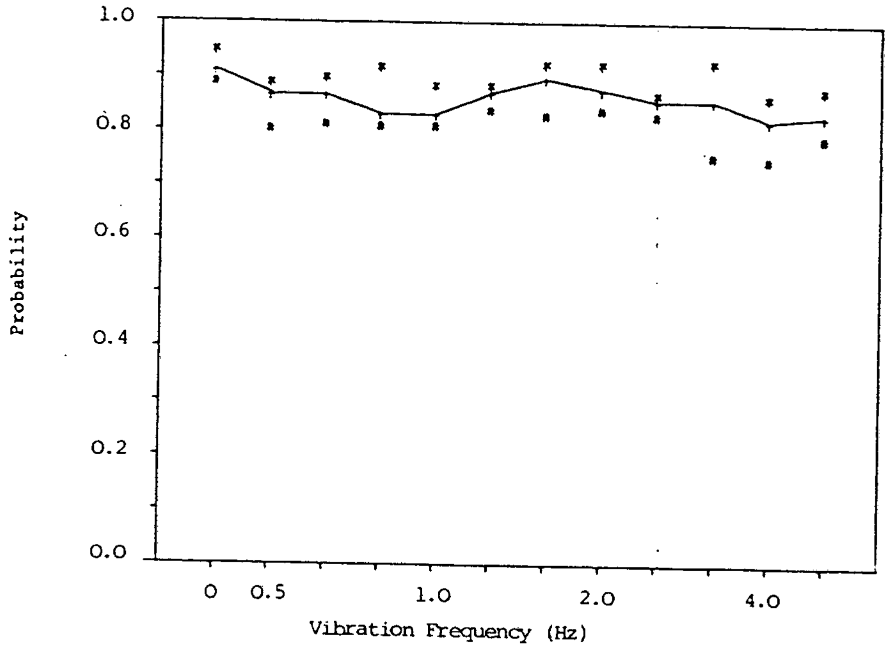
+ = median

* = upper quartile

= lower quartile



(a) Distribution of Data



(b) Median and Inter-quartile ranges

Figure 6.3 The probability of being on target - p(on) - as a function of vibration frequency on Session II.

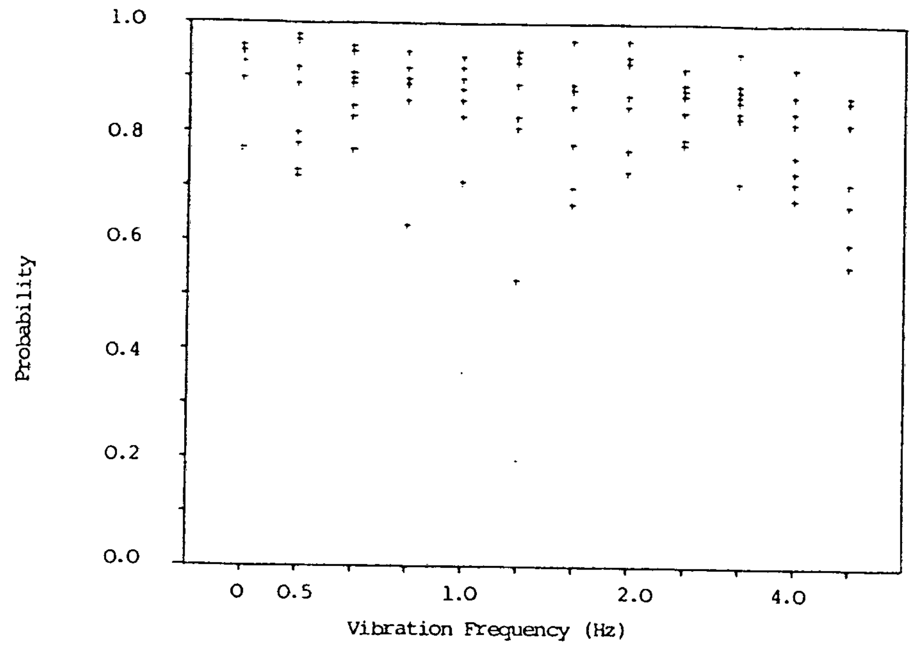
(a) Distribution of data

(b) Median and inter-quartile ranges

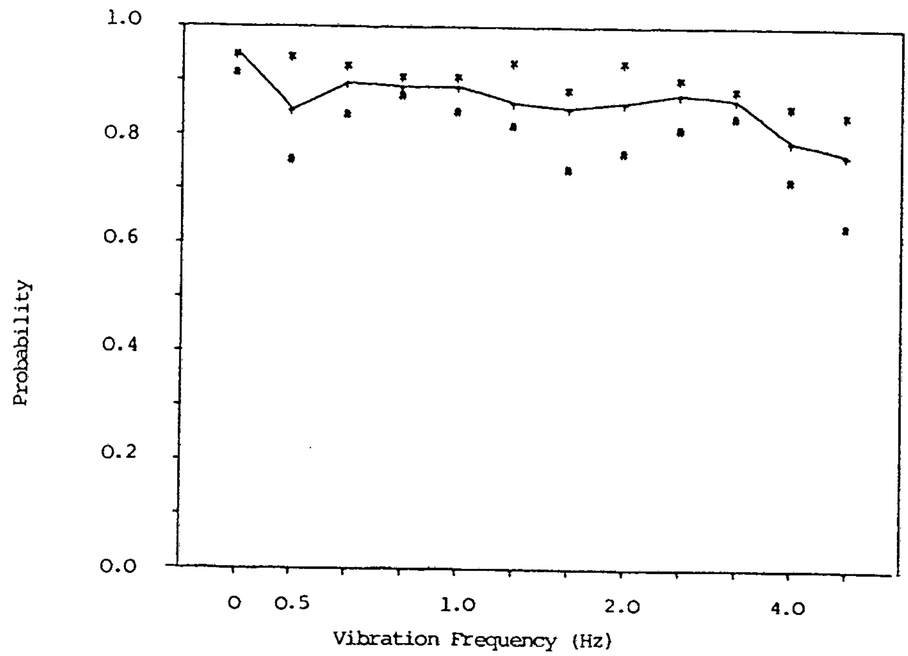
+ = median

* = upper quartile

= lower quartile



(a) Distribution of Data



(b) Median and Inter-quartile ranges

Figure 6.4 The probability of being on target - p(on) - as a function of vibration frequency on Session III.

(a) Distribution of data
(b) Median and inter-quartile range

+ = median, * = upper quartile,
# = lower quartile

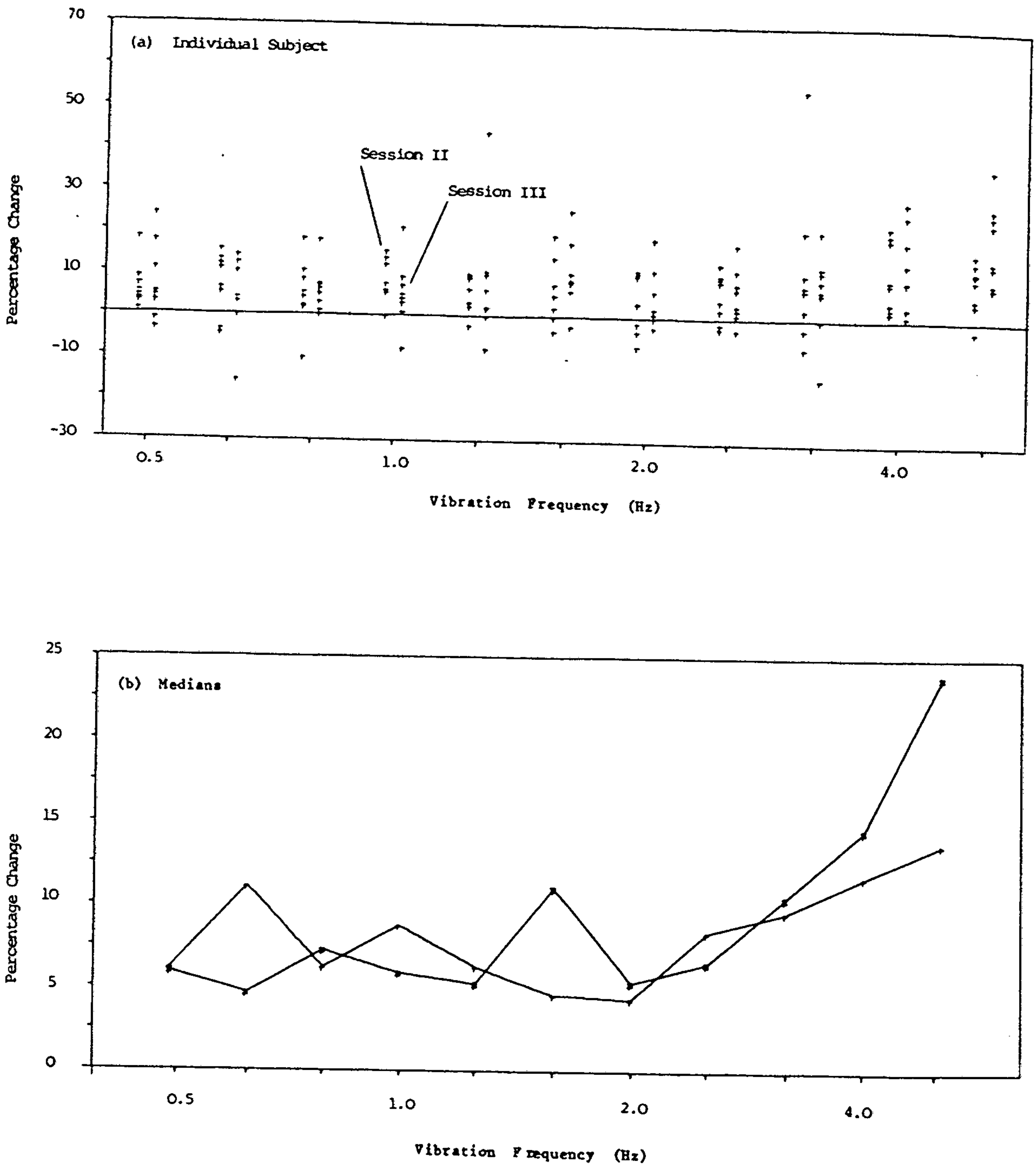


Figure 6.5 Percentage change in p(on) as a function of vibration frequency on Sessions II and III.

(a) Individual subjects' data (b) Medians

+ = Session II * = Session III

(NB. Data for Session II are on the left in all cases) the 'raw' data for Session III to test for differences between each vibration condition. Table 6.2 summarises the results of these tests. Although 65 tests were performed, and therefore a number of these apparently significant results can be attributed to chance, it is clear that the effect of frequency was mainly caused by vibration at 4.0 and 5.0 Hz combined with poorer performance under vibration compared with the no vibration conditions.

Summarising these data, the results show three main effects:

(i) On Session I, the variability of the data due to the incomplete training of subjects masked any effect of vibration which may have occurred;

(ii) On Sessions II and III performance under vibration was consistently poorer than performance without vibration; and

(iii) On Session III vibration at 4.0 and 5.0 Hz produced greater disruption than at lower frequencies.

The difference between Session I and Sessions II and III illustrates the importance of adequately training subjects before determining whether vibration can affect performance. From these data it is not possible to determine whether the variability on Session I included a component due to a lack of training under vibration conditions.

There was no significant difference between Sessions II and III either over all conditions or within any vibration condition. It is not clear therefore why a frequency dependent effect appeared on Session III but not on Session II. If subjects were, in some sense, learning to perform the task under vibration conditions on

Table 6.2: <u>Results of Wilcoxon tests between each vibration condition on Session III.</u>

	0	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0
0	-	*	NS	***	*	*	***	*	*	*	***	***
0.5		-	NS	NS	NS	NS	NS	NS	NS	NS	***	***
0.63			-	NS	*	NS	*	NS	NS	NS	***	***
0.8				-	NS	NS	NS	NS	NS	NS	*	***
1.0					-	NS	*	NS	NS	NS	*	***
1.25						-	NS	NS	NS	NS	NS	**
1.6							-	NS	NS	NS	NS	*
2.0								-	NS	NS	*	***
2.5									-	NS	*	*
3.15										-	*	*
4.0											-	NS
5.0												-

* = $p < 0.05$
** = $p < 0.01$
*** = $p < 0.001$

(1-tailed tests: H_1 = p(on) vibration < p(on) static)

Session II, it would be expected that performance would be poorer on this session during vibration. Comparing across sessions (Figure 6.5) shows poorer performance at some frequencies on Session II but better performance at others. Subjects had already experienced two vibration sessions prior to Session II. It therefore seems unlikely that the difference was attributable to re-learning under vibration.

The data show that vibration produced disruption to p(on) which was significant, although statistically independent of vibration frequency below 3.15 Hz. Significantly more disruption occurred with vibration at 4 Hz and 5 Hz than at lower frequencies or without vibration. These data suggest that a different, or additional, mechanism was responsible for the disruption at 4.0 and 5.0 Hz. It seems likely that visual impairment was the mechanism responsible for this increased disruption at 4.0 and 5.0 Hz. The data support the prediction made in the introduction that effects would increase as the vibration frequency approached 5 Hz. Due to the variability in the data it cannot be said that visual effects were not important at 2.0, 2.5 and 3.15 Hz however. Indeed, there is not likely to be some discrete acceleration threshold above which visual effects occur.

Moseley and Griffin (1982) suggested that effects of vibration on vision may principally depend on the velocity with which the image of the display elements move across the retina. The results from the present study show increasing performance disruption in the frequency range at which relative acceleration between the head and the display was expected to increase (see Chapter 5). Without more detailed investigation, however, it is not possible to determine the importance of relative acceleration, velocity or displacement between the head and the display in producing the observed effects.

The lack of a frequency dependence in the disruption at vibration frequencies below about 2.5 Hz suggests that vibration breakthrough appearing on the display was not an important mechanism in this study. Furthermore, if subjects had attempted to actively control out perceived breakthrough at the hand and arm, a frequency dependence would still be expected: such active control may be possible at frequencies below about 1.5 Hz but would be unlikely at higher frequencies. These results may indicate some central response to the induced stress. Subjects could, for example, have been distracted from the task through anxiety or otherwise diverted attention from performance to monitoring the well-being of the body. This type of central mechanism could be independent from the frequency of vibration. Alternately, the data may reflect some neuromuscular mechanism, such as increased muscular 'noise' due to an increase in muscle tension in response to the acceleration magnitude of the vibration.

3.2 Discrete Task

Figures 6.6 and 6.7 show the percentage change in the probability of pressing the button while on target - p(hit) - and while off target - p(FA) - on Sessions II and III. These data show the same general trends observed with p(on); approximately constant disruption at frequencies below 3.15 Hz and greater disruption at 4.0 and 5.0 Hz. There was an overall significant effect of vibration on each session for both of these measures ($p < 0.01$) although there was no significant frequency dependence, and no effect of session in either case.

The probability of pressing the button, whether while on target or while off target, is likely to be dependent upon the overall probability of being on target: subjects may alter their button pressing strategy depending upon the relative proportion of time spent on and off target. Changes in p (hit) and p(FA) may

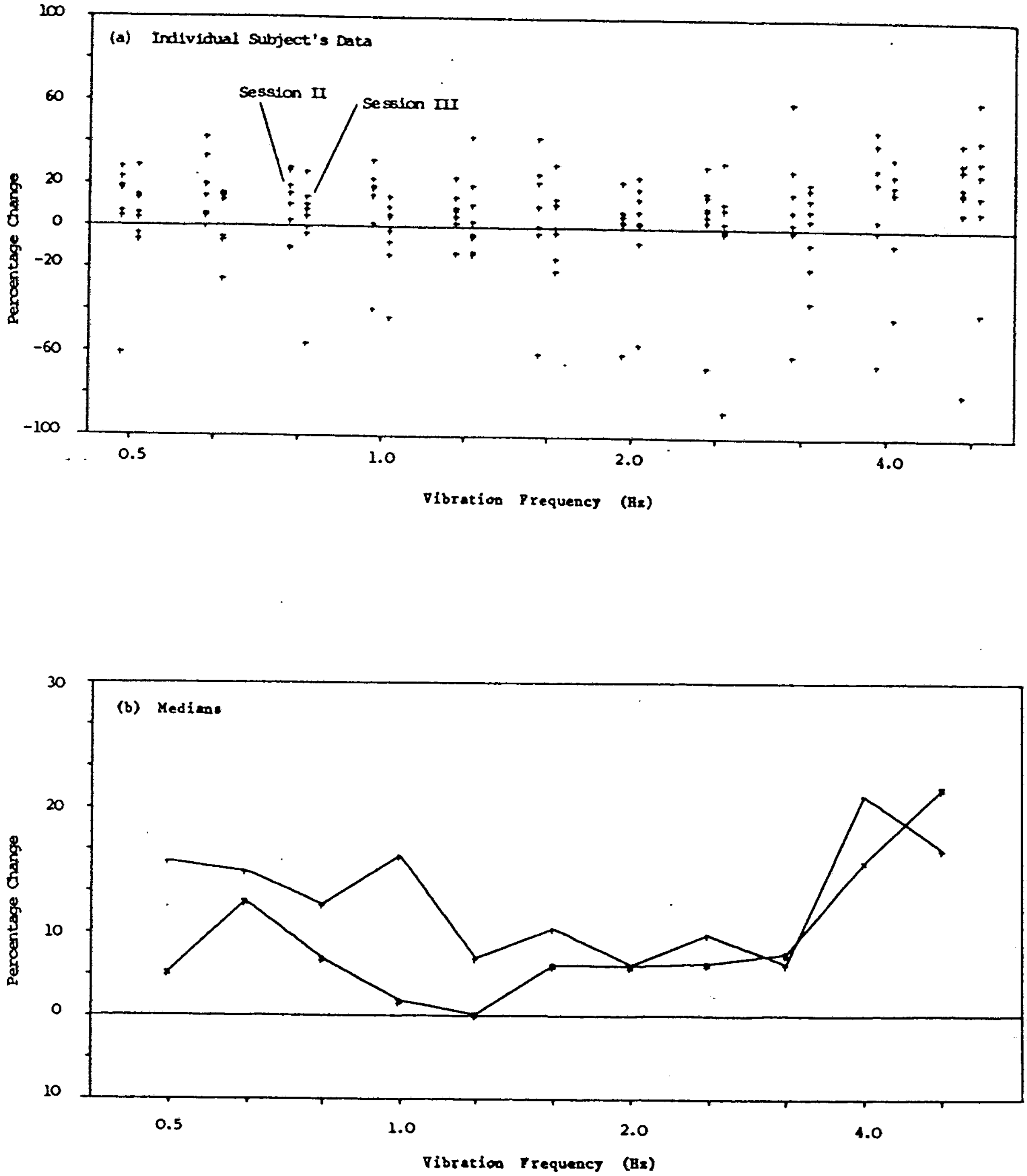


Figure 6.6 Percentage change in the probability of pressing the button while on target - p(hit) - as a function of vibration frequency on Sessions II and III.

(a) Individual subjects' data

(b) Medians

+ = Session II * = Session III

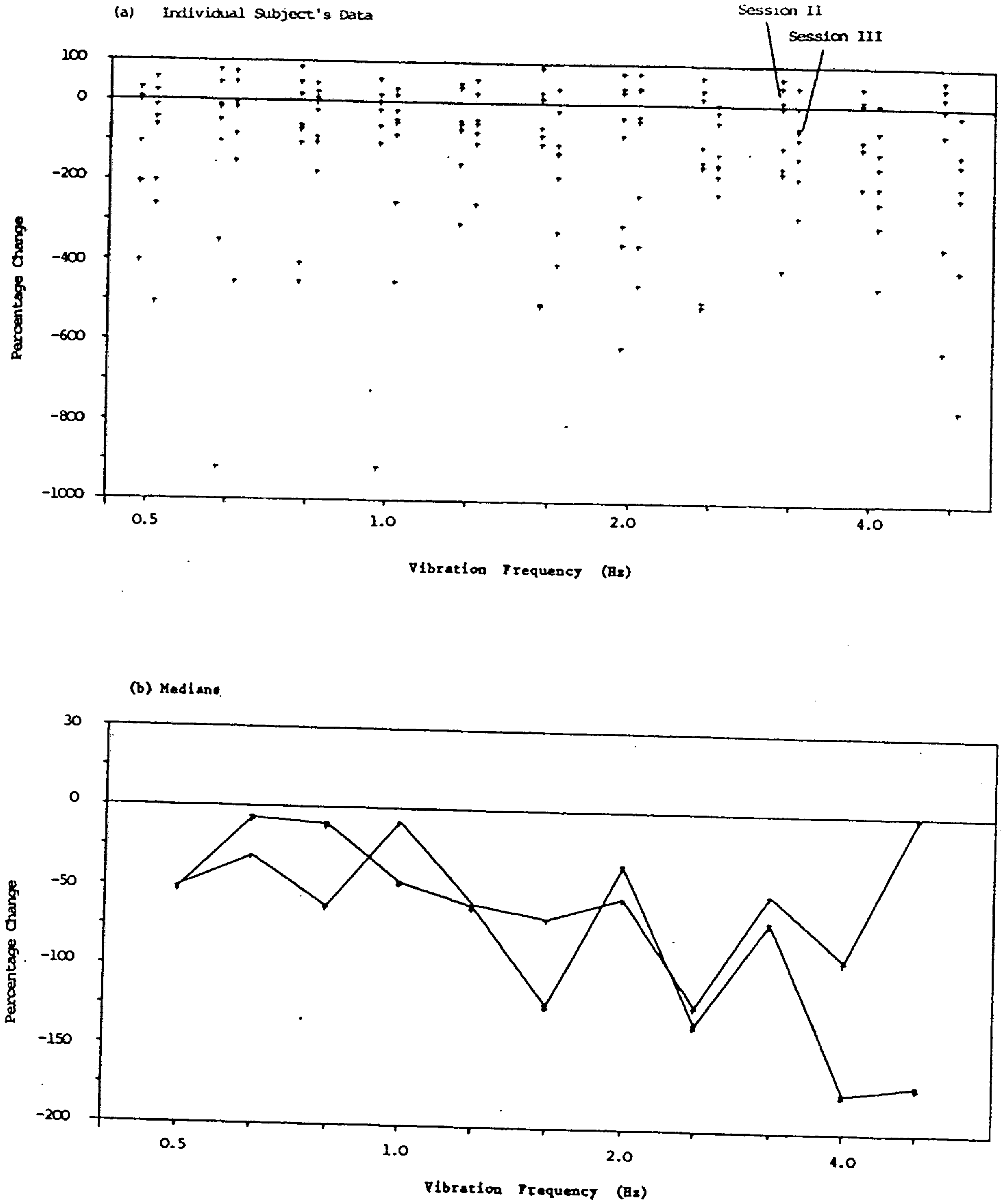


Figure 6.7 Percentage change in the probability of pressing the button while off target - p(FA) - as a function of vibration frequency on Sessions II and III.

(a) Individual subjects' data
(b) Medians

+ = Session II * = Session III

therefore reflect changes in p(on) rather than effects on discrete task performance as such. Figure 6.8 shows the probability of pressing the button - p(press) - as a function of p(on) for both sessions. Kendall's rank correlation coefficient showed a significant correlation between p(press) and p(on) on both sessions (for Session II, $\Upsilon = 0.37$, $p < 0.0001$, and for Session III, $\Upsilon = 0.27$, $p < 0.0001$). Because p(press) is dependent on p(on) therefore, p(hit) and p(miss) cannot be used as direct measures of effects of vibration on discrete task performance.

When the effect of changes in p(on) was removed from p(press) - by taking the ratio of p(press) to p(on), p(press/on) - there was no significant effect of vibration frequency for either session. Figure 6.9 shows the percentage change in p(press/on) for the two sessions. Although there is a consistent difference in the median data across the two sessions, the difference was not significant at any frequency. Taken over all frequencies, however, the percentage change in p(press/on) was significantly smaller on Session III than on Session II (Wilcoxon test, $p < 0.01$).

These data therefore show that the discrete task was not affected by the frequency of vibration independently from the effects observed on the continuous task. However, Figure 6.9 indicates a change in button pressing behaviour between Session II and III. The greater change in p(press/on) on Session II may indicate that subjects were more disturbed or distracted by the motion on this session, and were therefore less likely to press the button. With the more recent experience of vibration exposure on Session III, subjects may have been less disturbed or distracted by the motion.

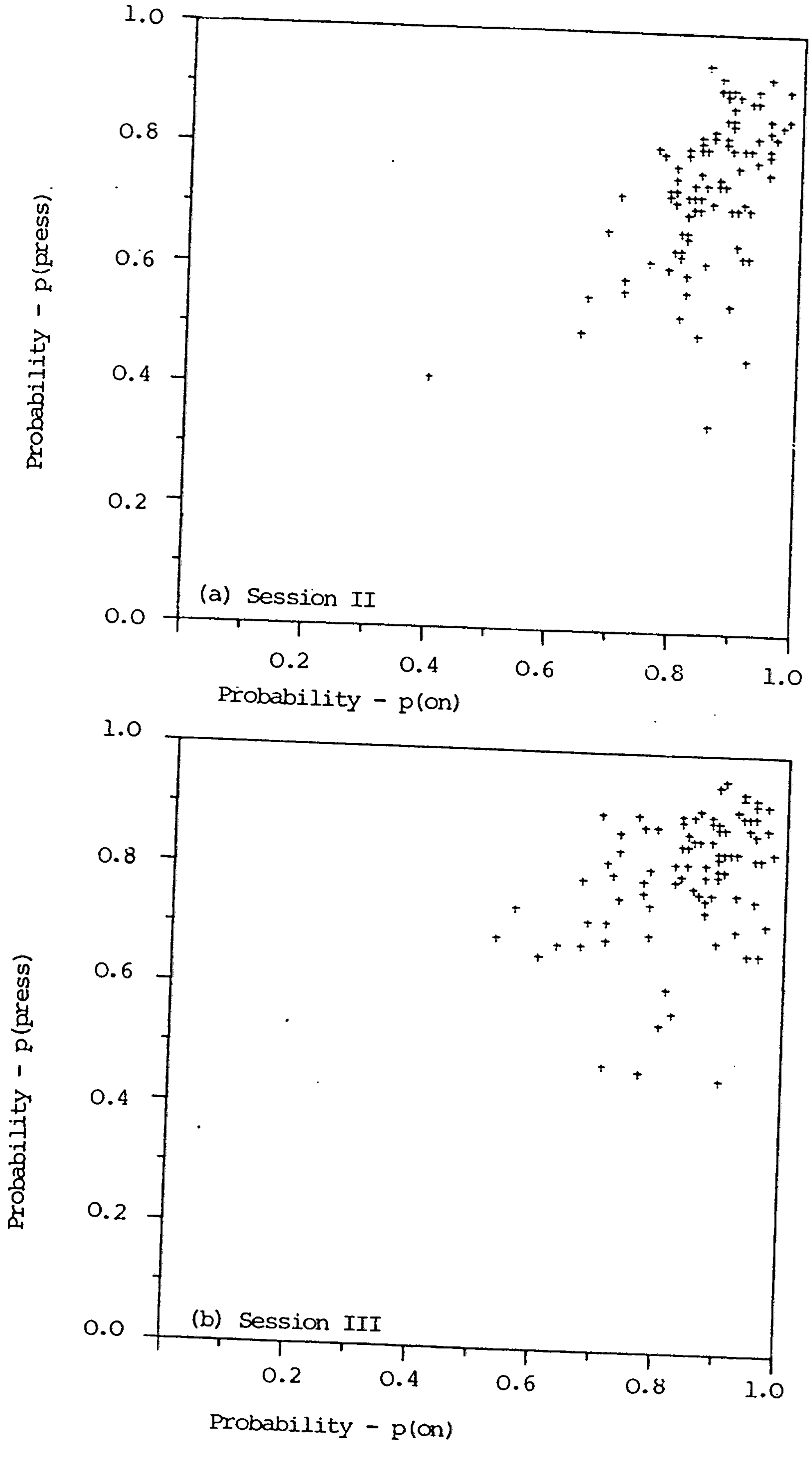


Figure 6.8 The probability of pressing the button - p(press) - against p(on) on Sessions II and III.

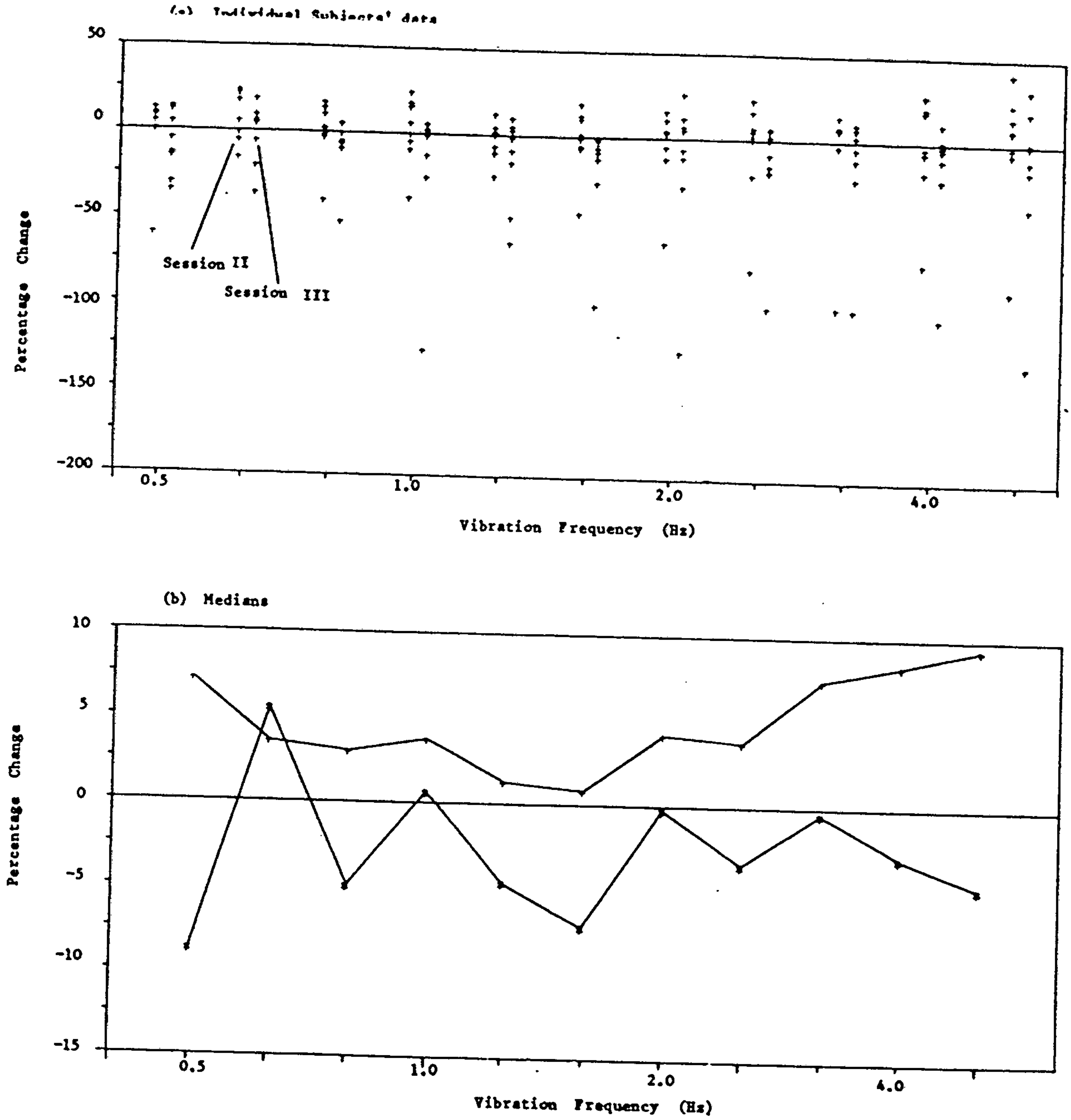


Figure 6.9 Percentage change in the probability of pressing the button as a proportion of the time-on target - p(press/on) - as a function of vibration frequency on Sessions II and III.

(a) Individual subjects' data

(b) Medians

+ = Session II * = Session III

4.0 Conclusions

Three main conclusions are drawn from this study:

(i) The results show that the continuous pursuit tracking task was sensitive to disruption by whole-body vibration in the region from 0.5 to 5.0 Hz. Greater disruption occurred at 4.0 and 5.0 Hz than at lower frequencies, and the disruption was independent of vibration frequency below 3.15 Hz. The discrete task appears not to be disrupted by the frequency of vibration independently from the effects on the continuous task.

(ii) The frequency dependence in the effect on the continuous task suggests that a different, or additional mechanism was responsible for the disruption at 4.0 and 5.0 Hz, than produced the effect below 3.15 Hz. It seems likely that impaired visual ability was responsible for the increase in disruption at 4.0 and 5.0 Hz. At frequencies below 3.15 Hz it was suggested that the lack of a frequency dependence may indicate either some central mechanism, such as distraction or anxiety, or some neuromuscular mechanism not dependent on the bio-mechanical response of the body.

(iii) The results show the importance of adequately training subjects in both vibration and no vibration environments before determining whether a task will be sensitive to disruption by vibration. With insufficient training

(Session I), any effects of vibration which may have occurred were masked by the large inter- and intra-subject variability. While Sessions II and III showed similar effects of vibration, a significant frequency dependence only appeared on Session III. The reason for the lack of a frequency dependence on Session II was not clear. The discrete task showed that subjects' button pressing behaviour changed between Session II and Session III. On Session II subjects were less likely to press the button during vibration exposure. This may indicate that subjects were less able to divide their attention between the two parts of the task, possibly due to anxiety or distraction due to the relative novelty of the motion on Session II (which followed 5 sessions without vibration).

The next Chapter describes an experiment performed to determine the relative importance of translational and rotational motion between the head and the display in producing the observed disruption at vibration frequencies between 2.0 Hz and 5.0 Hz.

CHAPTER SEVEN

EXPERIMENT THREE: THE EFFECT OF DISPLAY COLLIMATION AT VIBRATION FREQUENCIES FROM 2.5 to 5.0 HZ

1.0 Introduction

Visual performance has often been shown to be impaired during exposure to whole-body vibration. The ability to see detail can be reduced when the image of a viewed object is displaced across the retina; for example, when there is relative movement between the eye and the viewed object. In these conditions the object can appear blurred. (Griffin and Lewis, 1978, provide a review of the literature on effects of vibration on visual acuity).

Translational whole-body vibration can induce movements of the head in both translational and rotational axes. This was demonstrated in Experiment 1. Whether the eye moves relative to space however, depends on both the axis and frequency content of the head motion. There is evidence that the vestibular-ocular reflex (VOR) can compensate for rotational head acceleration to maintain a space-stable eye at frequencies up to at least 5 Hz (Benson and Barnes, 1978). It has been suggested that an otolith-ocular reflex can also induce rotational eye movements in response to translational head acceleration (Tokita et al, 1981). However, Barnes (1980), points out that for such eye movements to be effective in compensating for translational acceleration between the eye and a viewed object, the magnitude of induced eye rotation would have to depend upon the viewing distance. The extent to which the otolith-ocular reflex contributes to visual performance during translational head motion is therefore not clear.

The displacement of the image of an object across the retina during translational head movements will be inversely proportional to the viewing distance. During rotational head movements however, the displacement of the image will be independent of viewing distance. This provides a basis for distinguishing between visual impairments arising from translational and rotational eye movements. Griffin (1976) demonstrated that the minimum magnitude of whole-body vibration above 7 Hz which would produce visual blur is independent of viewing distance (at least for distances greater than 1.2 m). He therefore concluded that at frequencies above 7 Hz, decrements in visual acuity are mainly caused by rotational eye movements. Griffin suggested that translational eye movements could be more important at lower frequencies and shorter viewing distances.

A convex lens positioned at its focal length in front of an object will place the image of that object, viewed through the lens, at optical infinity. This is termed collimation. A collimating lens should remove visual disruption arising from translational eye movements, but not those due to rotational eye movements. Wilson (1974), demonstrated a significant improvement in tracking performance with a collimating lens during vibration at 4 and 6 Hz. There was no significant improvement at 2, 8 or 10 Hz, and, with collimation, a decrement remained at all frequencies.

It was hypothesised that disruption of the continuous pursuit tracking task observed in Experiment 2 at vibration frequencies between 2.5 and 5.0 Hz was attributable to visual blurring arising from translational movements of the image of the display elements across the retina. Collimating the display was therefore expected to remove the disruption. The discrete task was expected to show similar changes to the continuous task.

2.0 Method and Procedure

Six subjects performed the combined continuous and discrete task with the full cross-coupled system dynamics. They had all taken part in Experiment 2. The display was viewed either directly or through a collimating lens. In the 'no lens' condition, the display was situated about 750 mm directly in front of the subjects' eyes. In the 'lens' condition, the subject sat about 750 mm in front of the lens and the display was adjusted such that, in both conditions, the target subtended 33 minutes of arc at the subjects' eye.

Whole-body sinusoidal z-axis vibration was presented at 2.5, 3.15, 4.0 and 5.0 Hz at an acceleration magnitude of 2.0 ms^{-2} rms. Vibration was generated by a Derritron VP180LS electrodynamic vibrator. Both the display and the subjects' feet remained stationary. Other details of the task and equipment used were identical to Experiment 1. Table 7.1 summarises the experimental details for this study.

Subjects attended the laboratory for two, one hour sessions on separate days. On each day, they performed two blocks of seven runs each; one block with the collimating lens, and one block without. The order in which each block was presented was randomised across subjects with the alternative order of blocks being used for each subject on the second session. The first two runs of each block were performed without vibration. The next five runs included one run at each vibration frequency and one further run with no vibration. The order of presentation of these five runs was randomised across both subjects and sessions. The run without vibration in this block of five served as the control condition. After the first block of seven runs, subjects dismounted from the vibrator while the lens condition was changed.

Table 7.1 Details of Experiment 3

Independent Variables	Vibration frequency; display condition.
Dependent Variables	Simple probabilities - p(on), p(press), p(press/on).
Subjects	6 right-handed males. All had taken part in experiment one.
Task	Combined continuous pursuit tracking and discrete target acquisition task 180 seconds per run. The first 15 seconds of each run were excluded from the analysis.
Forcing Function	Gaussian random time-histories, low pass filered at 0.1 Hz with 24 dB/octave attenuation thereafter.
System Dynamics	First-order. Full, cross-coupled aircraft model.
Control	Isometric side-stick. No arm support.
Control gain	fore-and-aft = 1.0 v/kg = 0.53 ^{o}/s/kg (pitch) side-to-side = 0.2 v/kg = 5.2 ^{o}/s/kg (roll)

Table 7.1 (continued)

Display:

		No Lens	Lens
Viewing distance	=	750 mm	750 mm (to lens)
Target diameter	=	7 mm	3 mm
Angle subtended by target at eye	=	32 minutes 5 seconds of arc	32 minutes 9 seconds of arc
Maximum angular target displacement (+/-)	=	4^{o} 36 minutes of arc	4^{o} 34 minutes of arc

Vibrator : Derritron VP180LS. Electro-dynamic, z-axis.

Seat : Hard, flat, simulated helicopter seat with backrest and 5-point harness.

Vibration Exposure : Whole-body, sinusoidal vibration at 2.5, 3.15, 4.0 and 5.0 Hz at 2.0 ms^{-2} rms. Display not vibrated. Subjects' feet stationary.

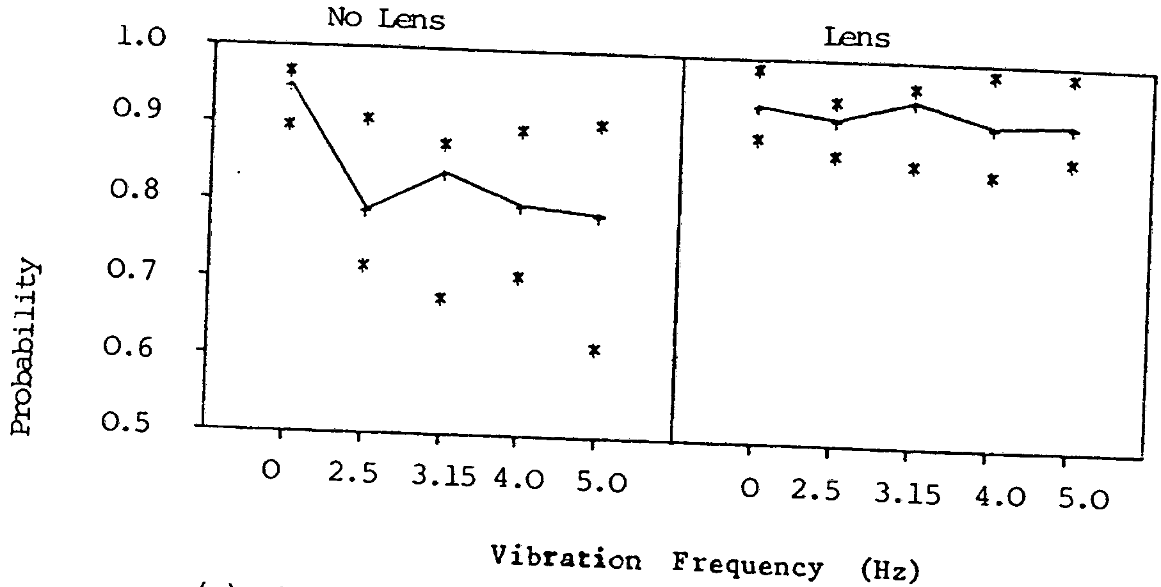
Session per Subject : Two. 'No lens' and 'Lens' sessions.

3.0 Results and Discussion

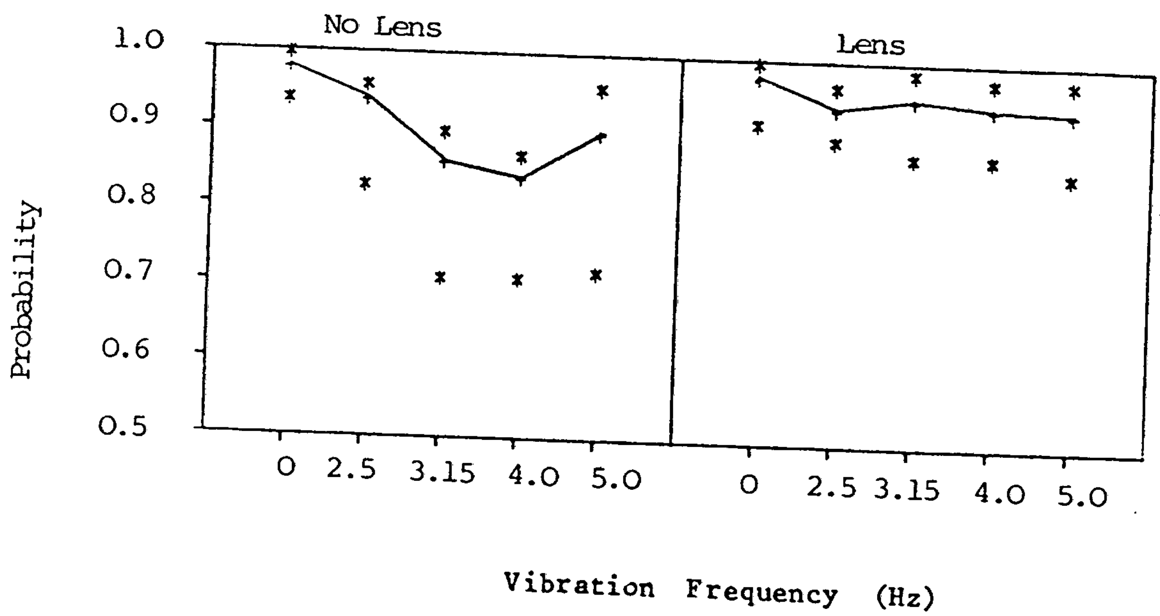
Figure 7.1 shows the median and range of the probability of being on target - p(on) - with and without display collimation as a function of vibration frequency on both sessions. Figure 7.2 shows the probability of pressing the button - p(press) - and Figure 7.3 shows the median percentage change in these measures at each vibration frequency compared with the no vibration condition. One-tailed Wilcoxon matched pairs signed-ranks tests were used to test for differences between conditions. In all cases, the level of significance was 0.025.

When p(press) was normalised for p(on) - by dividing p(press) by p(on) for each subject in each condition - there were no significant differences between any conditions on either session. The changes in p(press) on Figures 7.2 and 7.3 can therefore be attributed to the changes in p(on): the probability of pressing the button was determined by the probability of being on target. The remainder of the analysis therefore only considers p(on).

Without vibration, p(on) was very similar in both lens conditions within each of the sessions. There was no statistical difference between any of these no vibration data. In the 'no lens' condition, the effect of vibration was different on the two sessions. On session one, p(on) was significantly reduced at all vibration frequencies compared with the static condition. On session two, only 3.15 Hz and



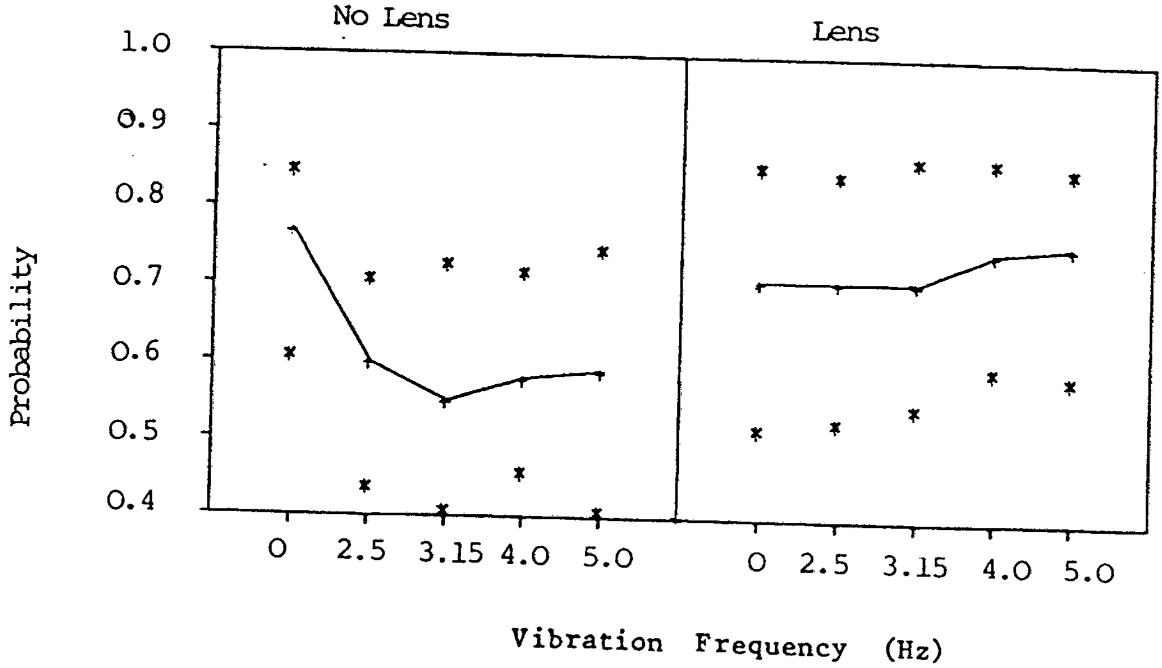
(a) Session I



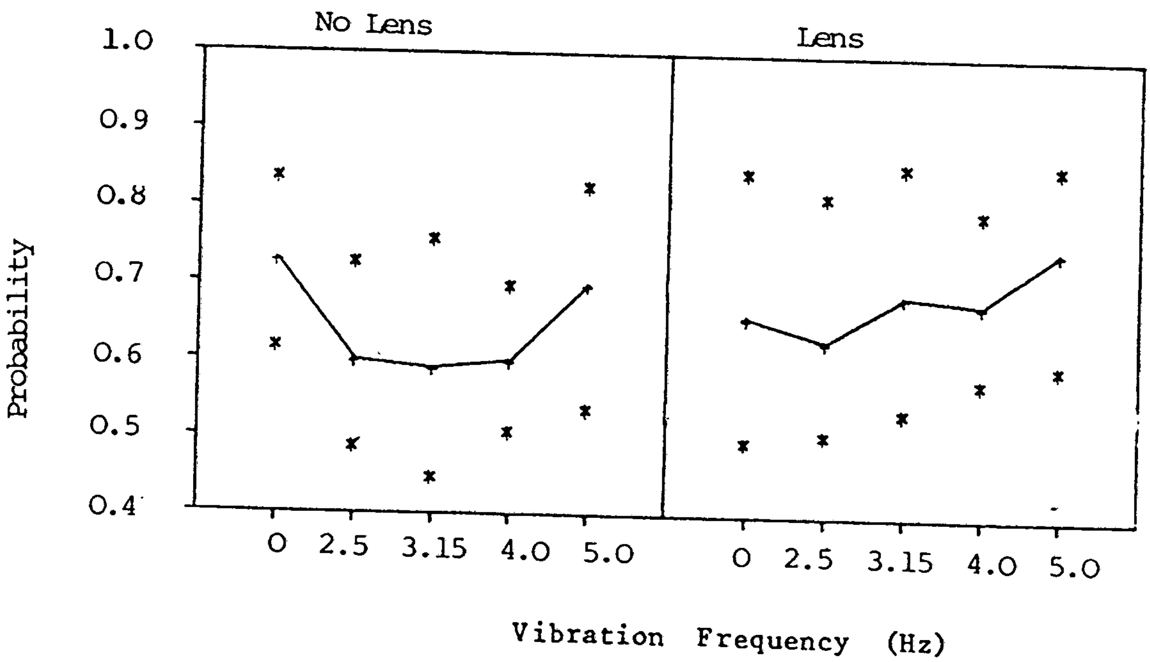
(b) Session II

Figure 7.1 Median and range for p(on) as a function of vibration frequency with and without display collimation.

(a) Session I (b) Session II



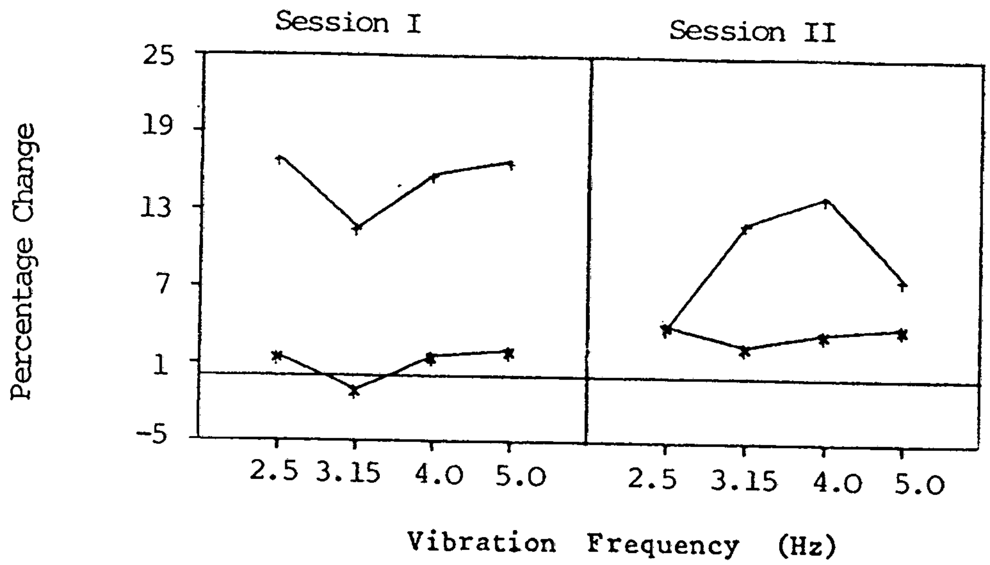
(a) Session I



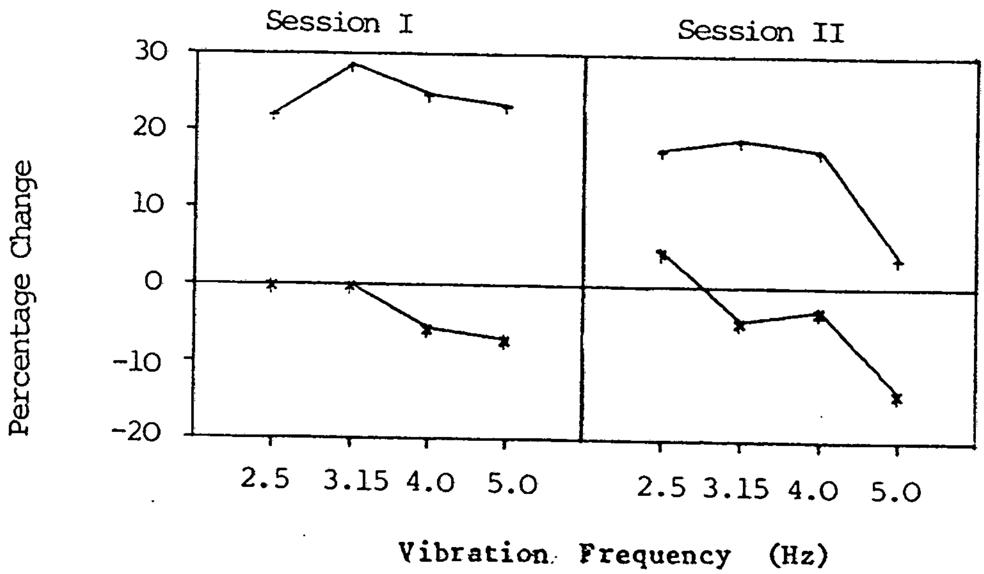
(b) Session II

Figure 7.2 Median and range for p(press) as a function of vibration frequency with and without display collimation.

(a) Session I (b) Session II



(a) p(on)



(b) p(press)

Figure 7.3 Median percentage change in p(on) and p(press) at each vibration frequency compared with static condition. With and without display collimation on two Sessions.

(a) p(on) (b) p(press)

+ = No lens * = Lens

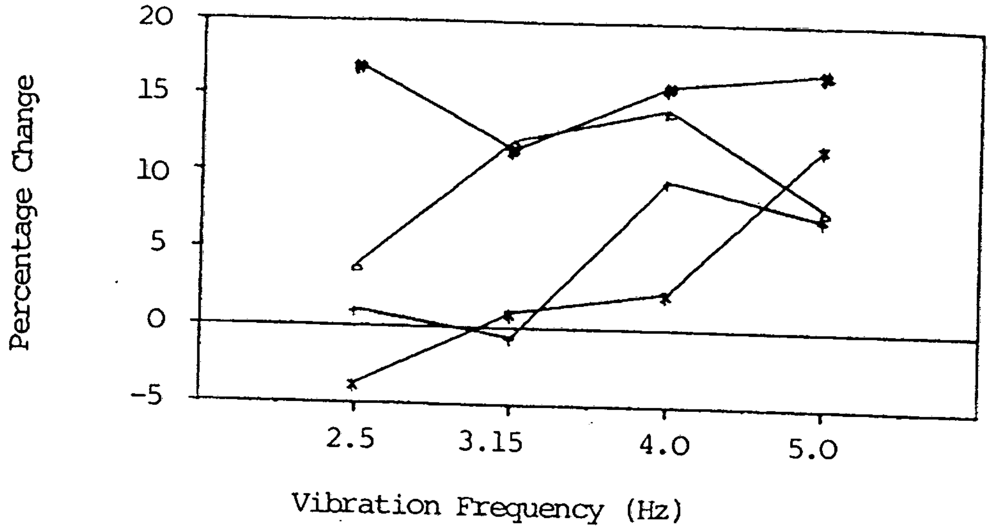
4.0 Hz vibration significantly affected p(on). There was no significant difference in performance at 3.15, 4.0 and 5.0 Hz across the two sessions, while the improvement with 2.5 Hz vibration on session two was significant. (The apparent inconsistency at 5.0 Hz can be attributed to the small number of subjects. For this test, all six subjects have to show a difference in the same direction in order to achieve significance. Effects detected with six subjects are therefore likely to be large relative to the inter-subject variability).

The differences in performance for the conditions with and without display collimation on session one were statistically significant at all vibration frequencies (Figure 7.3). On session 2, significant effects of collimation occurred only with 3.15 and 4.0 vibration. The lack of a significant effect of collimation with 2.5 and 5.0 Hz vibration on session 2 was due to the lack of a significant decrement in these conditions without the lens. It is not clear why these conditions did not produce a decrement. All subjects had taken part in experiment 2, where a significant decrement occurred with both 2.5 and 5.0 Hz without collimation. Indeed, performance was significantly worse at 4.0 and 5.0 Hz than at lower frequencies.

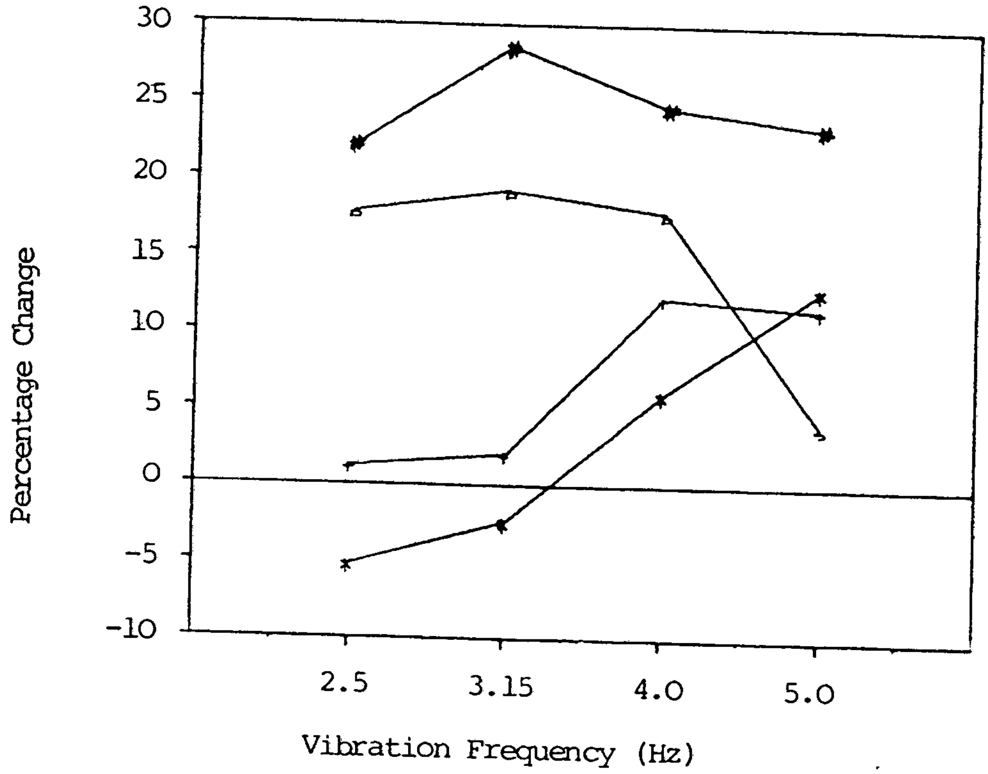
Figure 7.4 shows the median percentage changes in p(on) without collimation in the present study compared with data from experiment 2. For session one there were greater percentage changes at all vibration frequencies than in experiment 2. On session two however, the present data only show~~s~~ greater disruption than experiment 2 at 3.15 and 4.0 Hz. These results can be interpreted by assuming:

(i) that vibration produced greater visual impairment in the present study than in experiment 2; and

(ii) that the magnitude of performance disruption



(a) p(on)



(b) p(press)

Figure 7.4 Comparison of median percentage changes in p(on) and p(press) in Experiments 2 and 3 without display collimation.

(a) p(on) (b) p(press)

+ = Experiment 2, Session I

* = Experiment 2, Session II

= Experiment 3, Session I

□ = Experiment 3, Session II

is proportional to the amount of visual impairment.

In experiment 2, both the subjects and the display were vibrated. In the present study however, the display was stationary. At a particular vibration frequency, the magnitude of relative movement between the head and the display would therefore be expected to be greater in the present study. The amount of visual impairment is also likely to be increased. The assumption of greater disruption due to increased visual impairment in this study therefore seems reasonable.

Considering the results, the data with 5 Hz vibration on session 2 (Figure 7.4) shows less disruption than might be expected. Assuming that visual impairment is proportional to the transmission of vibration from the seat to the head, performance disruption would be expected to reduce with decreasing vibration frequency from 5.0 to 2.5 Hz (see experiment 1). The data at 2.5 Hz on session one in the present study therefore show~~s~~ greater disruption than expected.

Neither of these unexpected results is easily explained. They cannot be attributed to changes in the experimental procedure or equipment, such as the stationary display, because they did not occur on both sessions. The greater than expected disruption with 2.5 Hz vibration without collimation on session one may indicate a lack of training. All subjects took part in experiment 2, and were therefore experienced at tracking during vibration exposure. In addition, they were given at least two tracking runs without vibration before data collection, and half of the subjects performed the 7 runs with the lens prior to the run at 2.5 Hz without the lens. However, they had not performed the task with vibration, and without collimation, for approximately three months. There may therefore have been some interaction between the period between experiments and performance with a display which appeared blurred under vibration. During 4.0 and 5.0 Hz vibration, any such effect might not have appeared due to the greater decrement caused by visual impairment at those frequencies.

The lack of a decrement without display collimation during 5.0 Hz vibration on session 2 is similarly difficult to explain. After performing the task during 5.0 Hz vibration with the lens on session one, subjects may have attempted to adjust their posture or otherwise reduce the transmission of vibration to the head in order to achieve a similar reduction in visual blurring without the lens in the second session. This seems unlikely however, as subjects would have both had to discover that such a change could be effected, and induce the necessary change sufficiently quickly to affect performance over the 3 minute run.

Although both of these unexpected results may have occurred by chance, the possibility that subtle training effects occurred cannot be eliminated. This again reflects the importance of adequately training subjects and has implications for the design of experiments, particularly when repeated measures are taken from a small number of subjects.

4.0 Conclusions

Despite the difficulty in explaining the two unexpected results, the experiment provides a clear conclusion: performance disruption during z-axis, sinusoidal, whole-body vibration at frequencies from 2.5 to 5.0 Hz was caused by visual impairments arising from relative translational movement between the display and the subjects' eyes. Collimating the display removed the decrement due to vibration. Vibration-induced performance disruption was greater in this study than in experiment 2. This was attributed to the greater magnitude of relative movement between the head and the display which would have occurred in the present experiment.

The results suggest that complex training effects may occur under vibration even with highly experienced subjects. This highlights the importance of adequately training subjects in all experimental conditions prior to testing during whole-body vibration. Alternately, complex transfer effects could be avoided by using independent groups of subjects.

CHAPTER EIGHT

EXPERIMENT FOUR: THE EFFECT OF DISPLAY COLLIMATION AND VIBRATION WAVEFORM AT FREQUENCIES FROM 0.5 to 10.0 HZ

1.0 Introduction

1.1 Display Collimation

It was shown in Experiments 2 and 3 (chapters 6 and 7) that whole-body, z-axis, sinusoidal vibration in the frequency range from 0.5 to 5.0 Hz can disrupt performance of the first-order pursuit tracking task studied in this thesis. At frequencies between 2.5 and 5.0 Hz, visual impairment arising from relative translational movement between the subjects' eyes and the display was shown to be an important mechanism: collimating the display removed the disruption at these frequencies. The principal aim of the experiment reported in this chapter was to investigate the frequencies, in the range from 0.5 to 10.0 Hz, at which this mechanism would be important.

Experiment 1 (Chapter 5), demonstrated that for equal magnitudes of platform acceleration, the greatest magnitudes of head acceleration in the z- and pitch axes occurred with vibration at frequencies around 6 Hz. Below about 1 to 2 Hz there was little relative acceleration between the head and the platform (and, therefore, the display), in either axis. The vestibular-ocular reflex is known to compensate for rotational head acceleration to maintain a space-stable eye at frequencies up to at least 5 Hz (Benson and Barnes, 1978). Furthermore, with reducing frequency below 2 Hz subjects should increasingly be able to compensate for motion between the eye and the display by inducing pursuit eye movements (see Griffin and Lewis, 1978). It was therefore hypothesised that performance disruption at frequencies below about 1 to 2 Hz was not caused by visual impairment arising from translational eye movements. Collimating the display was not expected to alter the effect of vibration at these low frequencies.

At frequencies above 7 Hz, and at viewing distances greater than 1.2 m, Griffin (1976) reported that visual impairment was mainly caused by rotational movements of the eye relative to a displayed object. With the shorter viewing distances used in the present work (0.75 m), translational eye movements may be more important. Collimating the display should indicate the importance of translational eye movements at the higher frequencies presented (up to 10 Hz).

1.2 Vibration Waveform

A second aim of this experiment was to compare performance with sinusoidal and one-third-octave band random vibration. Using a zero-order tracking task, Lewis (1981) found no significant difference in the increase in total root-mean-square (rms) tracking error with the two types of motion at frequencies from 2.5 to 12.5 Hz. Differences may occur at lower frequencies however. For example, the ability to induce pursuit eye movements to compensate for relative motion between the head and the display at low frequencies might depend upon the predictability of the vibration waveform. With sinusoidal vibration, which is entirely predictable, such compensation may be possible at higher frequencies than with the less predictable random motions. The same argument would apply to other aspects of voluntary performance; for example, the ability to actively compensate for low frequency vibration-induced control activity could also depend on the predictability of the waveform.

At vibration frequencies above 2 Hz, a number of studies have demonstrated that performance disruption at each frequency is approximately linearly related to the acceleration magnitude (Lewis and Griffin, 1979; Weisz, Goddard and Allen, 1965). Differences between the two types of motion with equal rms acceleration magnitudes were therefore not expected at these higher frequencies.

1.3 Components of Tracking Error

Using spectral analysis techniques, total tracking error can be attributed to components arising from linear operations on either the platform vibration or the target motion. These components are known, respectively, as vibration-correlated error (or vibration breakthrough) and input-correlated error. The proportion of tracking error not linearly correlated with either the vibration or the target motion is termed remnant. The extent to which these three components can be distinguished depends on the statistical confidence associated with the spectral estimates used. This is indicated by the degrees of freedom associated with the estimates. (Chapter 4 describes the theoretical basis of these measures).

Vibration breakthrough depends on the transmission of vibration to the control output, and the gain of the system dynamics at the vibration frequency. Experiment 1 has shown that for the system being studied, breakthrough appearing at the control is attenuated by the system dynamics such that it does not appear on the display above 2.0 Hz. Small amounts of breakthrough appeared on the display at 0.5 and 1.0 Hz. A less sensitive control was used in this study than in Experiment 1; vibration breakthrough was therefore not expected to be an important mechanism.

For a particular set of system dynamics, changes in input-correlated error reflect changes in the parameters of the humans' linear transfer function relating movements of the target to the operators' response. Changes in input-correlated error may indicate adaptive changes in the way a task is performed. Remnant reflects both random activity induced by the operator and intentional tracking behaviour not linearly related to movements of the target.

A number of authors have found these measures to be useful in describing, and attempting to explain, effects of vibration on manual control performance. Changes in total error during vibration have mainly been accompanied by changes in remnant (Allen et al, 1973; Levison and Harrah, 1977; Lewis and Griffin, 1977, 1978, 1979). Lewis and Griffin (1979) demonstrated that with a zero-order task, increases in remnant could be attributed to perceptual confusion arising from vibration breakthrough appearing on the display. With first-order tasks, in which breakthrough is less important, a number of authors have attributed increases in remnant to interference with neuromuscular processes (eg., Levison, 1977). This has not been demonstrated experimentally however. Although changes in input-correlated error commonly occur during vibration exposure, they have generally not been statistically significant (eg., Lewis and Griffin 1977, 1978, 1979).

In the experiment reported in this chapter, rms tracking error and its components were measured. The closed loop system transfer functions relating movements of the target to movements of the controlled element were also obtained. (The transfer function is described in chapter 4). The main objective was to try to determine any changes in the way the task was performed during vibration exposure. It was expected that remnant or input-correlated error would show changes due to visual impairment. Collimating the display was expected to remove these changes.

2.0 Method and Procedure

2.1 Task

The forcing functions used with the full cross-coupled system dynamics in Experiments 2 and 3 had been low-pass filtered at 0.1 Hz. To obtain estimates of tracking error components at more than one tracking frequency with this task, it would have been necessary to substantially increase the duration of each run. For example, to obtain estimates with 52 degrees of freedom at a resolution of 0.025 Hz, each run would need to last 520 seconds. (Chapter 4, section 4 discusses the theoretical basis of the spectral estimates involved). This duration could introduce confounding fatigue effects within each run and would severely restrict the range of frequencies which could be studied in a single experiment. It was therefore decided to alter the task in order to induce tracking performance at higher frequencies. Changes were made to the system dynamics, forcing functions and control sensitivity, as follows.

(i) System Dynamics

The system dynamics were simplified by removing the cross-coupling between the three axes of the model (roll, pitch and yaw) and using only the pitch and roll dynamics. It was hoped to produce a task in which the circular target moved vertically up and down the centre of the display and the 'artificial horizon' moved vertically with the target and also rolled in the plane of the display. Unfortunately, this task could not be implemented without major re-building of the display electronics. In the task used, the circular target moved randomly around the screen as before. Subjects moved the controlled element in the horizontal axis of the display by applying forces in the side-to-side axis of the control. Fore-and-aft forces on the control moved the controlled element in the vertical axis of the display. The pitch and roll axis dynamics determined the response independently in the vertical and horizontal display axes respectively.

(ii) Forcing functions and control gain

With the simplified dynamics, the system was a great deal easier to control than with the cross-coupled dynamics. The forcing functions were altered in order to produce a task with power at the highest frequencies which could reasonably be controlled. Two trained subjects performed the new task with five different forcing functions, low-pass filtered at 0.1, 0.15, 0.2, 0.25 and 0.3 Hz, with attentuation of -12 dB per octave thereafter. The sensitivity of the control was varied with each forcing function around a region considered optimal by the subjects. With filtering at 0.1 Hz, the task was felt to be too easy, while with filtering at 0.3 Hz it was too difficult. It was not possible to establish a clear difference in performance in the other cases. The forcing function (filtered at 0.2 Hz) and control sensitivity adopted provided a task felt to be demanding by both subjects and required tracking behaviour at frequencies up to about 0.4 Hz. (The control gain used is detailed on Table 8.1).

2.2 Performance measures and signal conditioning

Vibration and forcing function time-histories were pre-recorded on a 7 channel FM tape recorder (RACAL, STORE 7). Time-histories were generated on a digital computer and output by digital-to-analogue (D-A) conversion at twenty times the centre frequency for each vibration condition, and at 25.6 samples per second for the forcing functions. Forcing functions were produced by integrating Gaussian random time-histories (to increase their low frequency content) and then band-pass filtered at 0.01 Hz and 0.2 Hz with attenuation of -12 dB per octave thereafter. They were then scaled to fill the area of the display. Finally, forcing functions were selected which had similar rms values. A different set of six forcing functions were generated to accompany each vibration condition. Every subject received a different forcing function pair at each vibration frequency, and no two subjects used the same pair at any frequency. Runs lasted for 150 seconds, although the first 10 seconds of each run were not analysed.

Subjects performed the combined continuous and discrete task as in experiments 2 and 3. The main interest in this study was the continuous task, although measures for the discrete task will also be presented. Root-mean-square tracking error and its components, as well as closed-loop human operator transfer functions between the target position and the controlled element position were measured in each axis of the task.

For the first four subjects, an attempt was made to measure vibration breakthrough appearing on the display. The platform acceleration as well as the forcing functions and system response were acquired directly to the digital computer at an analogue-to-digital (A-D) conversion rate of 102.4 samples per second with low-pass anti-aliasing filtering at 20 Hz. These data are presented in the results section (Figure 8.8). There was no evidence of vibration breakthrough; estimates obtained with a stationary platform did not differ from those during vibration. Any breakthrough which occurred was therefore within the range of equipment noise and measurement error. As substantial benefits would be gained by reducing both the time required for each session and the amount of computer storage required, it was decided to drop vibration breakthrough from the analysis.

For the remaining subjects only the forcing functions and system responses were acquired. The A-D conversion rate was reduced to 6.4 samples per second with anti-aliase filtering at 1.6 Hz.

2.3 Vibration

Whole-body z-axis vibration was presented at each preferred one-third octave centre frequency between 0.5 and 10.0 Hz. The large peak displacements which occurred with the one-third octave band motion at 0.5 Hz limited the acceleration in this condition to 1.6 ms^{-2} rms. The same magnitude was used with the 0.5 Hz sinusoidal motion. For all other conditions the acceleration magnitude was 2.1 ms^{-2} rms. Subjects sat on a hard flat simulated helicopter seat with a backrest and 5-point harness. The subject, display and control were all mounted on the 1-metre stroke, vertical axis, electro-hydraulic vibrator in the Human Factors Research Unit of the ISVR.

2.4 Procedure

Sixteen new subjects were recruited for this experiment. They were all right handed males with normal uncorrected vision (as measured using the Keystone Visual Skills Profile). Subjects were randomly assigned to two groups of 8. One group performed the task without display collimation ('no lens' group) and the other group performed with collimation ('lens' group). This design was used to remove the possibility of any interaction between the lens conditions. Within each group, all subjects were exposed to all vibration conditions.

Subjects were given 3 training sessions, on separate days, with 15, 150 second runs in each session. On the third session, subjects were exposed to both sinusoidal and one-third octave band random vibration centred on 0.5, 1.25, 3.15 and 10.0 Hz at acceleration magnitudes of 1.6 ms^{-2} rms at 0.5 Hz and 2.1 ms^{-2} rms at all other frequencies. Training data for all 16 subjects are shown in Appendix D. With the simplified dynamics used in this study, this training appeared to be sufficient.

Two procedures were adopted to try to reduce the variability in the data both within and across subjects. First, a scoring system was introduced in which subjects would receive payment dependent upon the performance they achieved. They were told they would earn one point for every instant the aircraft symbol was inside the target area, and a further point for every instant for which the button was pressed while inside the target. They would lose one point for every instant outside the target, and a further point for every instant pressing the button while outside the target. Subjects understood that the amount of money they could earn was directly related to the number of points they accumulated. This scoring system was explained at the start of each training session, and subjects were asked to explain it themselves before each experimental session. As well as helping to motivate subjects, it was hoped that this procedure would ensure that all subjects perceived the task in the same way and adopted a similar strategy.

The second procedure was to encourage subjects to rest between runs for as long as they wished. They were given at least 2 minutes rest between runs and all subjects dismounted from the vibrator after runs 6 and 11. In practice, only two subjects requested additional rests.

For each subject, the experiment was carried out over two sessions on consecutive days. The sinusoidal motions were presented on one session, and the random motions on the other. Within each group, half of the subjects received the sinusoidal motions on the first session.

After completing a consent form and explaining the scoring system, subjects performed a short 'settling-in' run of approximately 1 minute. They then received 16 runs of 150 seconds each. These 16 runs included 1 run at each of the 14 vibration frequencies and 2 runs without vibration. The 2 runs without vibration ('no vibration' runs) were presented both to improve the reliability of the control data and to indicate whether fatigue may have affected performance on later runs. The order of presentation of these 16 runs was randomised for each subject. Before commencing the first experimental run, subjects read the following instructions:

> "Please sit in a comfortable upright posture which you can maintain throughout each run. Do not change your posture to try to alter your experience of the vibration.
>
> Do you have any questions?"

Table 8.1 summarises the details of this experiment.

Table 8.1 Details of Experiment 4

Independent Variables	:	Vibration frequency; vibration waveform; display collimation.
Dependent Variables	:	1. Simple probabilities - p(on), etc. 2. RMS angular error and components (vibration-correlated error; input-correlated error; remnant). 3. Closed-loop system transfer functions.
Subjects	:	16 right-handed males in 2 independent groups of 8 ('No lens' and 'Lens' groups).
Task	:	Combined continuous pursuit tracking and discrete target acquisition task. 180 seconds per run. The first 15 seconds of each run were excluded from the analysis.
Forcing Function	:	Gaussian random time histories, integrated and band-pass filtered at 0.01 and 0.2 Hz with 12 dB per octave attenuation thereafter (see text for details).
System Dynamics	:	First-order. De-coupled pitch and roll axes of aircraft model.
Control	:	Isometric side-stick. No arm support.

Table 8.1 (continued)

Control gain	:	2.0 v/kg fore-and-aft (vertical) = 1.06 $^{\circ}$/s/kg (vertical) 0.41 v/kg side-to-side (horizontal) = 1.2 $^{\circ}$/s/kg (horizontal)
Display	:	Collimated ('Lens' group) and un-collimated ('No lens' group). (Details as in Table 7.1, chapter 7).
Vibrator	:	1-metre stroke electro-hydraulic. z-axis.
Seat	:	Hard, flat, simulated helicopter seat with backrest and 5-point harness.
Vibration Exposure	:	Whole-body, sinusoidal or 1/3rd-octave-band random vibration at; 0.5, 0.63, 0.8, 1.0, 1.25, 1.6, 2.0, 2.5, 3.15, 4.0, 5.0, 6.3, 8.0 and 10.0 Hz. Magnitude = 1.6 ms^{-2} rms at 0.5 Hz = 2.1 ms^{-2} rms at all other frequencies.
Sessions per Subject	:	Two. (Sinusoidal and 1/3rd-octave-band random vibration).

3.0 Results and Discussion

The results will be presented in three parts. In the first part, the main effects of the variables studied (vibration frequency, collimation and waveform) on the probabilities of being on target - p(on) - and of pressing the button - p(press) - will be considered. The second part will present the data for the components of tracking error and the third part shows the closed-loop system transfer function.

3.1 Main effects of independent variables

3.1.1 Continuous Task

Figure 8.1 shows the probability of being on target - p(on) - as a function of vibration frequency both with and without display collimation and for both sinusoidal and one-third octave-band random vibration. This figure shows the distribution of data for the 8 subjects in each condition. Figure 8.2 shows the distribution of the percentage change in p(on) in each vibration condition compared with the no vibration runs. In this study, the percentage change is defined as:

$$\text{percentage change} = \left[\frac{\left[\dfrac{p(S_1) + p(S_2)}{2}\right] - pV(f)}{\left[\dfrac{p(S_1) + p(S_2)}{2}\right]} \right] \times 100$$

where:

$p(S_1)$ is p(on) on the first no vibration run,

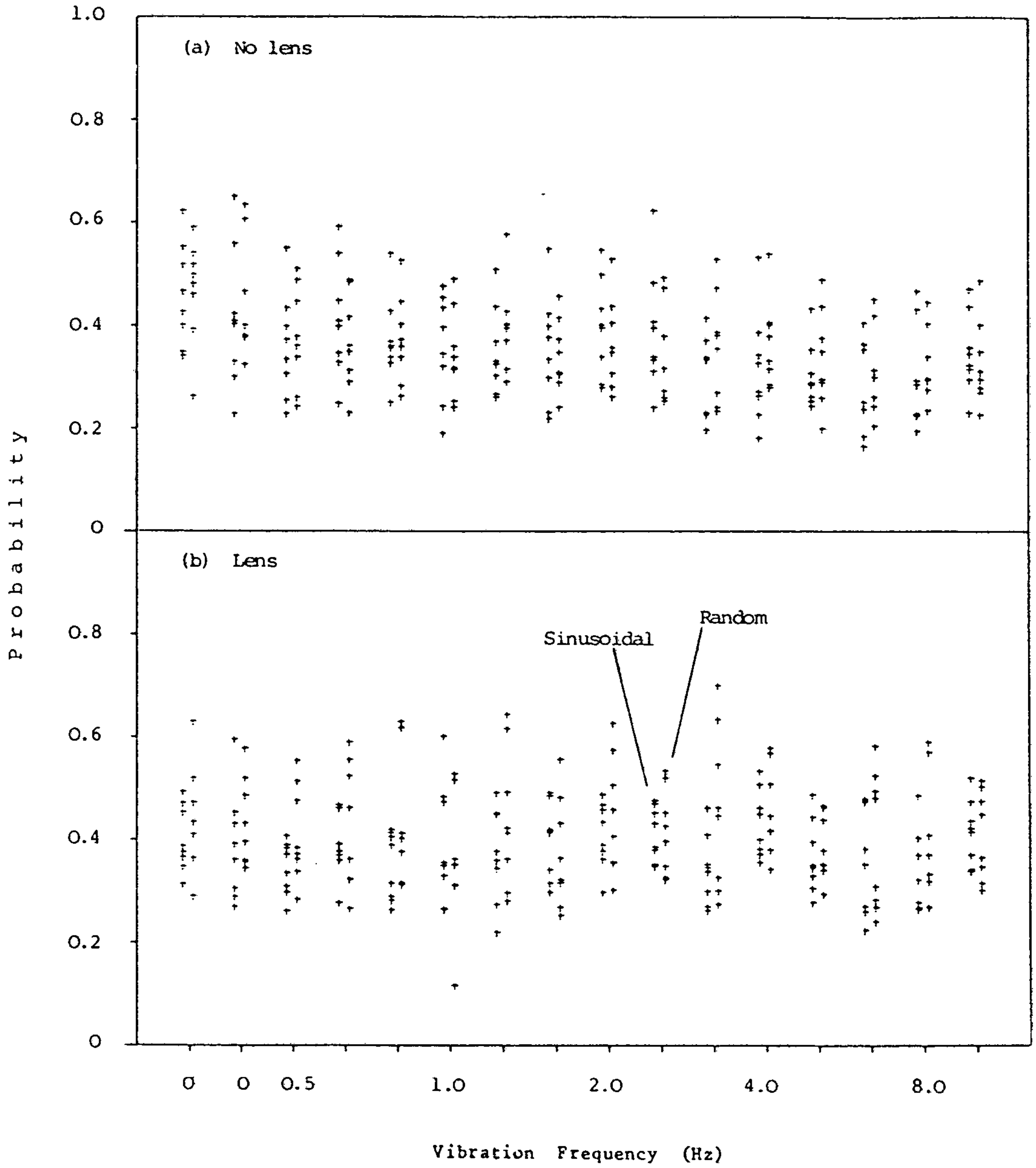


Figure 8.1 Probability of being on target - p(on) - as a function of centre frequency of sinusoidal and one-third octave-band random vibration.

(a) No lens (b) Lens

(NB. At each frequency, the data on the left are for sinusoidal vibration)

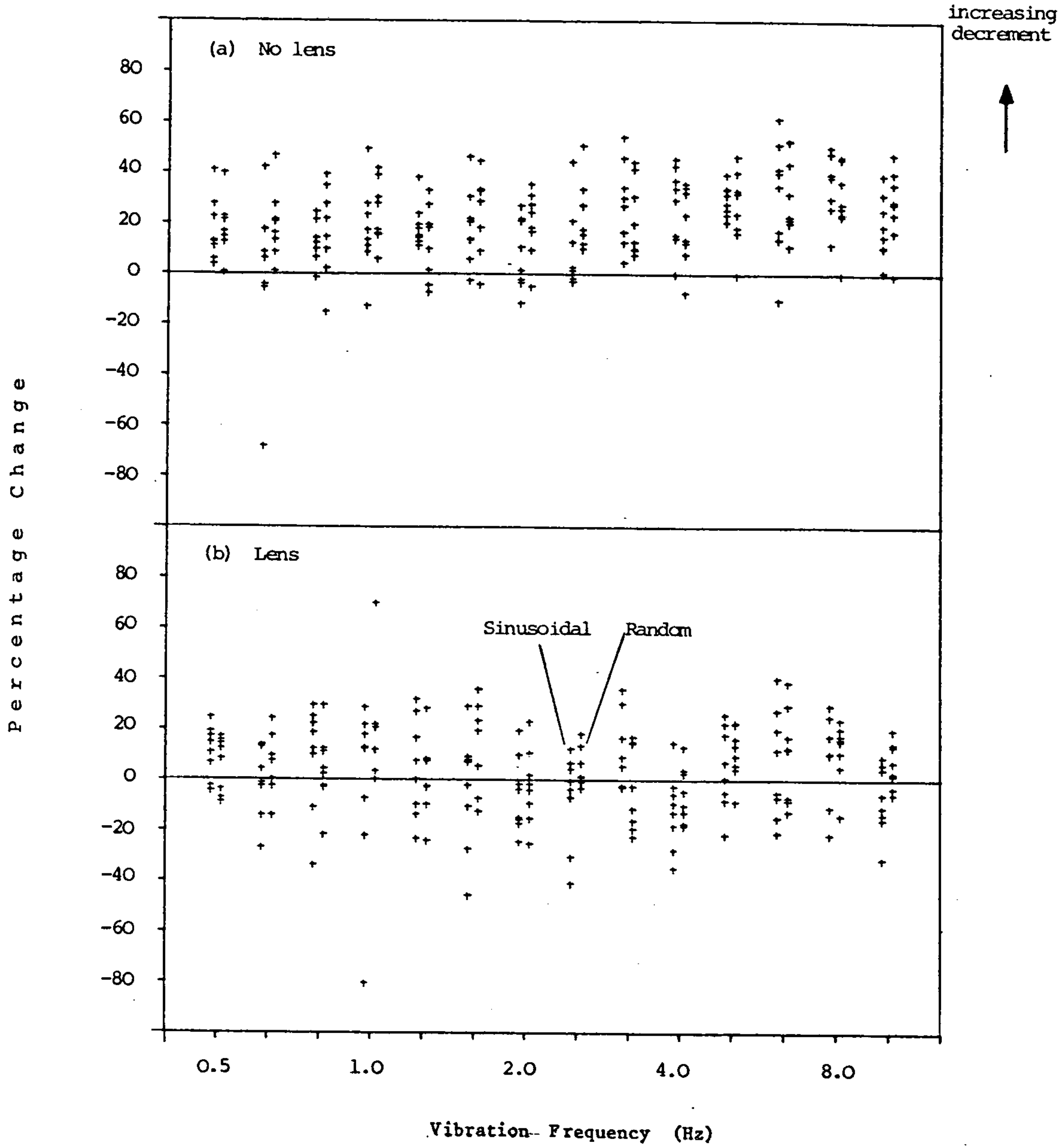


Figure 8.2 Percentage change in p(on) as a function of centre frequency of sinusoidal and one-third octave-band random vibration..

(a) No lens (b) Lens

(NB. At each frequency, the data on the left are for sinusoidal vibration)

p(S2) is p(on) on the second no vibration run, and
p V(f) is p(on) at vibration frequency f.

Sign tests showed an overall effect of vibration for the percentage change data for both types of vibration without the lens (Figure 8.2a) compared with an expected decrement of 0%. With the lens there was no overall effect of vibration. Figure 8.3 shows the median percentage change data for each condition. Friedman tests showed significant effects of vibration frequency in all conditions (no lens, sinusoidal, $p < 0.001$; no lens, random, $p < 0.01$; lens, sinusoidal, $p < 0.05$; lens, random, $p < 0.05$).

Wilcoxon tests were performed to test for differences in p(on) between each vibration frequency within each condition. In each case, 120 tests were performed. At a significance level of 0.05, therefore, 6 'significant' results would be expected to occur by chance alone. However, effects of vibration were expected to follow trends, with adjacent vibration frequencies showing similar effects. Where isolated significant results occur, these are more likely to be attributable to chance.

Figure 8.4 illustrates the results of the Wilcoxon tests performed. These figures compare performance at every vibration frequency with every other frequency and show the level of significance achieved. With sinusoidal vibration in the no lens condition (Figure 8.4a), all vibration frequencies except 0.63, 2.0 and 2.5 Hz were significantly different from the first no vibration run. However, compared with the second no vibration run, significant effects only appeared at 1.25 Hz and above 3.15 Hz. There were no significant differences between the 2 no vibration runs either within any condition or across conditions. Furthermore, the results of the Wilcoxon tests during random vibration without the lens (Figure 8.4b), show almost identical effects of vibration frequency when compared against both no vibration runs. It therefore seems likely that the poor performance on the second no vibration run during sinusoidal vibration without

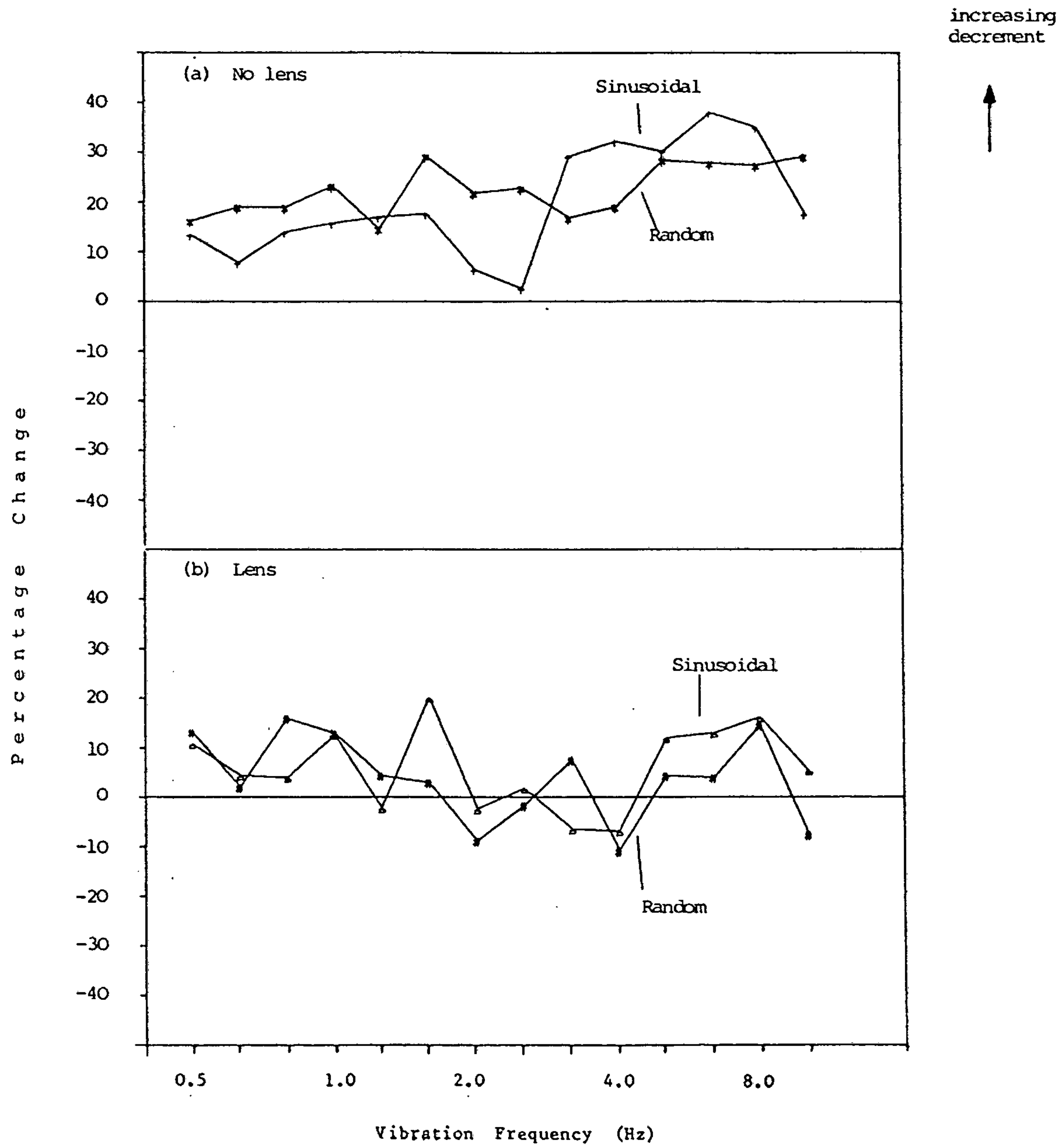
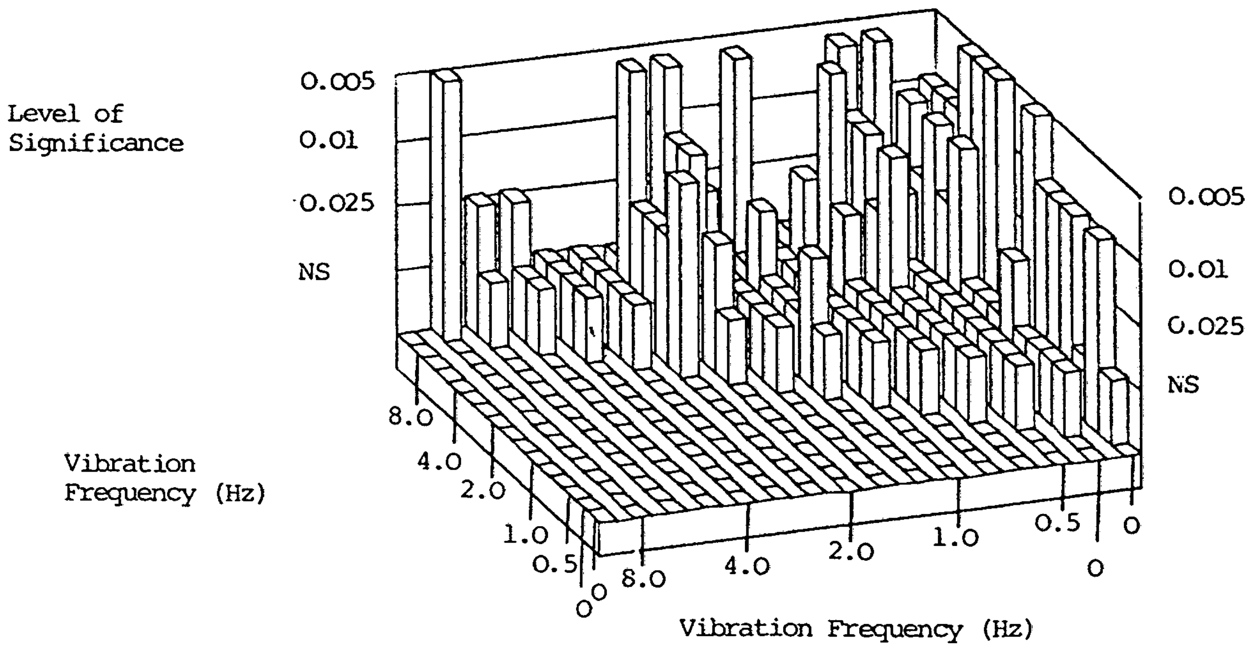
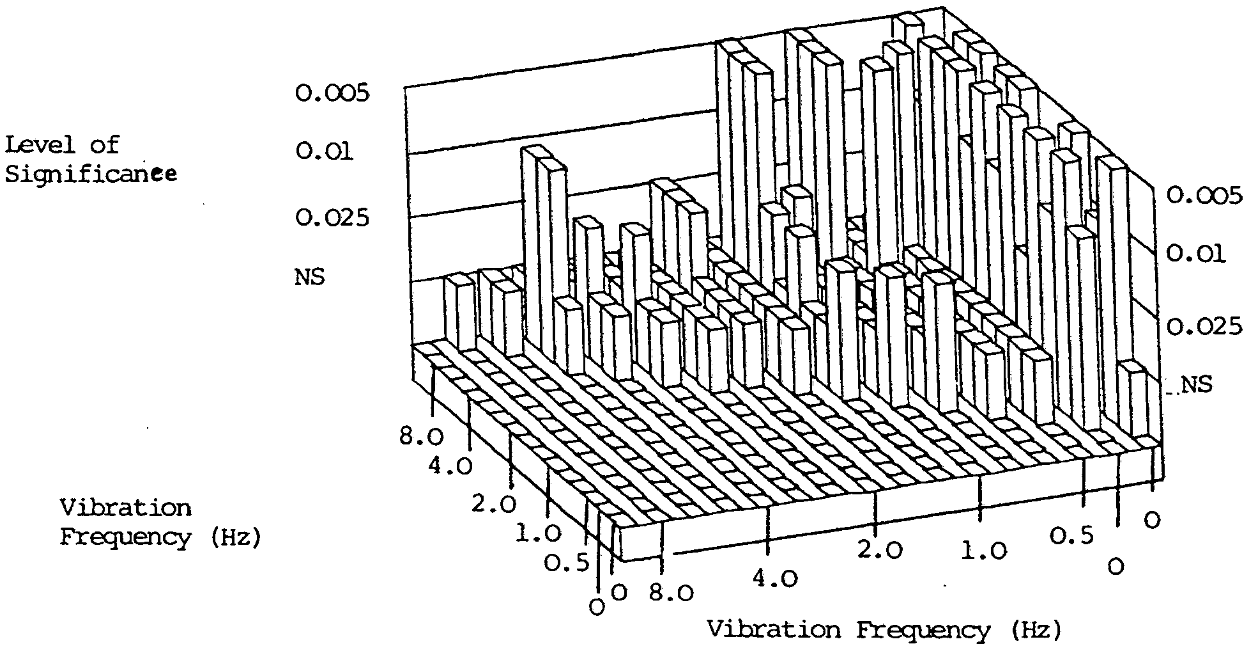


Figure 8.3 Median percentage change in p(on) for both vibration types and within each display condition as a function of vibration frequency.

(a) No lens (b) Lens



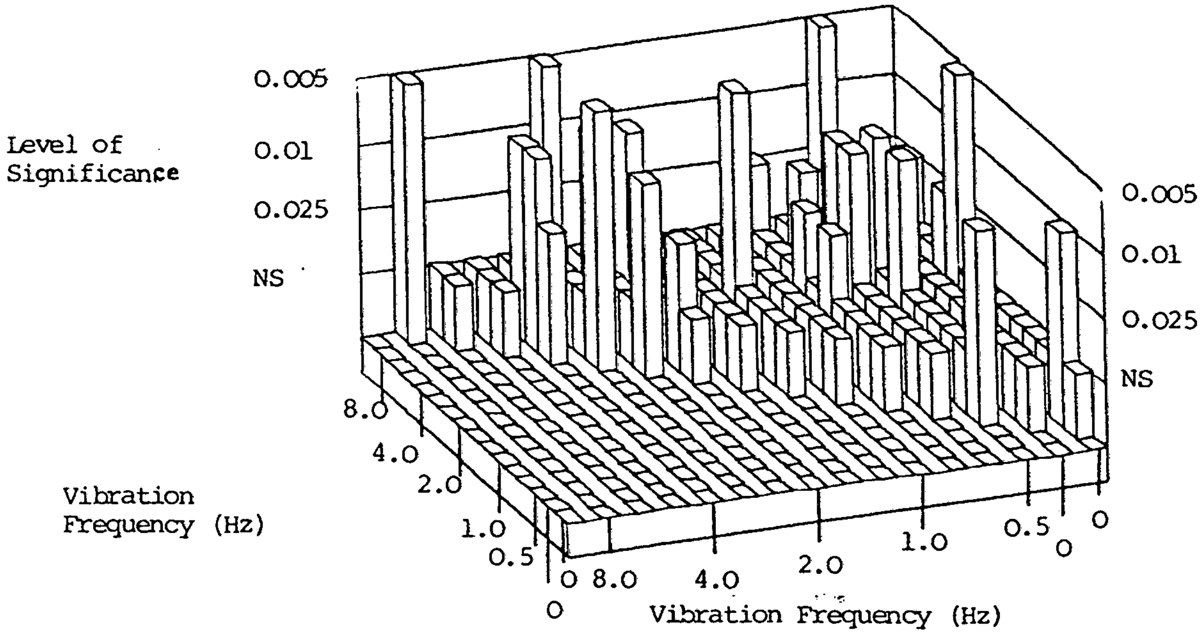
(a) Sinusoidal Vibration - No lens



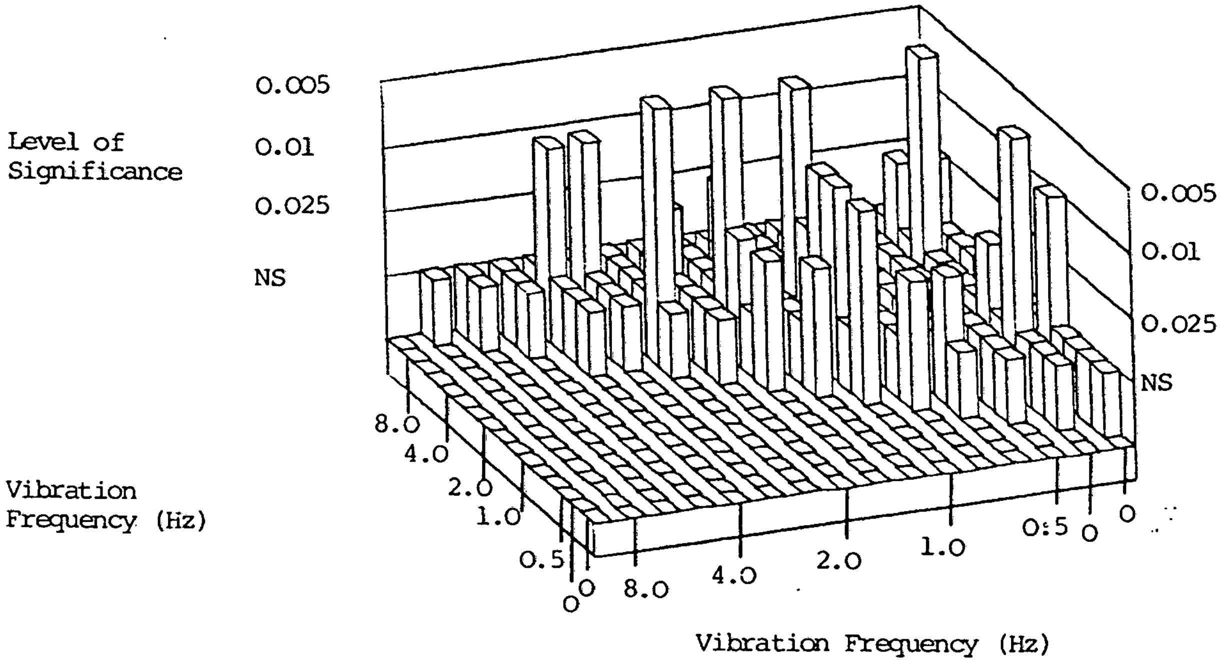
(b) Random Vibration - no lens

Figure 8.4 Results of Wilcoxon tests comparing differences in p(on) between each vibration frequency and within each vibration type and display condition. Figures show the one-tailed significance level achieved for each comparison.

NS = Not significant.



(c) Sinusoidal - Lens



(d) Random - Lens

Figure 8.4 (continued)

the lens was attributable to random variability rather than to any systematic effect.

For the percentage change data in the no lens condition (Figure 8.3), most vibration frequencies disrupted performance with both types of motion compared with the no vibration runs. Significant changes did not occur with sinusoidal vibration at 2.0 and 2.5 Hz in the no lens condition. There were also significant differences between the two waveforms at 2.0 and 2.5 Hz. This may reflect the ability to induce voluntary eye movements to compensate for relative movement between the head and the display: such compensation would be effective at higher frequencies with the predictable sinusoidal vibration than with the less predictable random vibration. Pursuit eye movements would be expected to be at least as effective at lower frequencies as at 2.0 and 2.5 Hz. The greater disruption at the lower frequencies with the sinusoidal motion implies that the impairment at these frequencies did not arise from relative movement between the eye and the display.

With the collimating lens, the pattern of results in the Wilcoxon tests is less clear (Figure 8.4). Significant effects of vibration occurred at 0.5, 3.15, 4.0 and 8.0 Hz compared with the no vibration conditions during sinusoidal vibration, and at 1.0, 1.6, 5.0 and 8.0 Hz with random vibration. With sinusoidal vibration, performance significantly improved around 2.5 to 4.0 Hz compared with frequencies below 0.8 Hz and above 5.0 Hz. There was no difference in performance at the extremes of the frequency range however. With random vibration, effects of vibration frequency are less consistent, although a similar trend appears: disruption tends towards a minimum around 2.0 Hz. There were no effects of waveform which could not be attributed to chance.

Figure 8.5 compares the median percentage change in p(on) with and without the collimating lens for each type of motion.

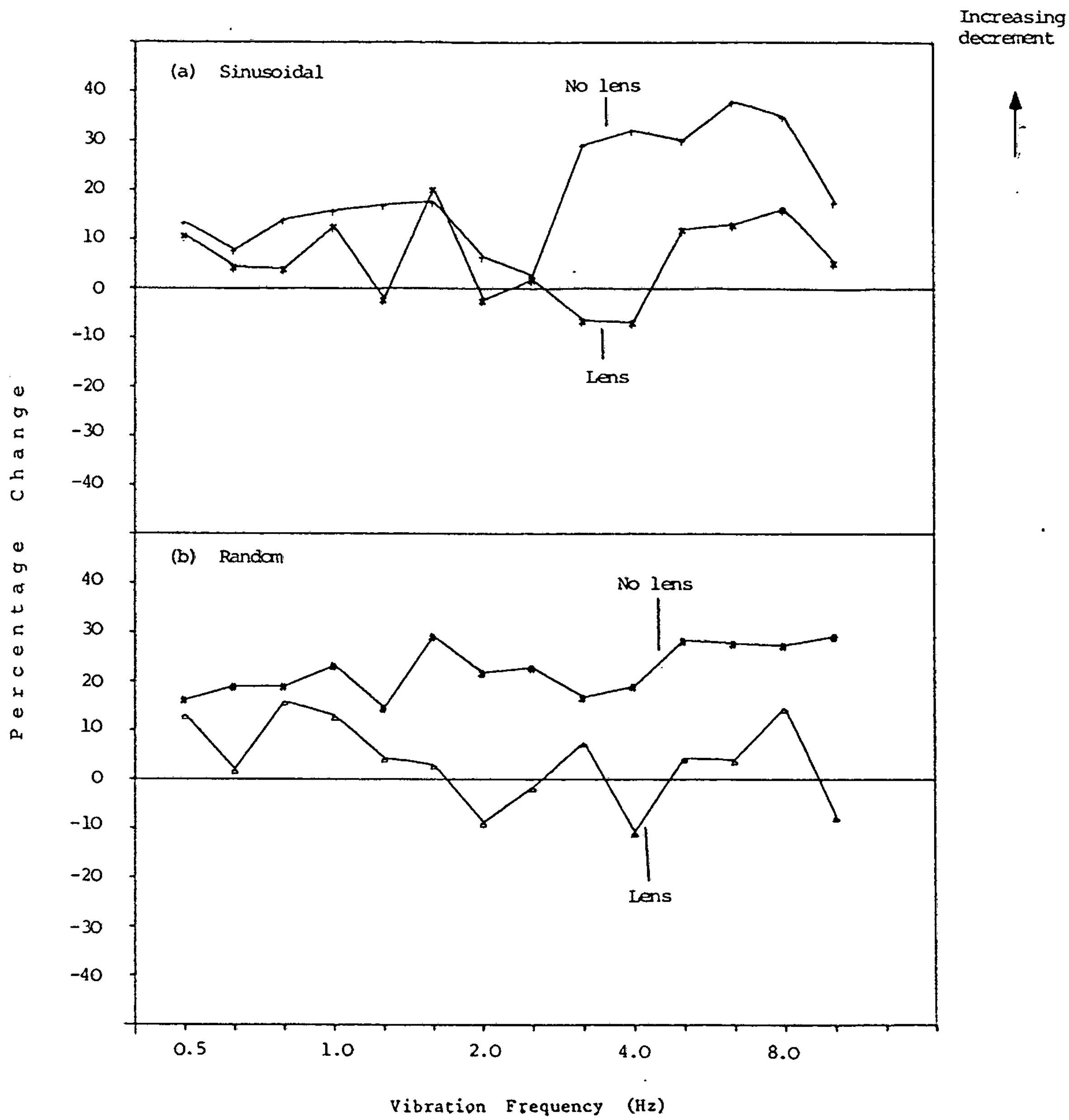


Figure 8.5 Median percentage change in p(on) for each display condition and within each vibration type as a function of vibration frequency.

(a) Sinusoidal (b) Random

With sinusoidal vibration there is an improvement in performance with display collimation during vibration at 3.15 Hz and above. With the random motion, the data without collimation show consistently poorer performance than with collimation.

Table 8.2 shows the results of Mann-Whitney 'U' tests performed to test for differences between the two lens conditions at each frequency. With the sinusoidal motion, significant differences occured at all frequencies from 3.15 to 10.0 Hz. With the random motion, significant results occurred at all frequencies above 1.6 Hz. The significant result at 1.25 Hz with sinusoidal vibration may be due to chance. With random vibration, significant results occurred at 0.63 and 1.0 Hz while non-significant results occured at 0.8 and 1.25 Hz. It would seem unlikely that significant visual impairment due to relative translational motion between the eye and the display would occur at 0.63 Hz. Experiment 1 showed that the seat-to-head tranmissibility is effectively unity below 1 Hz. Furthermore, at 0.63 Hz subjects should be able to visually compensate for any relative motion which did occur.

Summary of Effects on p(on)

At a viewing distance of 0.75 m therefore, performance disruption at frequencies above 1.6 Hz was mainly caused by visual impairment arising from relative translational movement between the subjects eyes and the display. With random vibration, this mechanism was important at lower frequencies than with sinusoidal vibration. Subjects may have been compensating for relative movement between the head and the display by inducing compensatory pursuit eye movements. Such compensation was effective at frequencies up to 2.5 Hz with predictable sinusoidal vibration, but only up to about 1.6 Hz with the less predictable random motions.

Table 8.2 Results of Mann Whitney 'U' tests comparing effects of display collimation on the percentage change in p(on) at each vibration frequency with sinusoidal and one-third octave-band random vibration

Vibration Frequency (Hz)

	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Sinusoidal	NS	NS	NS	NS	**	NS	NS	NS	**	***	***	*	***	*
1/3 Random	NS	**	NS	**	NS	**	**	***	**	**	**	**	*	***

* = $p < 0.05$
** = $p < 0.01$
*** = $p < 0.001$
Two-tailed tests

With both types of vibration, relative translational eye movements were important in producing disruption at frequencies up to at least 10 Hz. With sinusoidal vibration however, the data (Figure 8.5) suggest that the magnitude of the effect was smaller at 10 Hz than between 3.15 and 8.0 Hz.

3.1.2 Discrete Task

Figure 8.6 shows the distribution of p(press) as a function of vibration frequency in both display conditions. Figure 8.7 shows the median percentage change in p(press) at each vibration frequency compared with the no vibration runs. This figure shows similar trends to the data for the continuous task. After normalising for p(on) - by dividing p(press) by p(on) for each subject in each condition - there were no significant effects of frequency or collimation. As in the previous experiments, the probability of pressing the button was determined by the probability of being 'on target'. The discrete task was therefore not affected by vibration independently from the continuous task.

3.2 Error Components

For 4 subjects, an attempt was made to measure the proportion of tracking error attributable to vibration breakthrough. Two of these subjects were exposed to sinusoidal vibration, and the other 2 were exposed to random vibration. All 4 subjects were in the 'no lens' group. Figure 8.8 shows the estimates of vibration breakthrough for these subjects. The spectral estimates used in

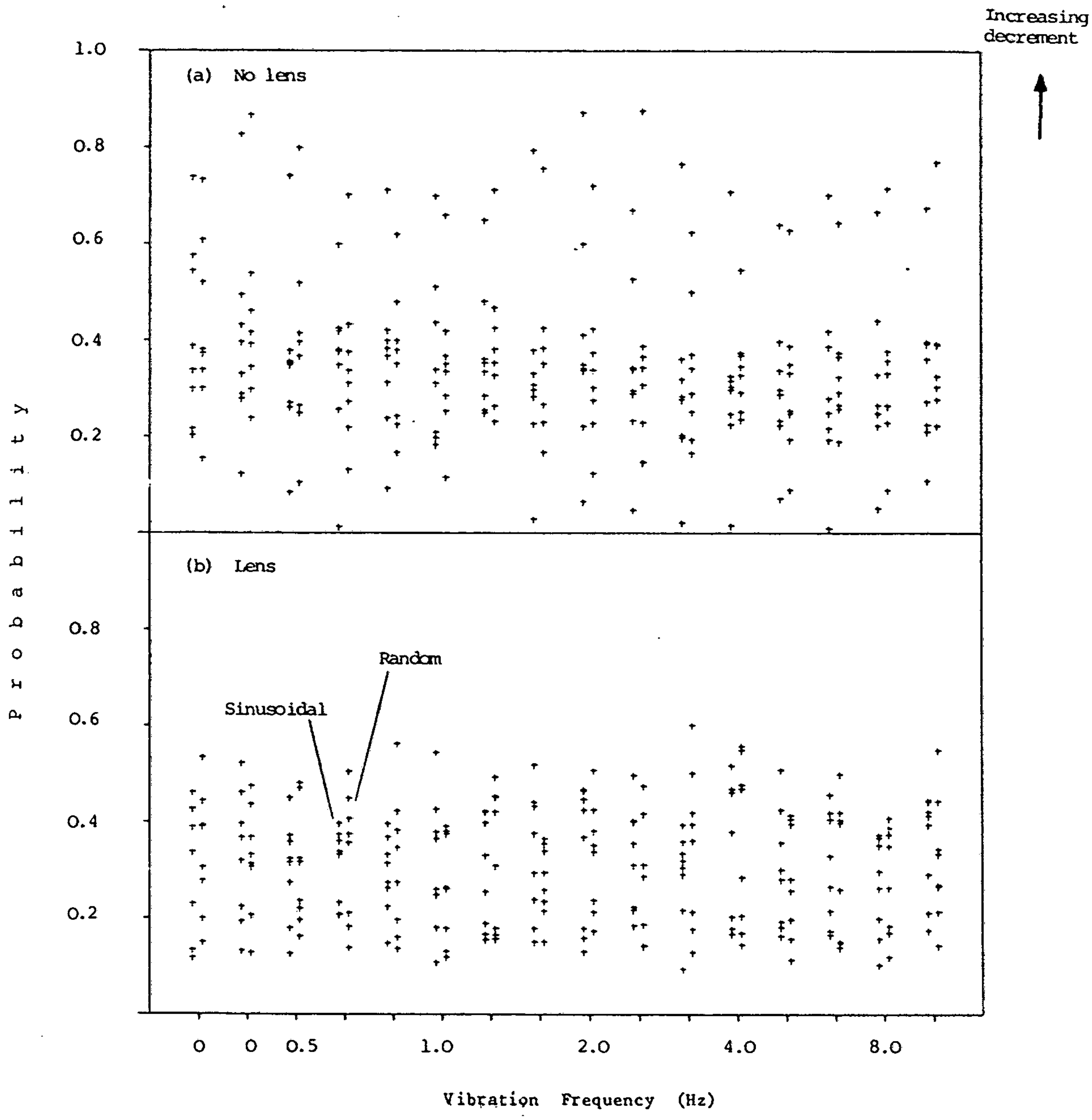


Figure 8.6 Probability of pressing the button - p(press) - as a function of centre frequency of sinusoidal and one-third octave-band random vibration.

(a) No lens (b) Lens

(NB. At each frequency, the data on the left are for sinusoidal vibration)

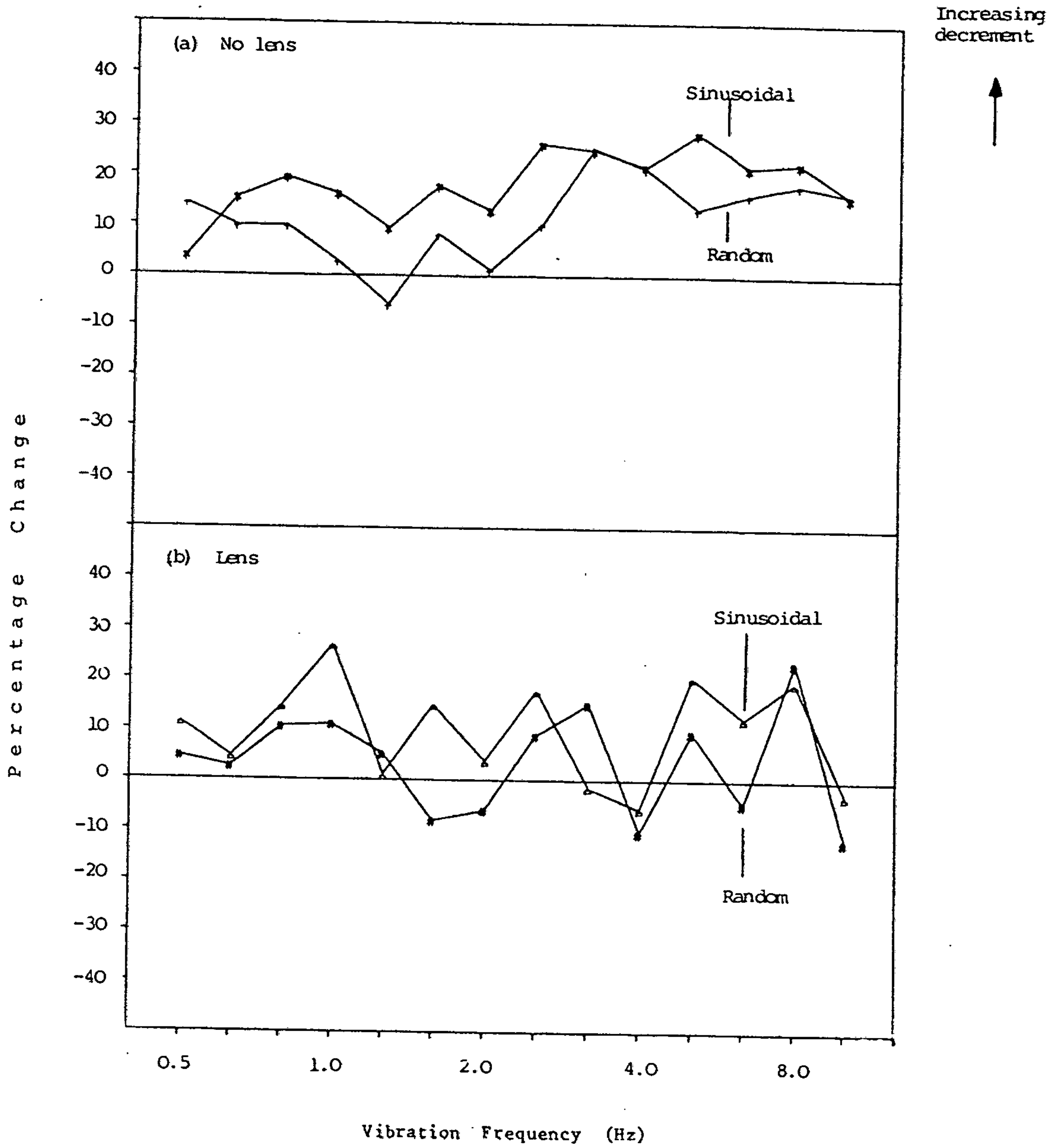


Figure 8.7 Median percentage change in p(press) for both vibration types and within each display condition as a function of vibration frequency.

(a) No lens (b) Lens

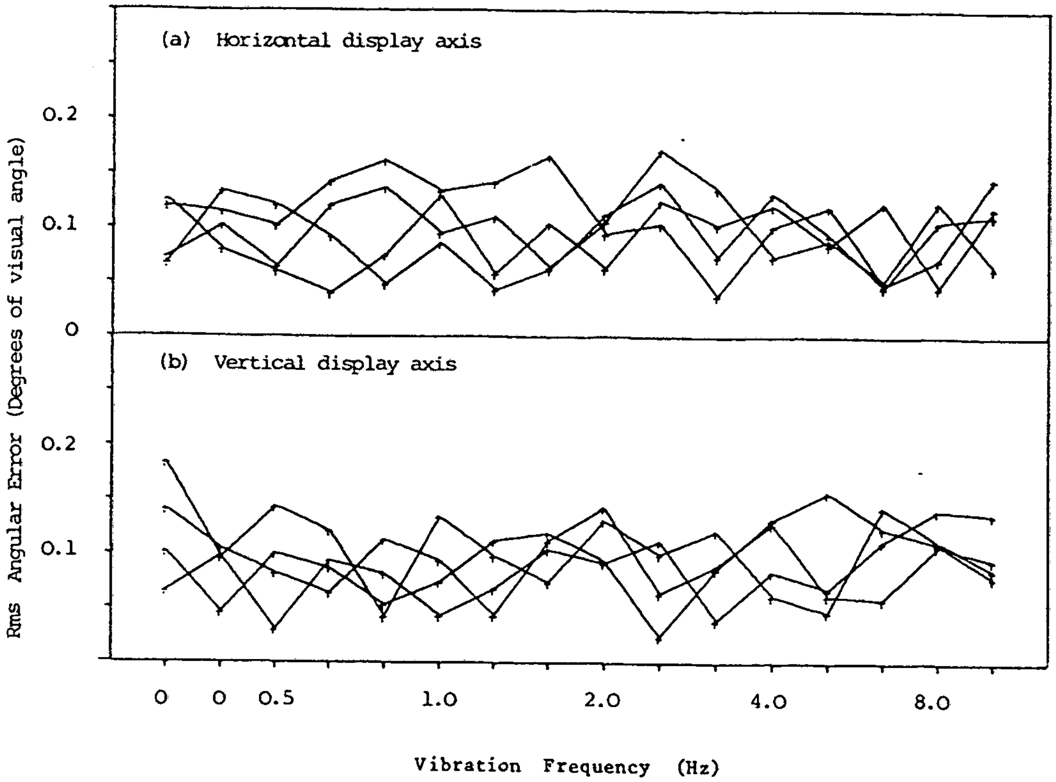
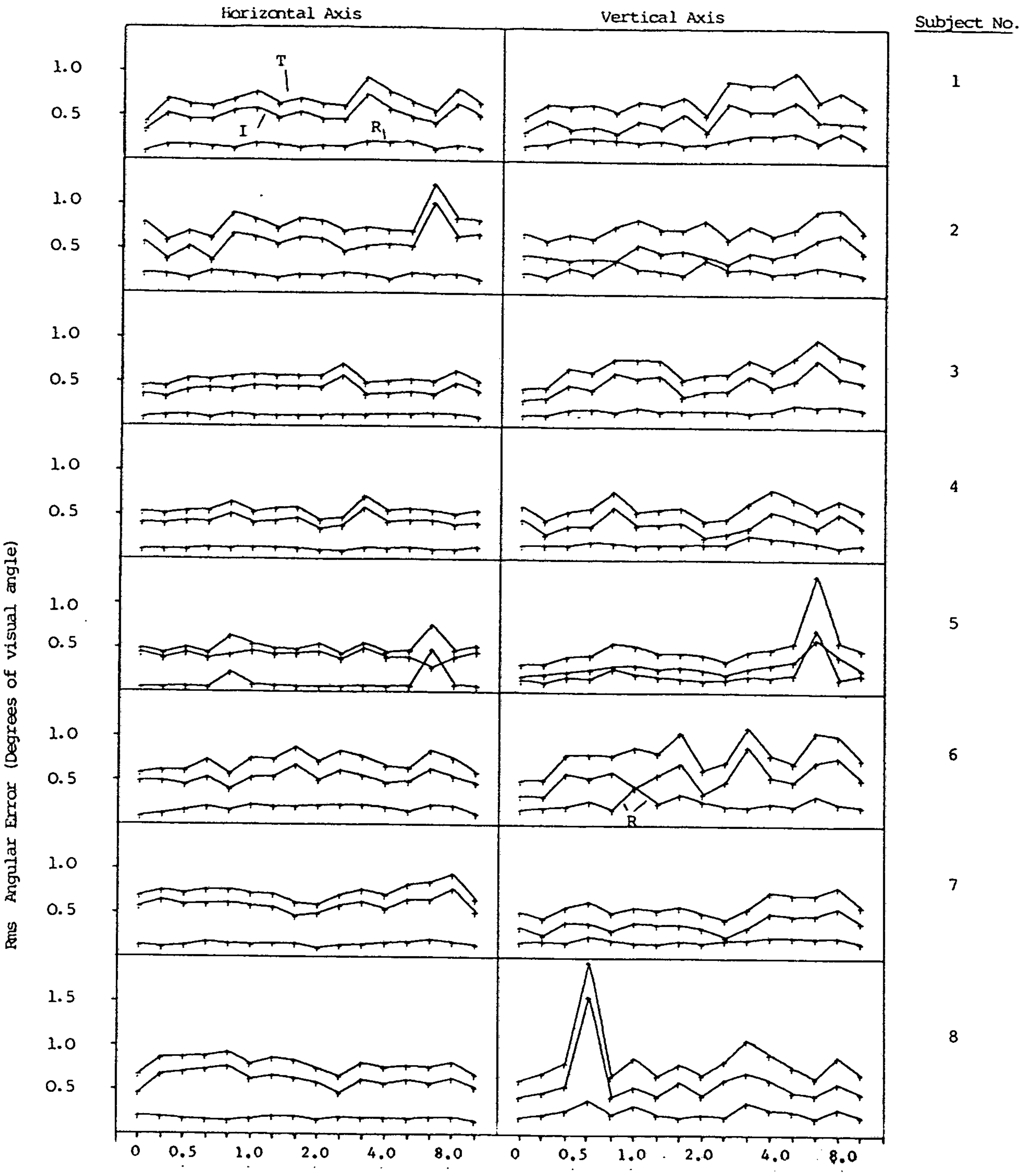


Figure 8.8 RMS angular error attributable to vibration breakthrough in each display axis as a function of vibration frequency. Data for 4 subjects. No lens.

calculating these data had a resolution of 0.1 Hz with 52 degrees of freedom. The estimates obtained with vibration at 0.5 Hz, where least attenuation of control activity in the system dynamics occurs, do not differ from those with vibration at 10 Hz, where attenuation is greatest. Furthermore, the estimates are of the same magnitude with a stationary platform. With this system, the magnitude of vibration breakthrough was smaller than the magnitude of estimation errors. While small magnitudes of breakthrough may have occurred, it was therefore concluded that direct vibration breakthrough did not significantly contribute to performance disruption during vibration.

The proportion of tracking error attributable to linear operations on the target motion (input-correlated error) was estimated using the ordinary coherence function (see Chapter 4). The difference between total rms error and input-correlated error was attributed to operator-induced noise, or remnant. Figure 8.9 shows the error components for individual subjects within each display and vibration waveform condition and at each vibration frequency. These figures show the data for both axes of the display. For all subjects, input-correlated activity accounts for the greatest proportion of total rms tracking error, and changes in total error are closely matched by changes in input-correlated error. Remnant contributes approximately 20 to 30% of total error in most cases.

Correlations between total error and each of the components were calculated for each condition using Kendalls rank correlation coefficient. In all cases highly significant correlations occurred ($p < 0.0001$). Higher correlations occurred between total and input-correlated error (from 0.77 to 0.84) than between total and remnant error (from 0.31 to 0.60). As an example, Figure 8.10 illustrates the correlations for sinusoidal vibration without the lens.



(a) Sinusoidal Vibration - No lens

Table 8.9 Components of tracking error in both axes of the display for each subject as a function of vibration frequency.

(a) Sinusoidal vibration; no lens.

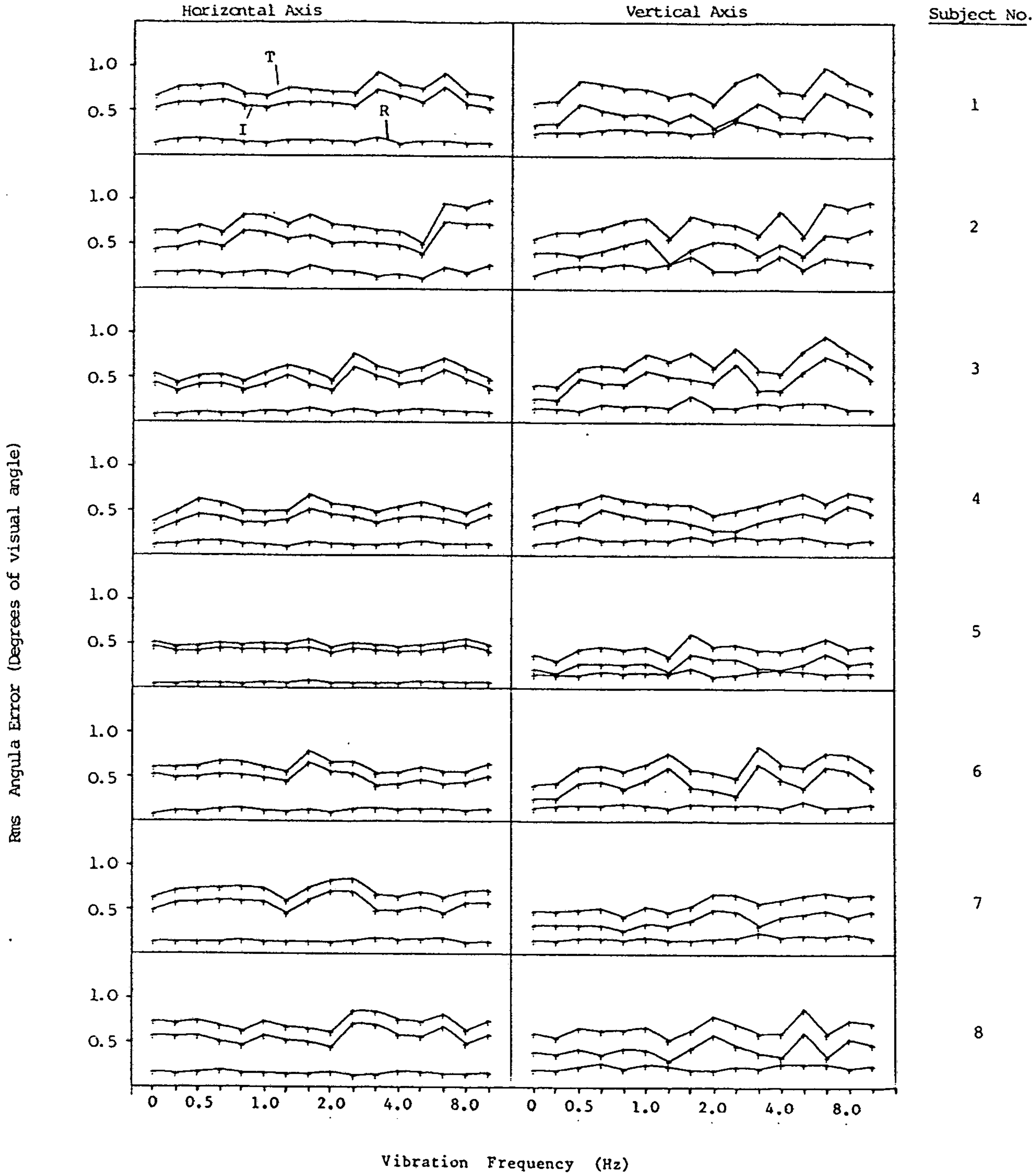
(b) Random vibration; no lens.

(c) Sinusoidal vibration; lens.

(d) Random vibration; lens.

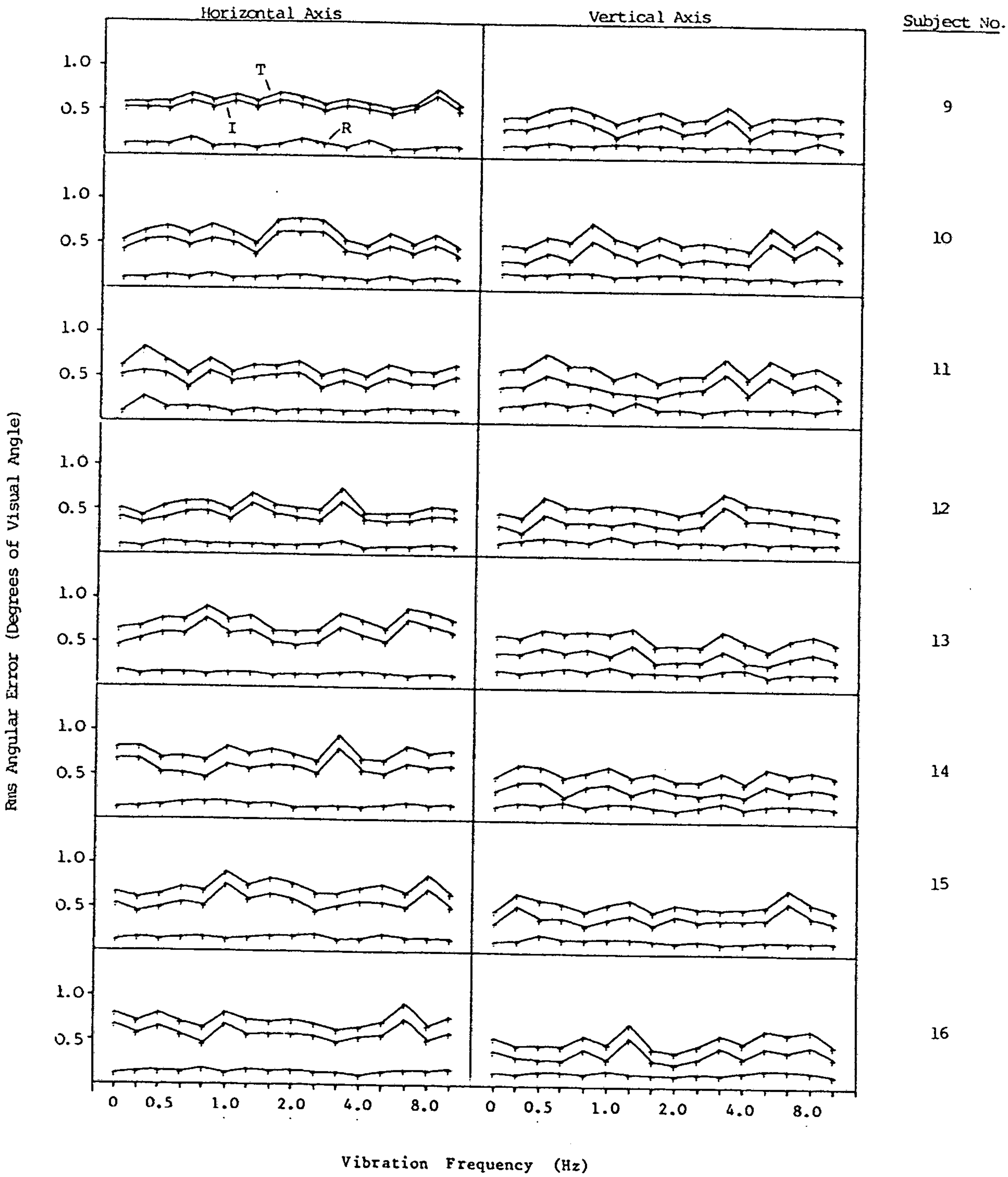
T = total error I = Input-correlated

R = remnant error



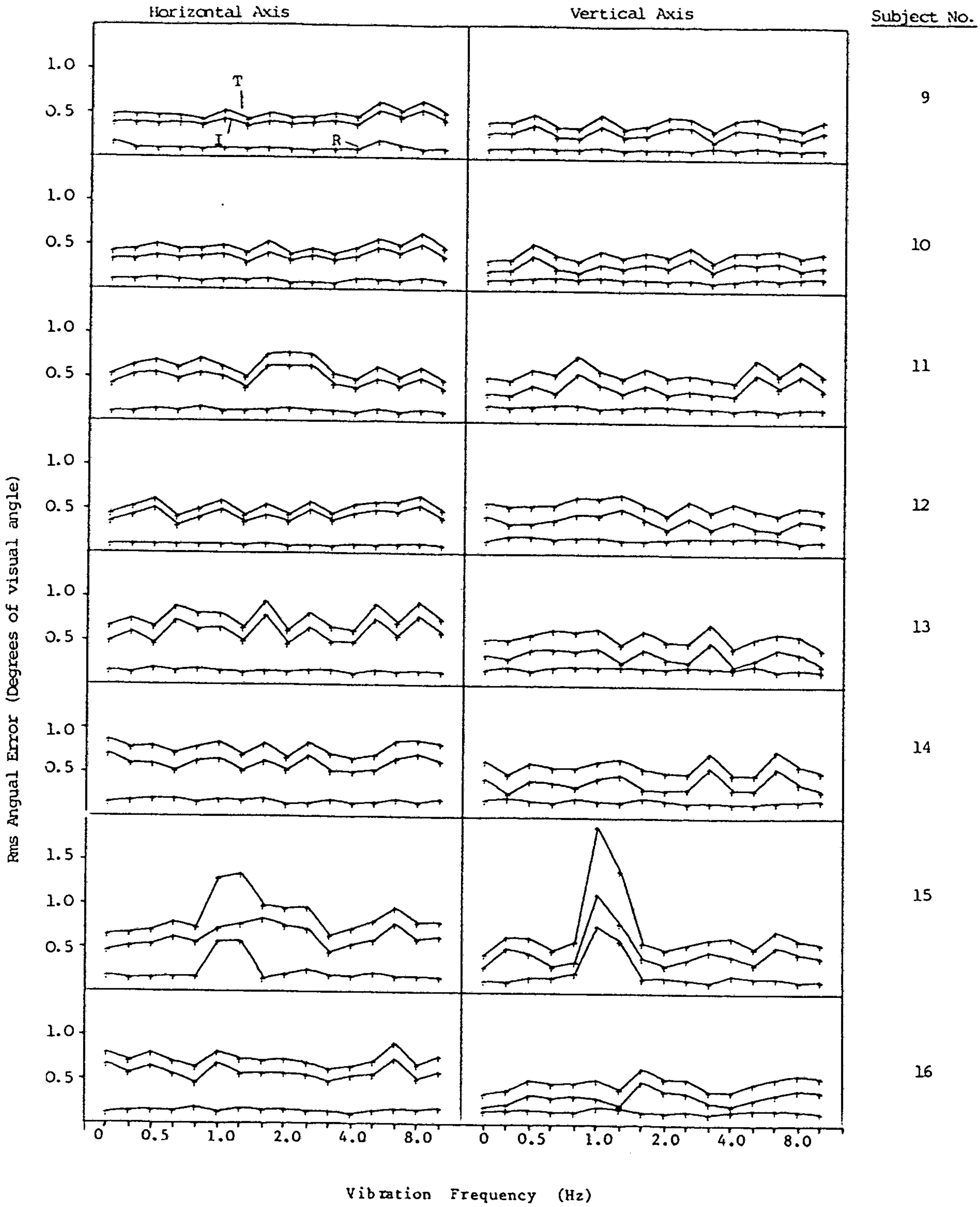
(b) Random Vibration - No lens

Figure 8.9 (continued)



(c) Sinusoidal Vibration - Lens

Figure 8.9 (continued)



(d) Random Vibration - Lens

Figure 8.9 (continued)

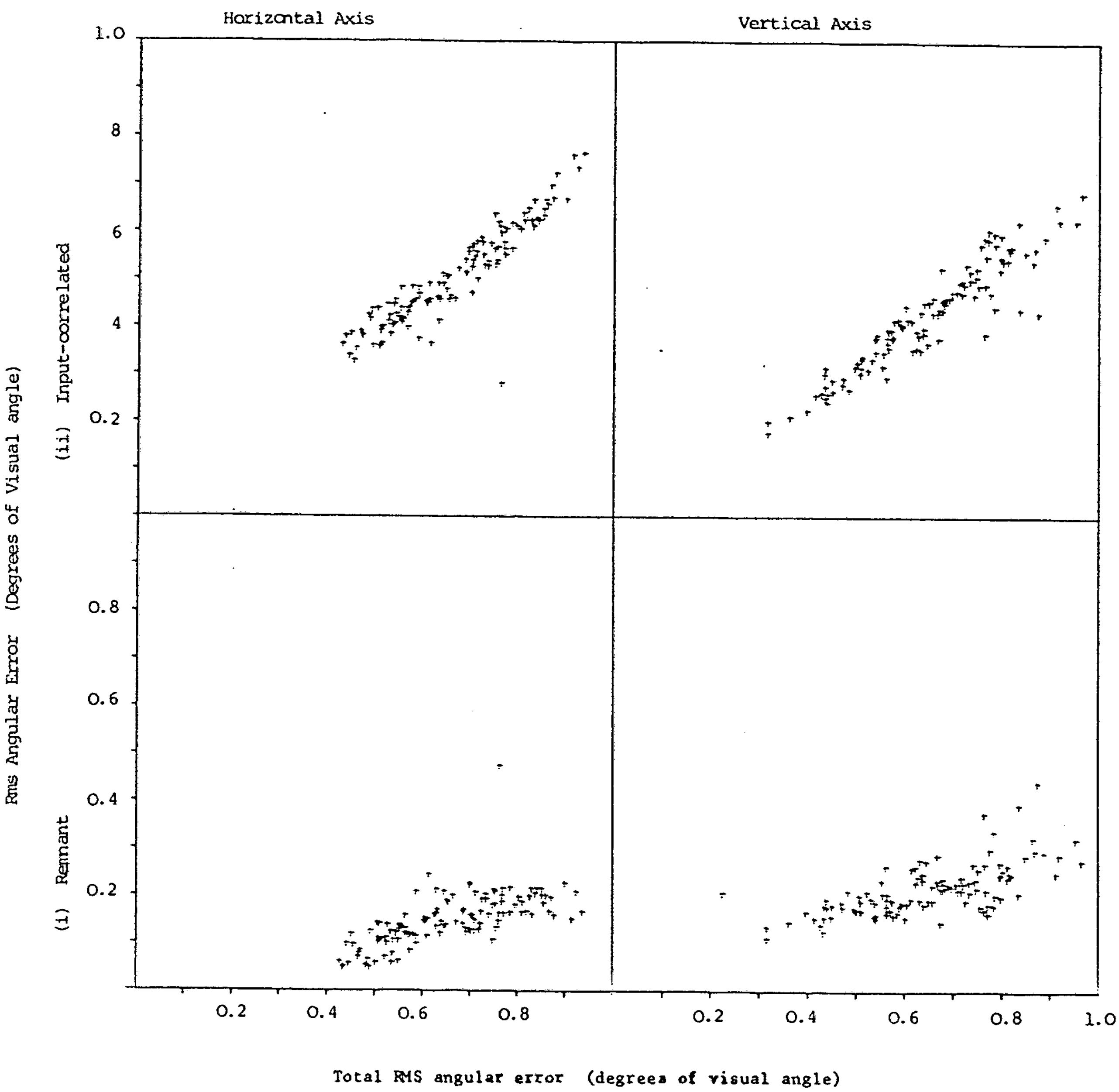


Figure 8.10 (i) Input correlated, and (ii) Remnant as a function of total RMS angular tracking error.

Sinusoidal vibration. No lens.

These results demonstrate that while changes in total error could mainly be attributed to changes in input-correlated error, there were also accompanying, and correlated, changes in remnant.

The median rms error data in each display axis are shown on Figure 8.11. These data again show the close correspondence between total and input-correlated error. Without display collimation, there were significant overall effects of vibration frequency in both display axes and with both types of vibration for all 3 measures. With both types of vibration in the 'no lens' condition, the increases in rms error during vibration compared with the no vibration runs were greater in the vertical axis of the display. Collimating the display reduced the change in total error to approximately equal magnitudes in each axis of the display.

Wilcoxon tests were performed to compare the percentage change in total rms error at each vibration frequency between each display axis. Figure 8.12 shows the median percentage changes, and Table 8.3 summarises the results of these tests. Significant differences mainly occurred at vibration frequencies above 2.5 Hz in the 'no lens' condition. There is no pattern to the differences which occurred with the lens suggesting that these results were due to random variability.

The increased disruption in the vertical axis of the task without display collimation is consistant with the axis of vibration and, therefore, the axis of greatest relative motion between the display and the subjects' head. The lack of a similar axis dependence with collimation indicates that the difference without collimation was attributable to effects on vision.

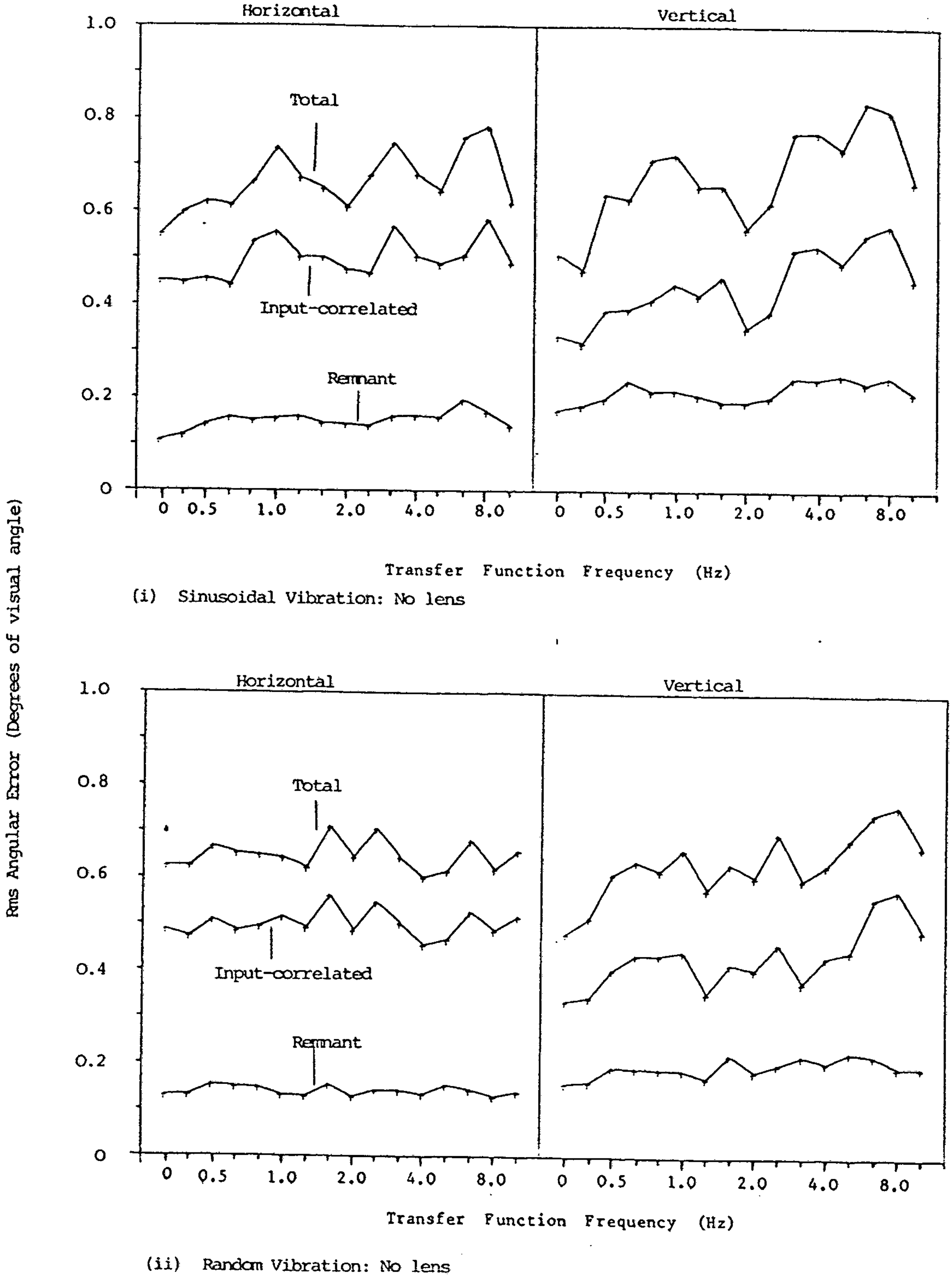


Figure 8.11 Median rms tracking error components in each axis of the display and for both types of motion as a function of vibration frequency.

(i) Sinusoidal vibration; no lens,
(ii) Random vibration; no lens
(iii) Sinusoidal vibration; lens
(iv) Random vibration; lens.

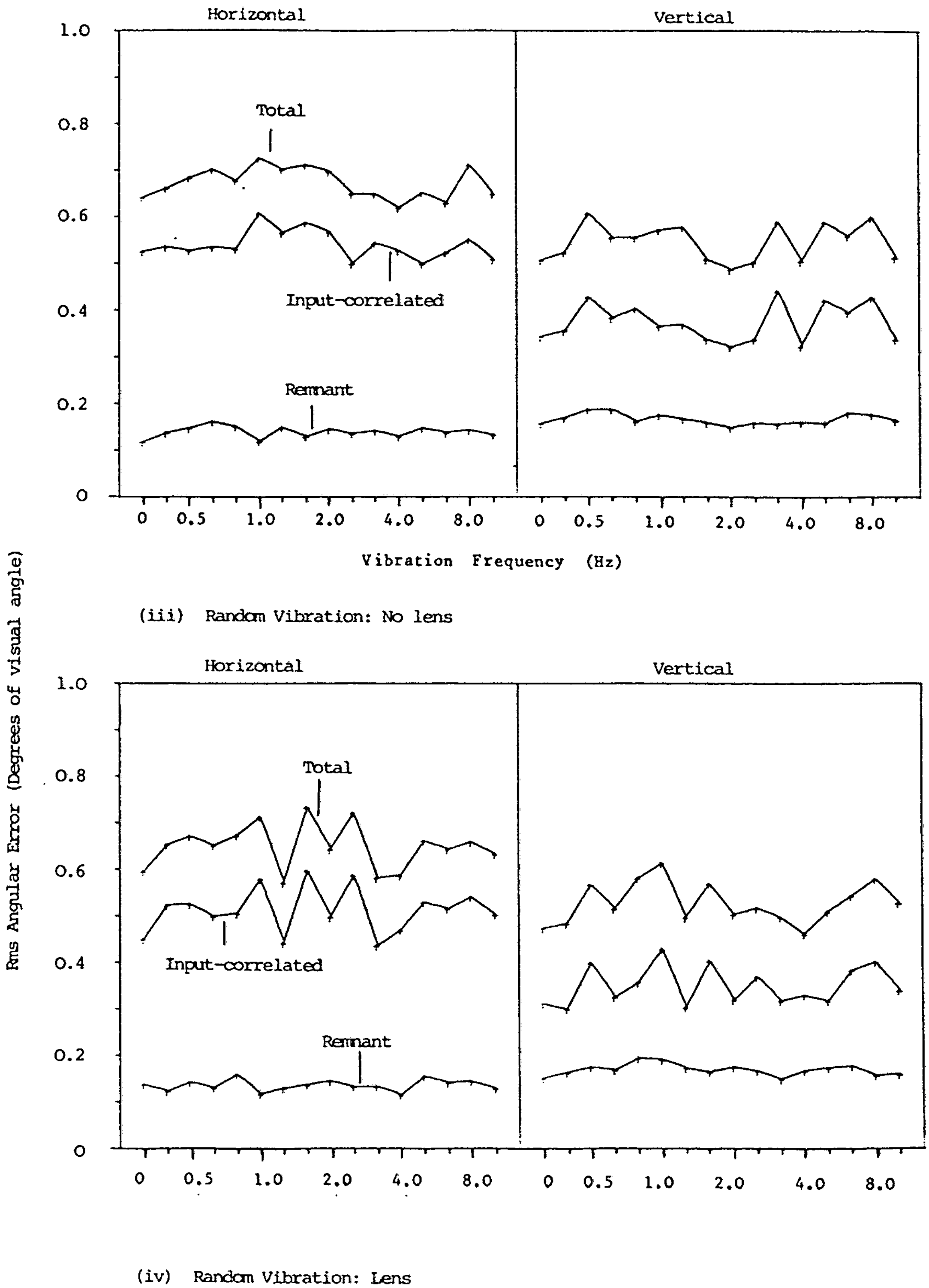


Figure 8.11 (continued)

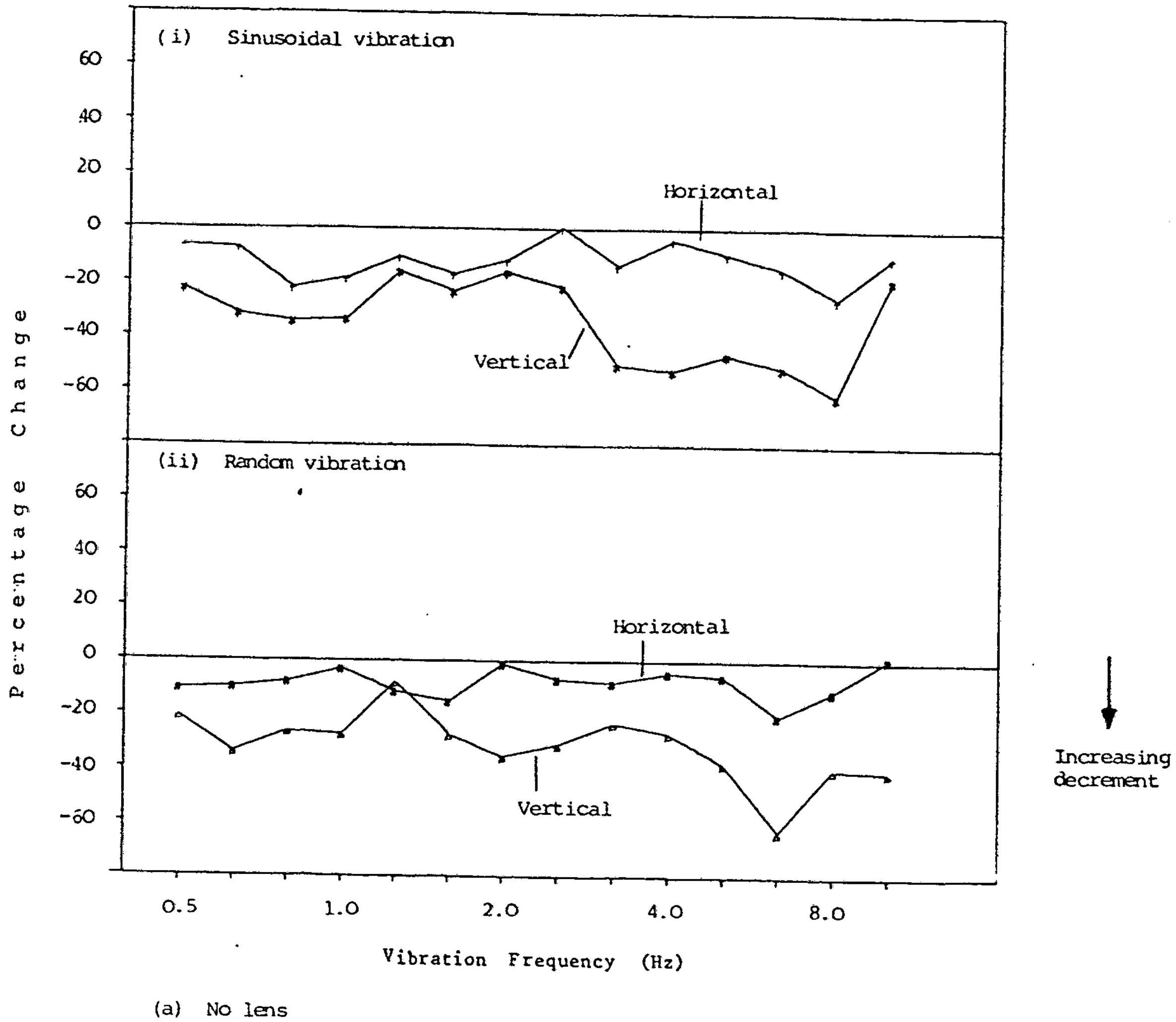
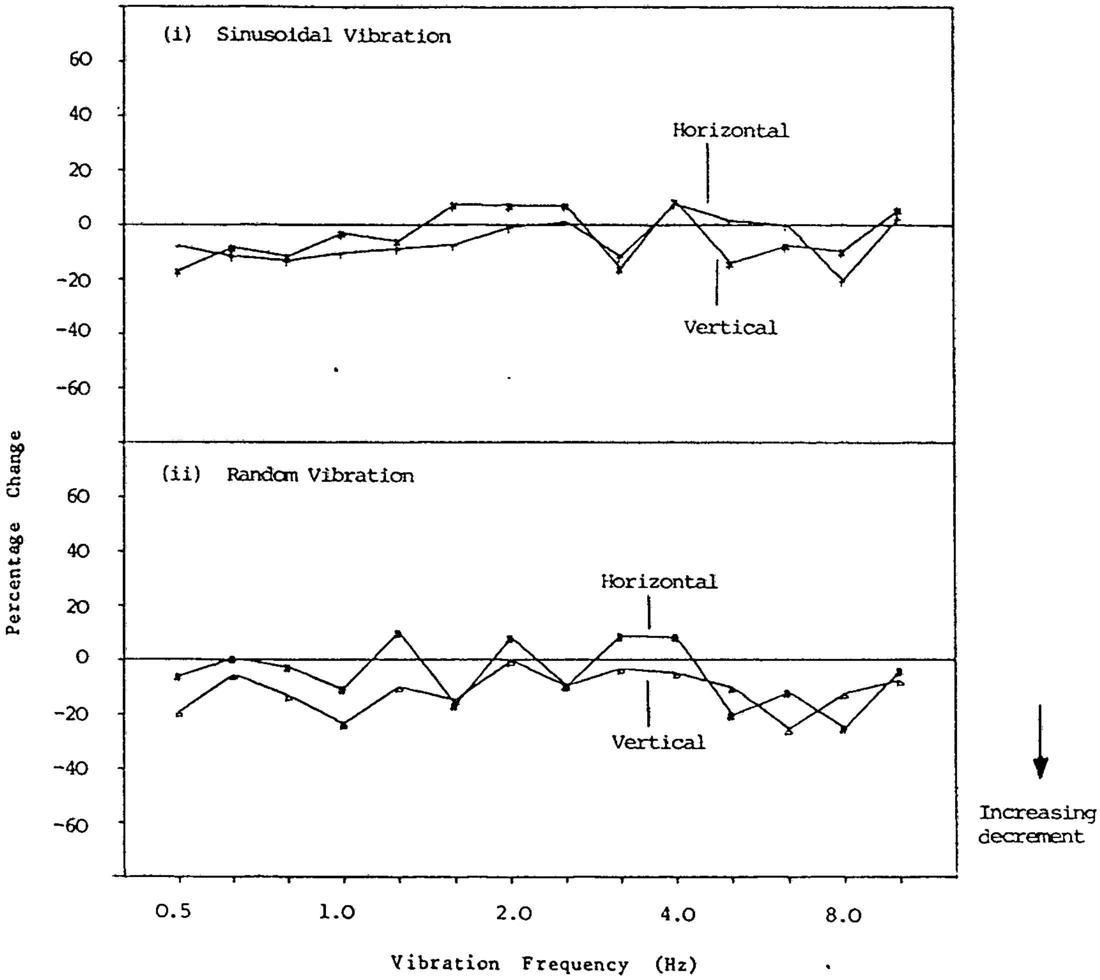


Figure 8.12 Median percentage change in total rms tracking error for each axis of the display and within vibration types and display conditions as a function of vibration frequency.

(a) No lens (i) Sinusoidal (ii) Random

(b) Lens (i) Sinusoidal (ii) Random



(b) Lens

Figure 8.12 (continued)

Table 8.3: Results of Wilcoxon tests comparing the percentage change in total rms tracking error between each axis of the display

Vibration Frequency (Hz)

	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Sinusoidal: No lens	*	NS	*	NS	NS	NS	NS	NS	*	***	***	**	**	NS
Random: No lens	NS	NS	NS	*	NS	NS	NS	*	*	***	***	**	**	*
Sinusoidal: Lens	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS
Random: Lens	NS	NS	NS	**	**	NS	NS	NS	NS	*	NS	NS	NS	NS

* = $p < 0.05$

** = $p < 0.02$

*** = $p < 0.01$

Two-tailed tests

3.3 Transfer Functions

Closed-loop system transfer functions between the target position and the system response were calculated. These data indicate the nature of changes in subjects linear response to movement of the target indicated by the measures of input-correlated error. (The theoretical basis of these transfer functions is discussed in Chapter 4).

Figure 8.13 compares median closed-loop system transfer functions in the vertical display axis without vibration and with vibration at 0.5, 1.0, 2.0, 4.0 and 8.0 Hz. At each vibration frequency, the figure shows transfer functions in both display conditions and with both sinusoidal and one-third-octave band random motion. (The spectral estimates used in calculating these transfer functions had a resolution of 0.1 Hz and 52 degrees of freedom. The coherency was greater than 0.9 at transfer function frequencies below 0.2 Hz and dropped below 0.5 above about 0.5 Hz. The data can therefore be considered to be reliable at transfer function frequencies below about 0.5 Hz).

Figure 8.14 shows the median moduli and phase lags at transfer function frequencies between 0.2 and 0.5 Hz with both display conditions as a function of vibration frequency. These data are for the vertical display axis with sinusoidal vibration. (The data for the horizontal display axis showed similar, though generally smaller and often non-significant results). The moduli and phase at transfer function frequencies up to 0.5 Hz were subjected to statistical analysis.

Although Figure 8.13 shows consistent reductions in moduli at transfer function frequencies between about 0.3 and 0.5 Hz during vibration, Friedman tests showed no overall significant effect of vibration frequency on the moduli. However, there were significant overall effects on phase at 0.2, 0.3, 0.4 and 0.5 Hz

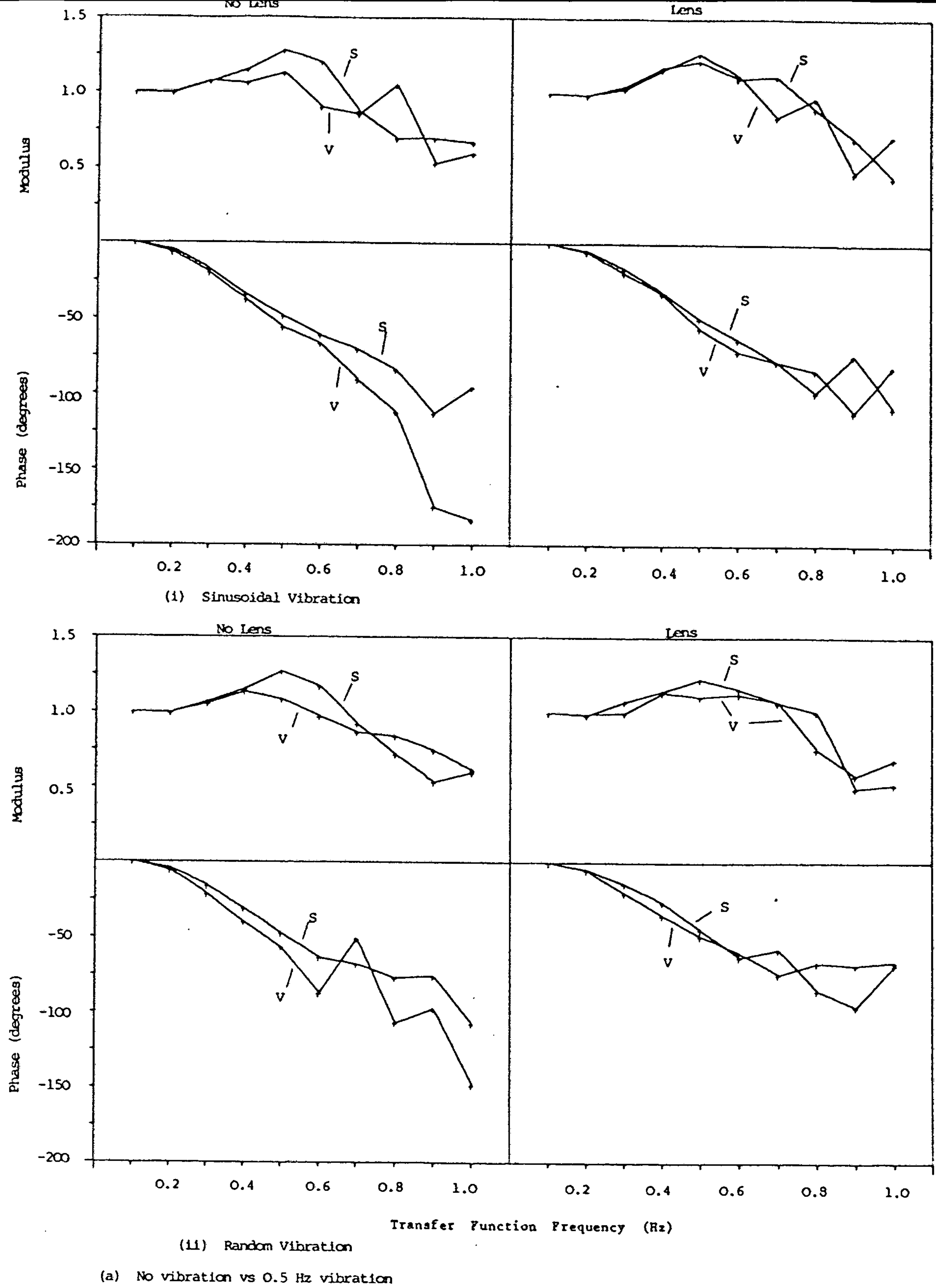
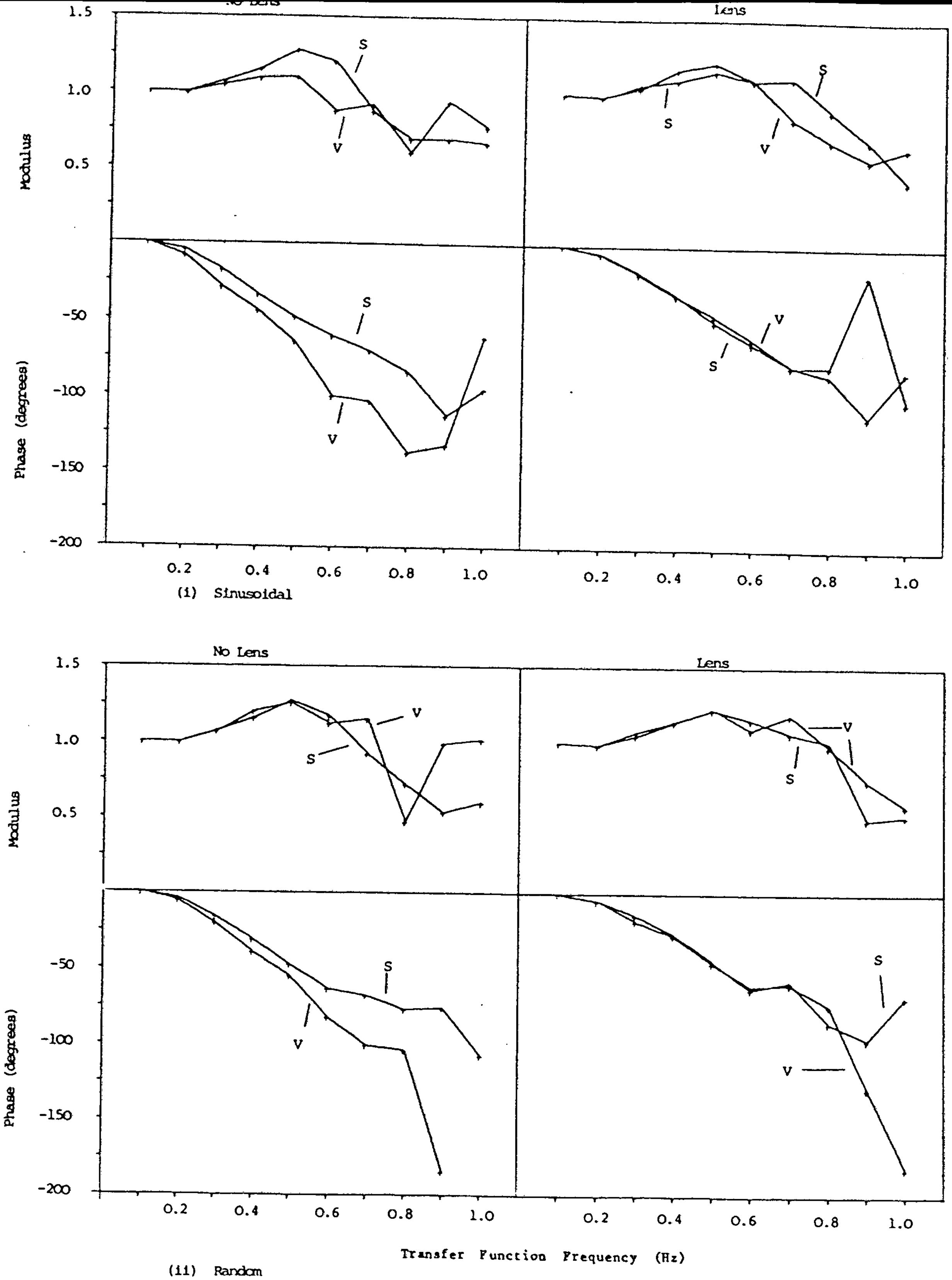


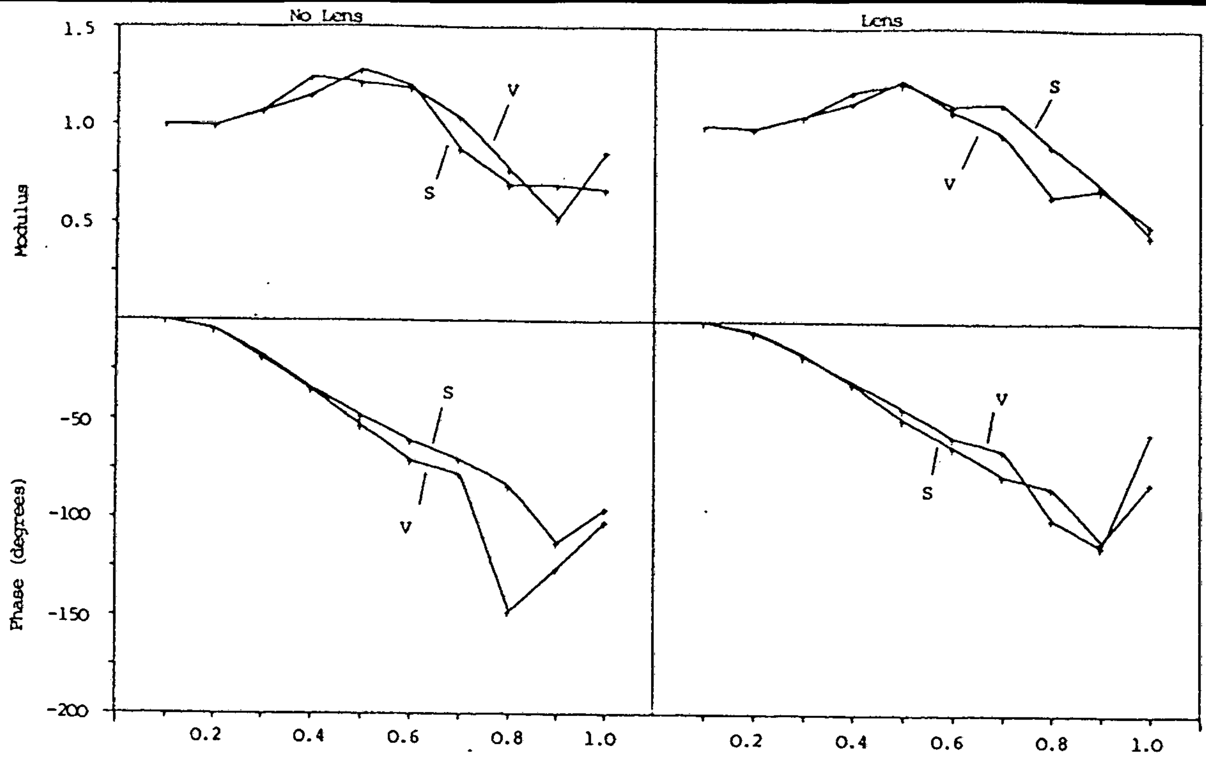
Figure 8.13 Comparisons of median closed-loop system transfer functions within vibration type and with vibration at (a) 0.5 Hz, (b) 1.0 Hz, (c) 2.0 Hz, (d) 4.0 Hz and (e) 8.0 Hz for each display and vibration waveform condition Vertical display axis.

S = static V = vibration

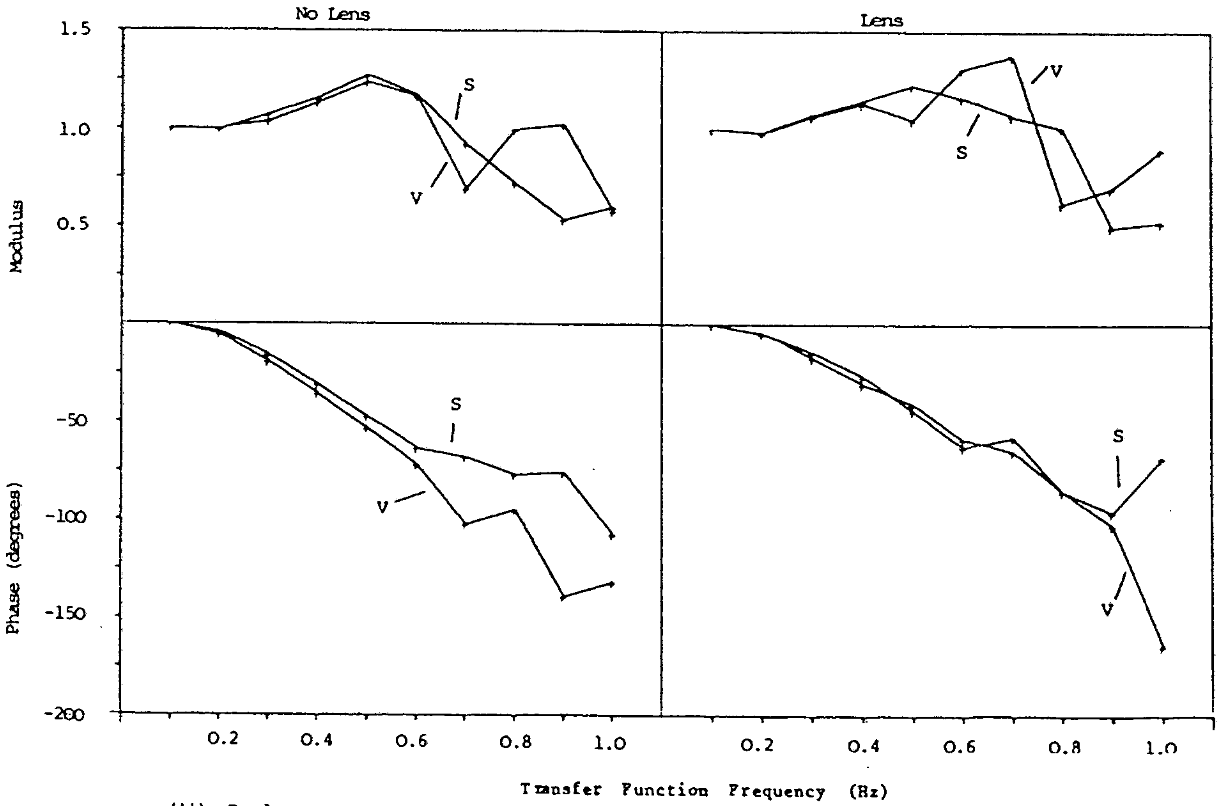


(b) No vibration vs 1.0 Hz vibration

Figure 8.13 (continued)



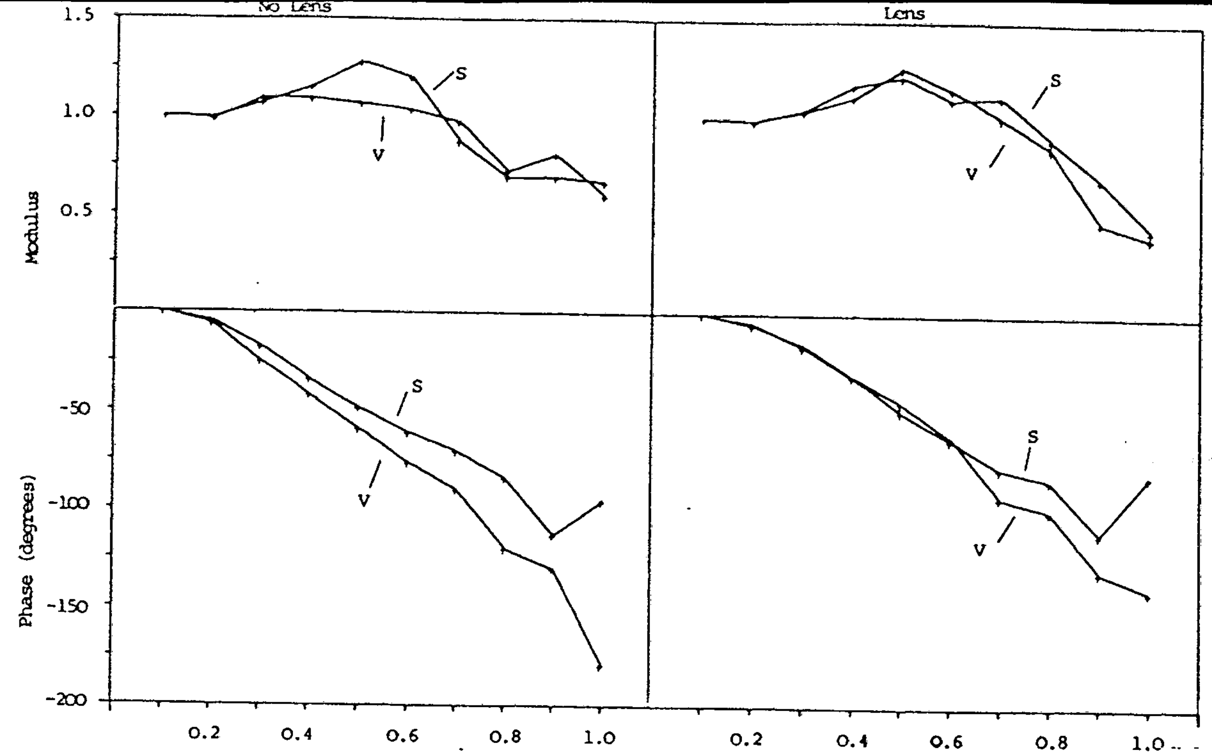
(i) Sinusoidal



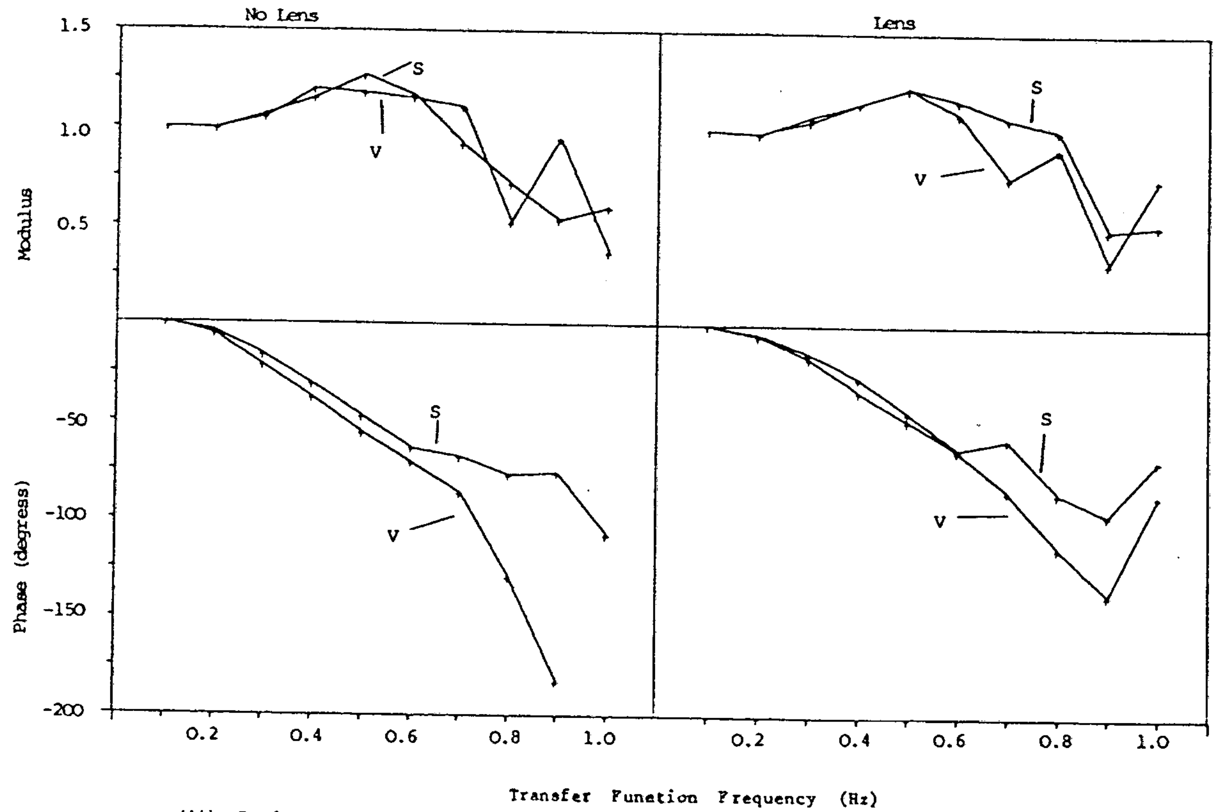
(ii) Random

(c) No vibration vs 2.0 Hz vibration

Figure 8.13 (continued)



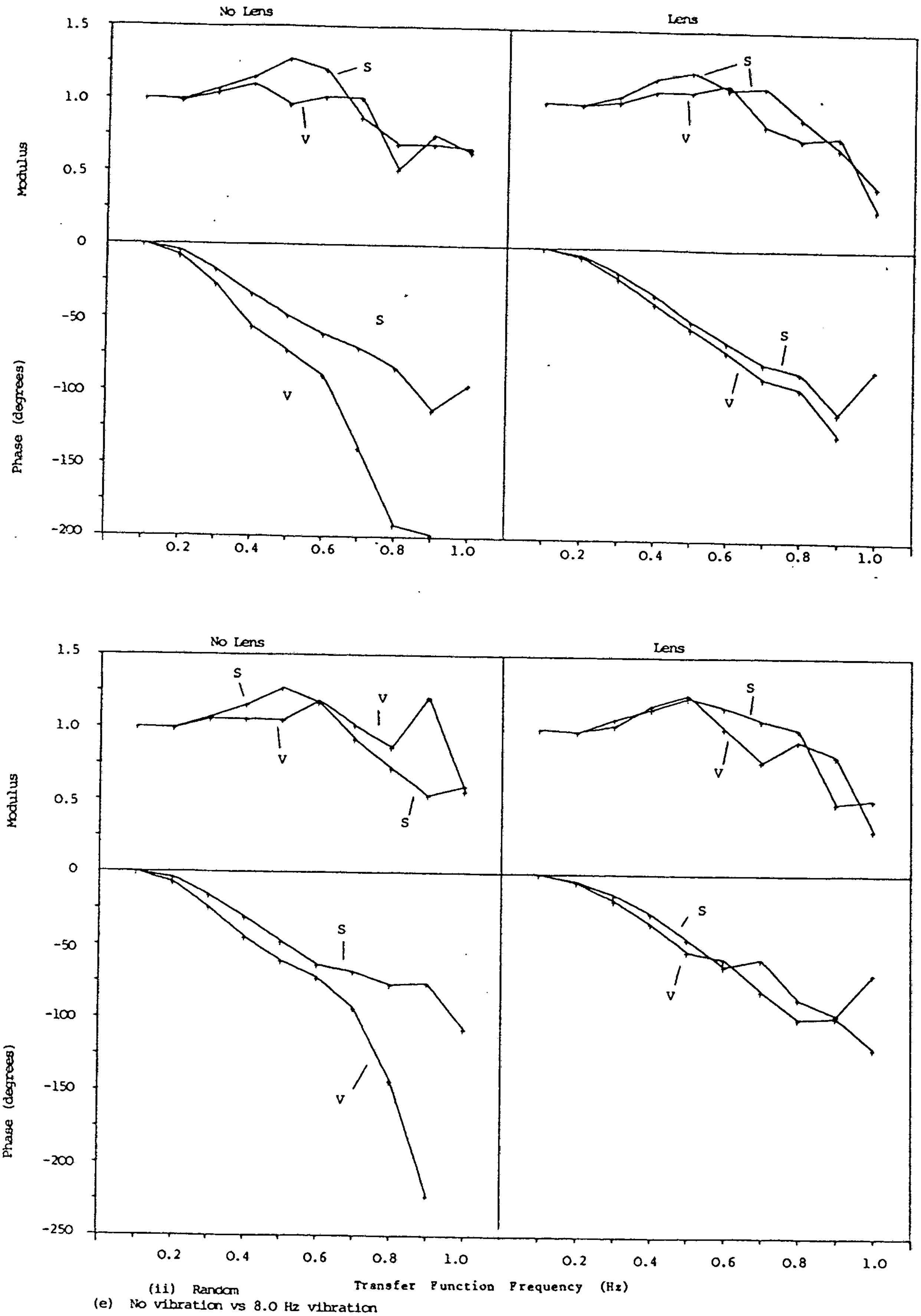
(i) Sinusoidal



(ii) Random

(d) No vibration vs 4.0 Hz vibration

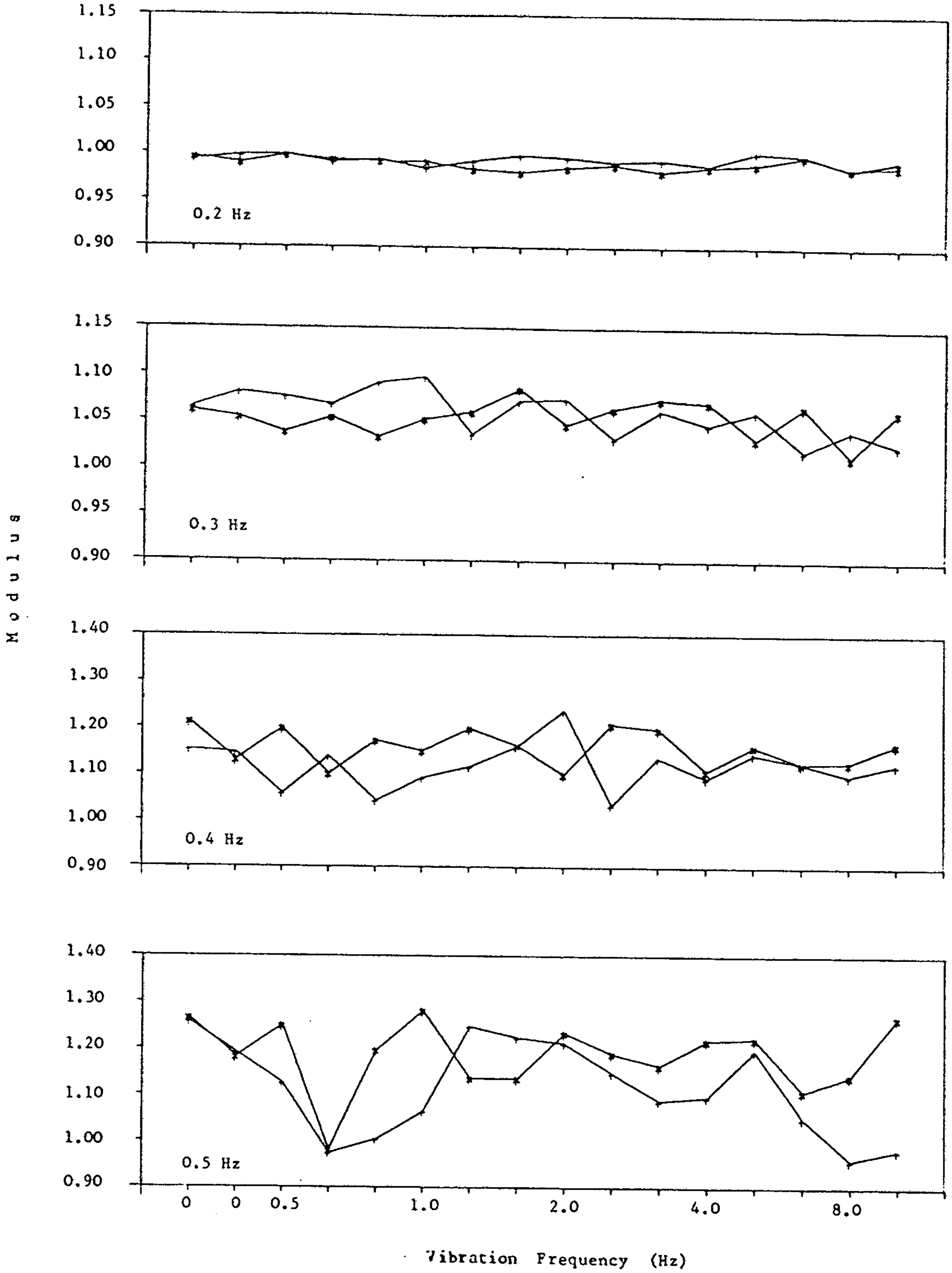
Figure 8.13 (continued)



(ii) Random

(e) No vibration vs 8.0 Hz vibration

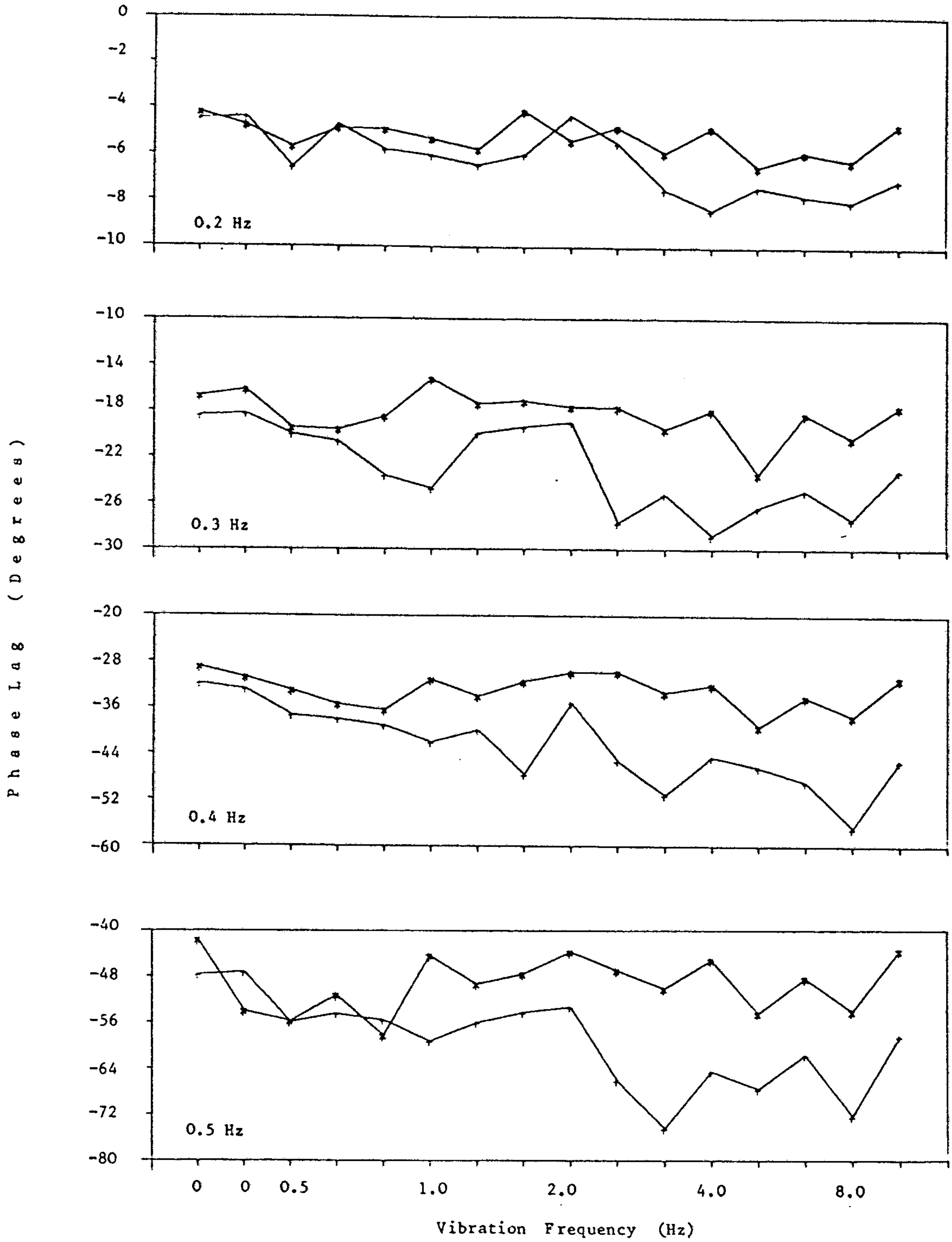
Figure 8.13 (continued)



(a) Modulus

Figure 8.14 Median Moduli and phase lags of the closed-loop system transfer functions at 0.2, 0.3, 0.4 and 0.5 Hz within display conditions as a function of vibration frequency. Vertical display axis. Sinusoidal vibration.

+ = No lens * = Lens



(b) Phase Lag

Figure 8.14 (continued)

in all conditions with the exception of 0.5 Hz during random vibration with the lens.

Table 8.4 shows the results of Wilcoxon test comparing the phase lag at each vibration frequency with the mean of the 2 runs without vibration. There were significant increases in phase lag at all four transfer function frequencies. The pattern of results is very similar to those observed for p(on): there are increased phase lags at all vibration frequencies in all conditions, although they are most consistent at vibration frequencies above 2.5 Hz. Collimating the display reduced the effect at these high frequencies.

The main effect of vibration was therefore to increase the delay between movements of the target and the response of the controlled element. At high vibration frequencies, this increase can be attributed to impaired visual ability. When they could not see the target clearly, subjects may have been unable to quickly detect, or predict, changes in target motion. They may also have been uncertain of the precise position of the controlled element relative to the target and, therefore, unsure of the precise response required.

At vibration frequencies below about 1.6 Hz, the increased phase lags could not be attributed to visual impairments. These could reflect either perceptual confusion arising from interference with neuromuscular processes, or distraction arising, for example, from anxiety or discomfort. Alternately, subjects may have attempted to compensate for perceived motion in the controlling limb. The results from experiment 5 suggested this could occur at 0.5 and 1.0 Hz. If subjects did attempt such compensation it would presumably detract attention from the tracking task and could lead to increased delays in responding.

Table 8.4: Results of Wilcoxon tests for the effect of each vibration frequency compared with the mean of the two no vibration runs at four transfer function frequencies (N=8)

Condition	Transfer Function Frequency (Hz)	Vibration Frequency (Hz) 0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Sinusoidal No lens	0.2	NS	NS	NS	NS	**	**	NS	NS	NS	*	***	**	**	***
	0.3	**	NS	*	**	*	*	NS	***	**	***	***	***	***	***
	0.4	NS	NS	NS	*	NS	**	NS	NS	**	***	***	***	***	***
	0.5	NS	NS	*	***	NS	***	NS	**	***	**	***	*	***	***
Sinusoidal Lens	0.2	***	NS	NS	NS	NS	NS	NS	NS	*	NS	*	*	**	*
	0.3	*	*	*	NS	NS	NS	NS	NS	*	NS	*	NS	***	NS
	0.4	NS	*	**	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
	0.5	NS	NS	**	NS	NS	NS	NS	NS	*	*	*	NS	NS	NS

Table 8.4: (Continued)

Condition	Transfer Function Frequency (Hz)	Vibration Frequency (Hz) 0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
One-third	0.2	NS	***	NS	*	NS	***	NS	*	NS	***	**	***	***	***
Random	0.3	***	***	**	**	NS	***	**	***	**	***	***	***	***	***
No lens	0.4	***	***	*	**	NS	*	NS	*	**	***	**	***	***	***
	0.5	*	*	**	NS	NS	*	**	***	**	***	***	**	**	**

One-third	0.2	**	NS	*	**	NS	**	NS	*	NS	NS	NS	NS	***	NS
Random	0.3	***	*	NS	NS	NS	NS	**	NS	***	NS	NS	***	*	**
Lens	0.4	***	NS	NS	*	***	NS	NS	NS	NS	NS	NS	**	NS	NS
	0.5	N O O V E R A L L S I G N I F I C A N C E													

4.0 Summary and Conclusions

In summary, this study has shown 6 main results:

(i) Both sinusoidal and one-third-octave band random vibration significantly disrupted performance of the continuous task at all vibration frequencies from 0.5 to 10.0 Hz without display collimation.

(ii) Collimating the display removed the vibration-induced disruption at frequencies above 1.6 Hz. The disruption at these frequencies was therefore attributed to visual impairment arising from relative translational movement between subjects' eyes and the display.

(iii) Differences between effects of sinusoidal and random vibration only occurred with vibration at 2.0 and 2.5 Hz. It was assumed that with predictable sinusoidal vibration at these frequencies subjects were able to compensate for movement of the head relative to the display by inducing compensatory eye movements. With the less predictable random vibration, such compensation was not effective above about 1.6 Hz.

(iv) Vibration breakthrough to the display was not an important mechanism in producing the impairments in performance.

(v) Changes in tracking performance were accompanied by changes in input-correlated error: these were mainly caused by increased delays in the response of the system to movements of the target. There were also reductions in the moduli of the transfer functions, although these were not statistically significant. The increased phase lags at vibration frequencies above 1.6 Hz were attributed to uncertainty about the positions of the target and controlled element on the display. At lower frequencies, they may reflect either neuromuscular interference or some cognitive effect, such as anxiety or distraction.

(vi) Performance of the discrete task was not affected independently from the continuous task: changes in p(press) were attributed to changes in p(on).

The results of this experiment differ from previous studies (eg., Allen et al, 1973; Lewis and Griffin, 1977, 1978, 1979; Levison, 1977), in that vibration did not produce large changes in remnant. This probably reflects a lower control sensitivity used in this study. Lewis and Griffin (1977) demonstrated that remnant was proportional to the sensitivity of the control. (Direct comparisons of control gains between different experiments are not possible due to both the different systems studied and the different ways in which control gain is expressed).

There are three possible explanations for the small changes in remnant which did occur. First, they may reflect the inability of the signal processing techniques used to entirely distinguish activity linearly and non-linearly related to movements of the controlled element. The spectral estimates were calculated with

52 degrees of freedom: this provides greater than 98% confidence that the estimated magnitudes of breakthrough, input-correlated error and remnant were within $\pm$ 2½ dB of the 'true' values, or greater than 60% confidence that they were within $\pm$ 1 dB (Mercer, 1973).

Secondly, the changes in remnant may reflect the use of non-linear tracking strategies (such as, for example, producing ballistic responses). These would be expected to be related to the sensitivity of the control. Thirdly, and as has previously been suggested (eg., Allen et al, 1973; Levison, 1977), remnant may indicate direct effects of vibration on the neuromuscular system, producing increases in random muscle activity. The first of these possibilities is likely to be at least part of the explanation. On the basis of this experiment however, it is not possible to determine whether either of the other possibilities was important.

CHAPTER NINE

EXPERIMENT FIVE: INDUCED CONTROL ACTIVITY DURING EXPOSURE TO SINUSOIDAL VIBRATION AT 0.5 AND 4.0 HZ

1.0 Introduction

Chapters 7 and 8 have shown that observed decrements in tracking performance induced by whole-body vibration at frequencies between about 1.6 and 10.0 Hz were mainly due to impairments in visual ability. Translational movement between subjects' eyes and the display caused the image of the display to move across the retina. Subjects were therefore less able to see the elements on the display clearly. In general, the extent to which this mechanism contributes to performance disruption during vibration exposure will depend upon the viewing distance.

In the experiments reported in previous chapters, vibration-correlated activity of the controlled element on the display (vibration breakthrough) has not been a significant mechanism in producing the observed vibration effects: breakthrough at the control was attenuated by the system dynamics such that it did not produce measurable activity on the display (Chapter 8).

As well as visual impairment and vibration breakthrough, the behavioural model presented in Chapter 3 indicates two additional mechanisms which may contribute to performance disruption during vibration: interference with neuro-muscular processes, and central effects. These mechanisms are assumed to be involuntary (in the sense that subjects have no direct control over them). The model also indicates a number of ways in which subjects could change the way the task is performed during vibration exposure. These secondary effects are considered to be under voluntary control.

The experiment reported in this chapter investigated whether neuro-muscular or central effects were likely to have been important in disrupting performance during exposure to vibration at 0.5 Hz. For comparison, vibration was also presented at 4 Hz. The study also investigated the extent to which secondary effects may be important. Effects arising from involuntary mechanisms (neuromuscular or central) were not expected to depend on feedback of performance. Voluntary, secondary effects however may depend on the type of feedback.

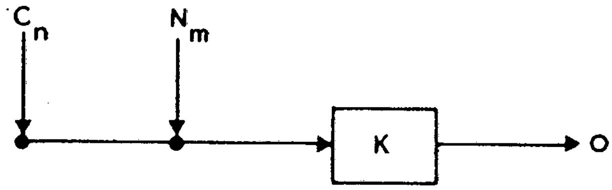
Three simple tasks were used. These are described in the next section. The principal dependent variable of interest was the frequency content of induced activity at the control.

1.1 Tasks

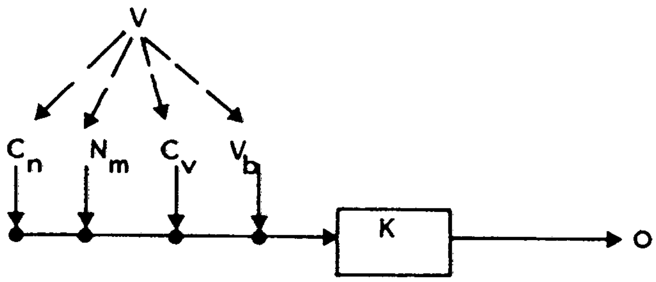
1.1.1. Task A

Description

With the simplest task (Task A), the display was switched off and subjects therefore received no visual feedback of their performance. The subjects' task was to hold the control as if they were keeping the controlled element stationary in the centre of the display, using the same grip as for continuous tracking. Figure 9.1 shows a simple model of the possible components of control activity with this task in both no vibration and vibration environments. (These figures are intended simply to illustrate the various sources of control activity for each task. They do not, for example, show the feedback loops and interactions which may occur within the body).



(a) Without vibration



(b) During vibration

C_n = Central 'noise'

C_v = Intentional response to percieved body movement

N_m = Neuro-muscular 'noise'

V_b = Vibration breakthrough to the control

V = Whole-body vibration

K = Control gain

O = Control output

Figure 9.1 A simple model of the components of control activity with Task A.

Without Vibration

Without vibration (Figure 9.1a), control activity can be attributed to central and muscular noise processes (respectively C_n and M_n). Central 'noise' in this case is any activity at the control arising from subjects' behaviour. For example, changes in grip or arm position, or general fidgeting may contribute to C_n. Without visual feedback, subjects would be likely to introduce a directional bias in the force applied on the control. Muscular noise includes tremor and other types of spontaneous muscular activity.

With vibration

There are suggestions that vibration may both directly induce muscular activity (increasing M_n) and cause feelings of stress, or otherwise increase subjects levels of arousal (see Chapter 2, sections 4.3 and 4.4). Increased stress or arousal may produce an increase in C_n. Any voluntary stiffening of the body may further increase the effects from both C_n and M_n. There is little a priori reason to expect differential effects on either C_n or M_n at the two vibration frequencies.

Figure 9.1b shows two further ways in which vibration could affect control activity with this task. First, vibration breakthrough, V_b, would be expected to appear in the control activity at both vibration frequencies. Second, if subjects are able to perceive induced limb and body motion, they may voluntarily induce compensating limb activity, C_v. Voluntary compensation at the vibration frequency may be possible with 0.5 Hz vibration, which is well within the operators' response bandwidth, but is unlikely at 4.0 Hz.

1.1.2. Task B

Description

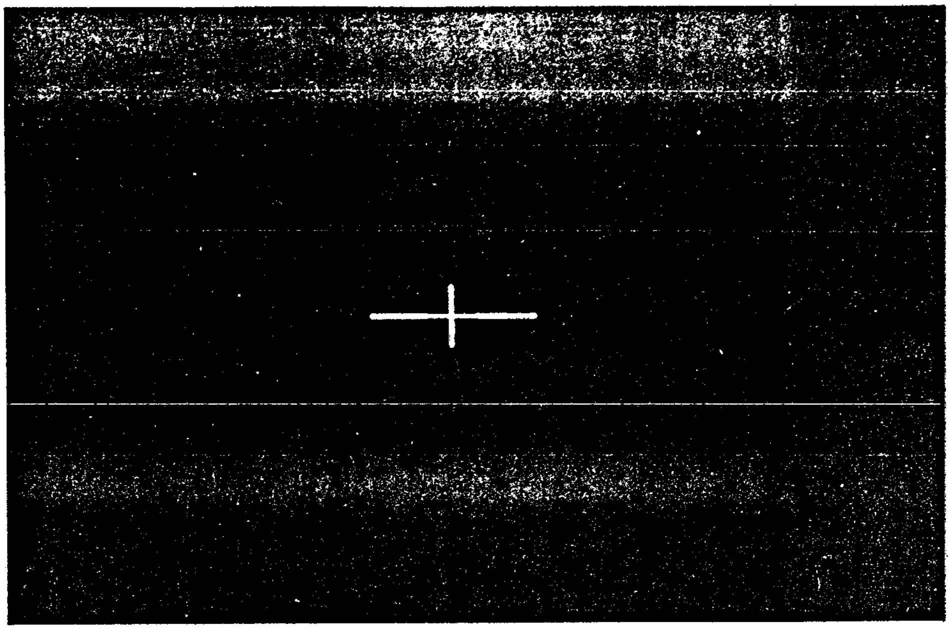
In the second task (Task B), the display was switched on but only the controlled element was displayed; the target and horizontal 'horizon' line were absent. Figure 9.2a shows the display in this case. The task was to keep the controlled element stationary in the centre of the display. Subjects were therefore given visual feedback of the response of the system. However, due to the attenuation of control activity in the system dynamics, they did not see all of the activity occurring at the control. Figure 9.3 shows simple models of this task both with and without vibration.

Without Vibration

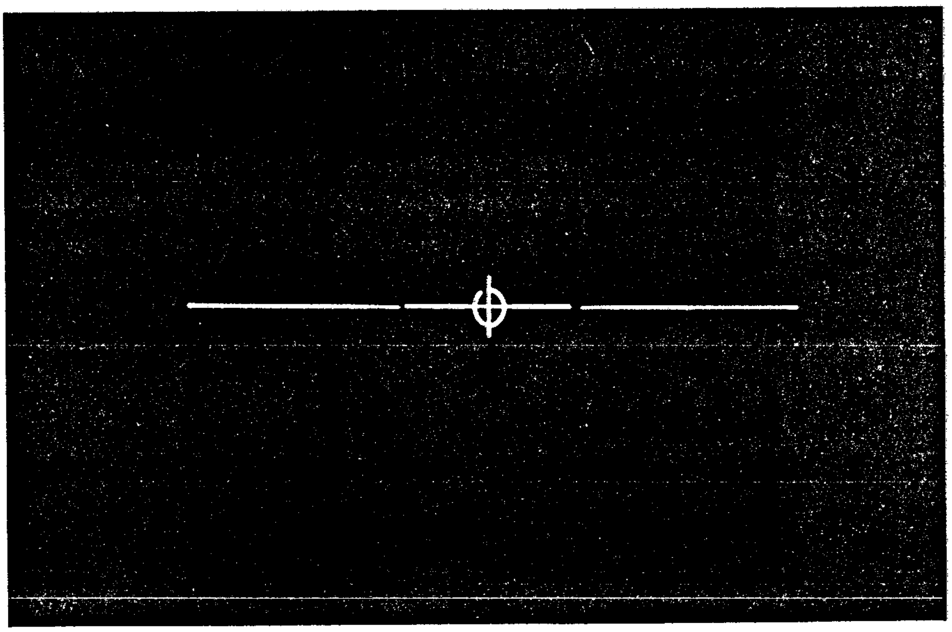
Without vibration (Figure 9.3a), control activity again contains components from C_n and M_n, although in this task these may be influenced by intentional controlling activities, C_i. Subjects observe the controlled element on the display. If the movement of the controlled element exceeds some threshold for detection, (d), the subject should induce control activity, C_i (which would depend on the sensitivity of the control as well as the system dynamics), to return it to the centre and prevent further movement. With the visual feedback, subjects should be able to detect and compensate for any directional bias in the forces they apply on the control.

With Vibration

During vibration exposure, the same arguments hold for C_n, M_n, V_b and C_v as for Task A. With this task, however, there may also be a component, V_v, if visual ability is impaired.

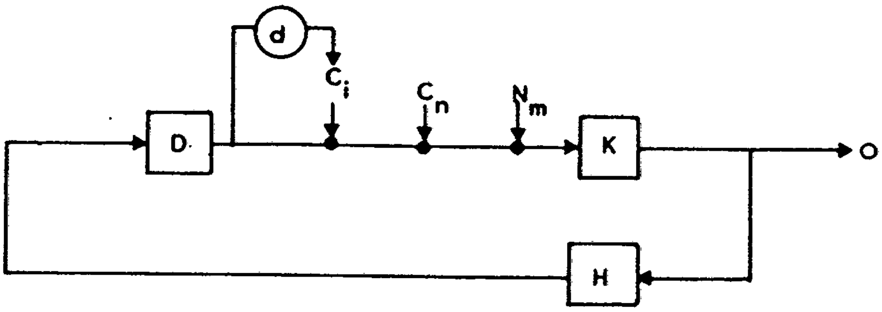


a) Task B

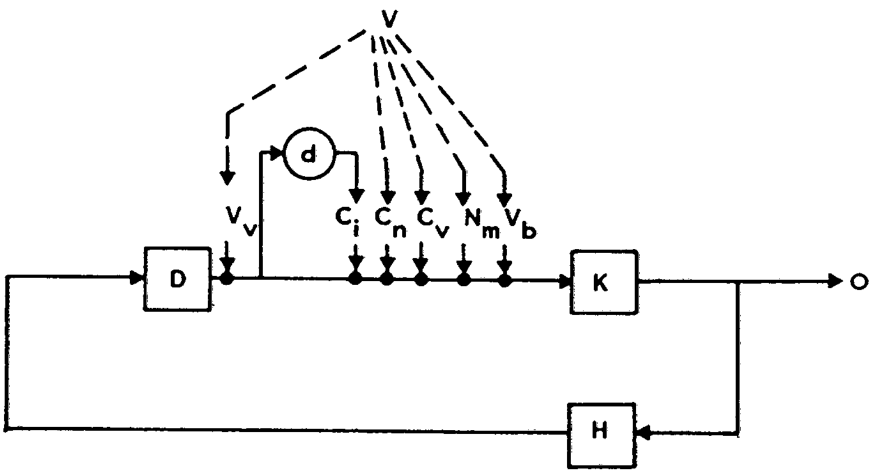


b) Task C

Figure 9.2 The display as it appeared for (a) Task B, and (b) Task C.



(a) Without vibration



(b) During vibration

D = Display

d = detection threshold

N_m = Neuro-muscular 'noise'

C_i = intentional response to activity observed on the display

C_v = intentional response to percieved body movements

C_n = Central 'noise'

K = Control gain

O = Control output

H = System dynamics

V = Whole-body vibration

V_b = Vibration breakthough to the control

Figure 9.3 A simple model of the components of control activity with Tasks B and C.

However, the display was collimated in this study. Results from experiments 3 and 4 suggest that visual effects would therefore not be large. If visual effects do occur, they would be expected with vibration at 4.0 Hz but not at 0.5 Hz.

If any of these sources introduce motion of the controlled element, intentional, compensating control activity, Ci, would be expected to increase.

1.1.3 Task C

Description

The third task (Task C), used the full display as in the tracking experiments: the controlled element, target and horizon line were all displayed as shown on Figure 9.2b. The target did not move. The task was to keep the controlled element stationary in the centre of the target. The presence of the target was expected to produce a more sensitive threshold for detecting movement of the controlled element. The models describing this task are the same as for Task B (Figure 9.3).

Without Vibration

Without vibration, control activity would be expected to show more high frequency activity than with Task B: subjects should detect small movements quickly and frequently and should therefore induce small amplitude intentional correcting activity,

C_i, more often. Directional biases in the applied force should be entirely removed with this task.

With Vibration

During vibration, the same arguments hold as for Task B although, again, more intentional high frequency activity, C_i, would be expected if control activity is induced through any of the other sources.

1.2 Arm Support

This study also compared the effect of providing an arm support on induced control activity. Experiment 1 showed that an arm support could reduce the magnitude of vibration-induced activity in the side-to-side axis of the control. Comparing results with and without the arm support may assist in interpreting the source of any induced activity which occurs.

2.0 Method and Procedure

In order to detect changes in voluntary behaviour reflected in activity at the control, it was considered necessary to measure control activity at frequencies up to 2 Hz with a resolution of approximately 0.05 Hz. To achieve this resolution using Power Spectral densities would have required excessively long runs, restricting the number of conditions which could be studied. Furthermore, it seemed likely that central 'noise' (through, for example, fidgeting or changes in posture) would be greater with long data collection runs. To avoid these difficulties, 20 seconds of data were acquired in each condition at a sample rate of 51.2 samples per second. The frequency content of control activity was calculated using 1024 point FFTs, giving a frequency resolution of 0.05 Hz.

Subjects sat on a hard, flat seat with a backrest and were restrained by a 5-point harness. The seat was mounted on a 1-metre stroke electro-hydraulic vibrator which was constrained to move in the vertical (z-) axis only. Sinusoidal, z-axis, whole-body vibration was presented at 0.5 and 4.0 Hz at a magnitude of 2.1 ms^{-2} rms. Subjects also performed a control run, without vibration exposure, in each condition.

Vibration exposures lasted for 30 seconds, with the first and last 5 seconds being shaped using a cosine weighting to ensure smooth progressions to and from rest. These 10 seconds were omitted from the analysis. In the conditions without vibration, data were also acquired for 30 seconds. In all cases, subjects were given 5 seconds warning before the start of each run. There were approximately 45 seconds rest between each exposure.

The simplified system dynamics were used allowing independent control in each axis of the display. As in experiment 1, the sensitivity of the control was increased compared with the performance studies in order to accentuate, and therefore assist in detecting, any effects which occurred (see Table 9.1). For tasks B and C, the position of the elements on the display were adjusted so that they were in the centre of each subjects' field of view.

The experiment used a completely randomised block design in which all subjects received all conditions. All 8 subjects had previously taken part in experiments 1, 4 and 6.

Table 9.1 Details of Experiment 5

Independent Variables :	Type of task; vibration frequency; arm support.
Dependent Variables :	Fourier transforms of activity at the control.
Subjects :	8 right-handed males.
Tasks :	A. Hold control with constant grip (no visual feedback). B. Hold controlled element stationary in centre of display (no target). C. Hold controlled element stationary in centre of target.
Forcing Function :	None.
System Dynamics :	First-order. De-coupled pitch and roll axes of aircraft model.
Control :	Isometric side-stick. With and without arm supports.
Control Gain :	fore-and-aft = 3.76 v/kg = 2 $^{\circ}$/s/kg (vertical) side-to-side = 0.69 v/kg = 2 $^{\circ}$/s/kg (horizontal)
Display :	Collimated. (Details as in 'Lens' condition on Table 7.1).

Table 9.1 (continued)

Vibrator	:	1-metre stroke, electro-hydraulic z-axis.
Seat	:	Hard, flat, simulated helicopter seat with backrest and 5-point harness.
Vibration Exposure	:	Sinusoidal, whole-body vibration at 0.5 or 4.0 Hz at an acceleration magnitude of 2.0 ms^{-2} rms for 20 seconds. Person, control and display vibrated.
Sessions per Subject	:	One.

Subjects attended the laboratory for a single session lasting approximately 40 minutes. After completing a consent form, subjects mounted the vibrator and the various exposure conditions were explained. Subjects then read the following instructions:

> "Please sit in a comfortable, upright posture which you can maintain throughout each run. Do not change your posture to try to alter your experience of the vibration.
>
> When the display is turned on and the target is in the centre of the screen, try to keep the aircraft symbol stationary inside the target. Do not let the aircraft symbol move outside the target.
>
> When the display is turned on and there is no target, try to keep the aircraft symbol stationary in the centre of the display.
>
> When the display is turned off, hold the control as if you were keeping the aircraft symbol stationary."

The exposures were presented in two blocks (arm support and no arm support) of 9 runs each (3 tasks with 3 vibration conditions). The order of presentation of each condition was randomised within each block using a Latin square procedure. Four subjects used the arm support on the first block and the remaining four subjects used it on the second block. The arm support was adjusted for each subject such that the arm was comfortably supported, but ensuring that the position of the hand on the control did not change from the condition without the arm rest.

Vibration exposures were controlled on-line from a PDP 11/34 digital computer. The time-histories were digital-to-analogue (D-to-A) converted at a rate of 200 samples per second using a 10-bit D-to-A convertor. Signals from the control were anti-aliase filtered at 12.5 Hz and acquired to the digital computer at 51.2 samples per second. Fourier transforms were calculated using a Fast Fourier Transform (FFT) algorithm from the DATS 11 software package.

3.0 Results

Friedman analyses of variance by ranks tests showed significant overall effects of the frequency of activity at the control in all conditions ($p<0.01$). Wilcoxon matched pairs signed ranks tests were then used to test for effects of the type of task (A, B or C) and the vibration frequency (0, 0.5 or 4.0 Hz) at each frequency of control activity. Because of the large number of tests performed, results are only reported as being 'significant' when they occur consistently either over a range of frequencies or in different conditions at the same frequency.

The moduli of the Fourier transforms of activity in the fore-and-aft axis of the control with task A during vibration exposure at 0.5 and 4.0 Hz are shown on Figure 9.4. This figure shows the median data without the arm support. Apart from vibration-correlated activity (ie., vibration breakthrough) at 4.0 Hz and its harmonics at 8.0 and 12.0 Hz, activity at the control was almost entirely confined to frequencies below 2 Hz.

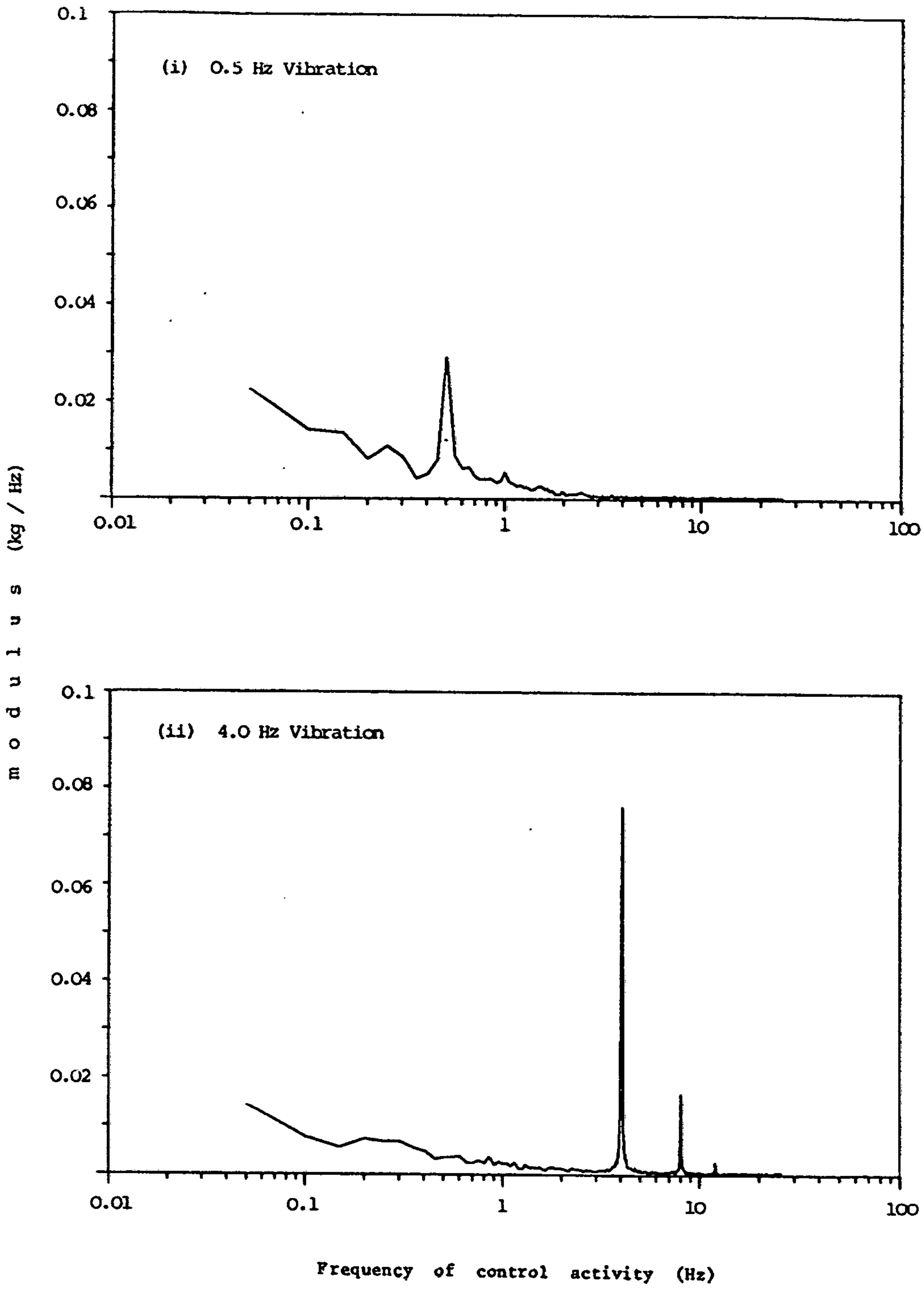


Figure 9.4 Median Moduli of the Fourier transforms in the fore-and-aft control axis. Task A No arm support

(i) 0.5 Hz vibration,
(ii) 4.0 Hz vibration. N = 8

Without the arm support, significantly more breakthrough occurred at 4.0 Hz than at 0.5 Hz for all three tasks in both axes of the control ($p < 0.01$). With the arm support however, the differences were significant only in the fore-and-aft axis of the control ($p < 0.02$).

Figures 9.5 to 9.8 show the median and inter-quartile range for the moduli of the Fourier transforms in each arm support condition and in each axis of the control. These figures show control activity at frequencies up to 2.0 Hz, and illustrate the consistency of the data obtained in each condition.

Detailed analysis of the results will be presented in 2 sections: the first section compares the results for the 3 tasks within each vibration condition, and the second section considers the effect of vibration frequency within each task.

3.1 The Effect of Task Within Vibration Frequency

Without Vibration

Figure 9.9 shows the median moduli of the Fourier transforms for the 3 tasks without vibration exposure (ie., with 0 Hz vibration). Most of the activity is confined to frequencies below 1.0 Hz. The data are similar in both axes of the control without the arm support: activity was significantly reduced at 0.1 Hz with task C compared with tasks A and B ($p < 0.01$). This indicates that the presence of the target in task C enabled subjects to detect directional biases in the forces applied on

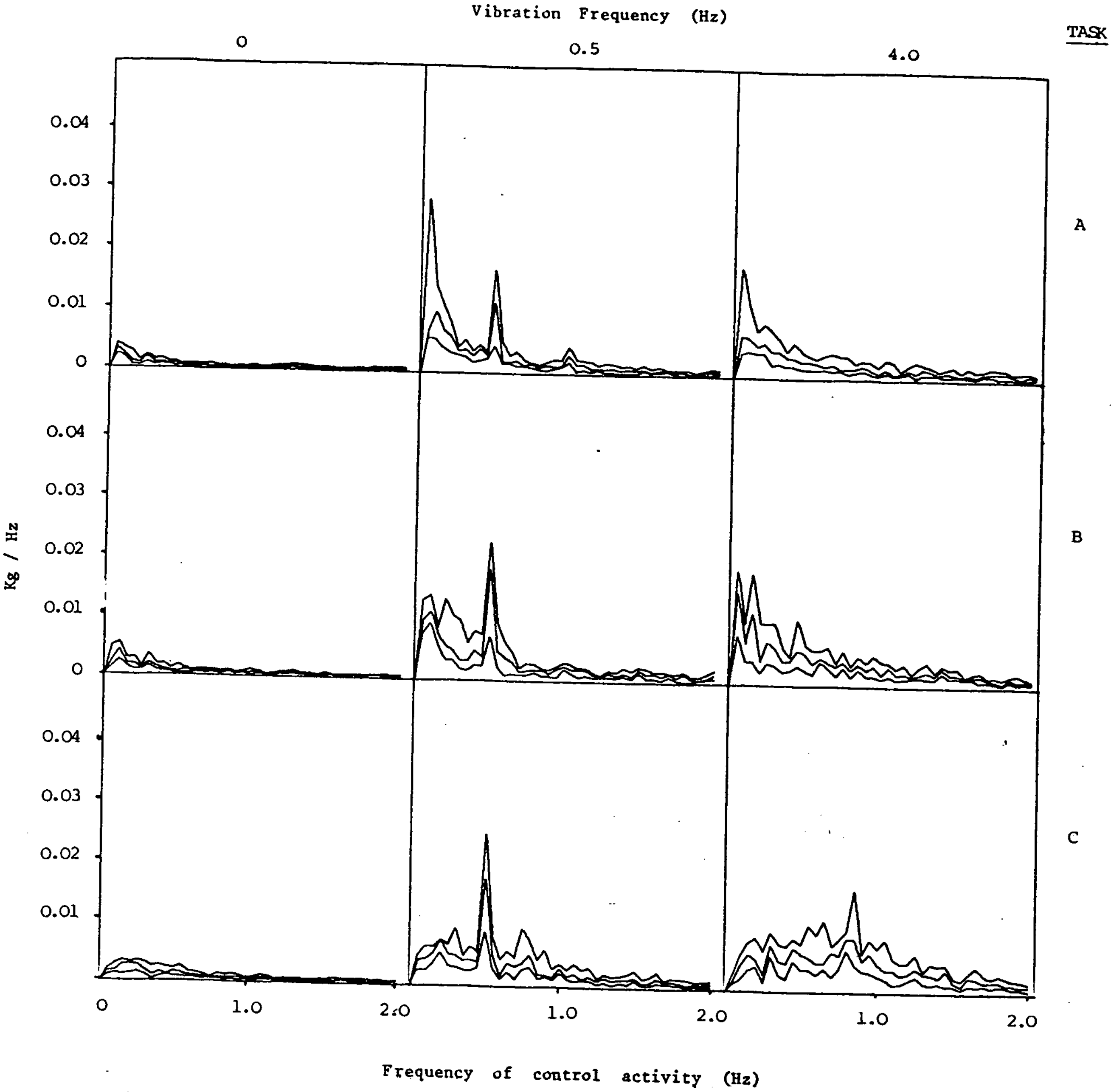


Figure 9.5 Moduli of the Fourier transforms of activity in the side-to-side control axis within task and vibration frequency conditions. Median and inter-quartile ranges over 8 subjects. No arm support.

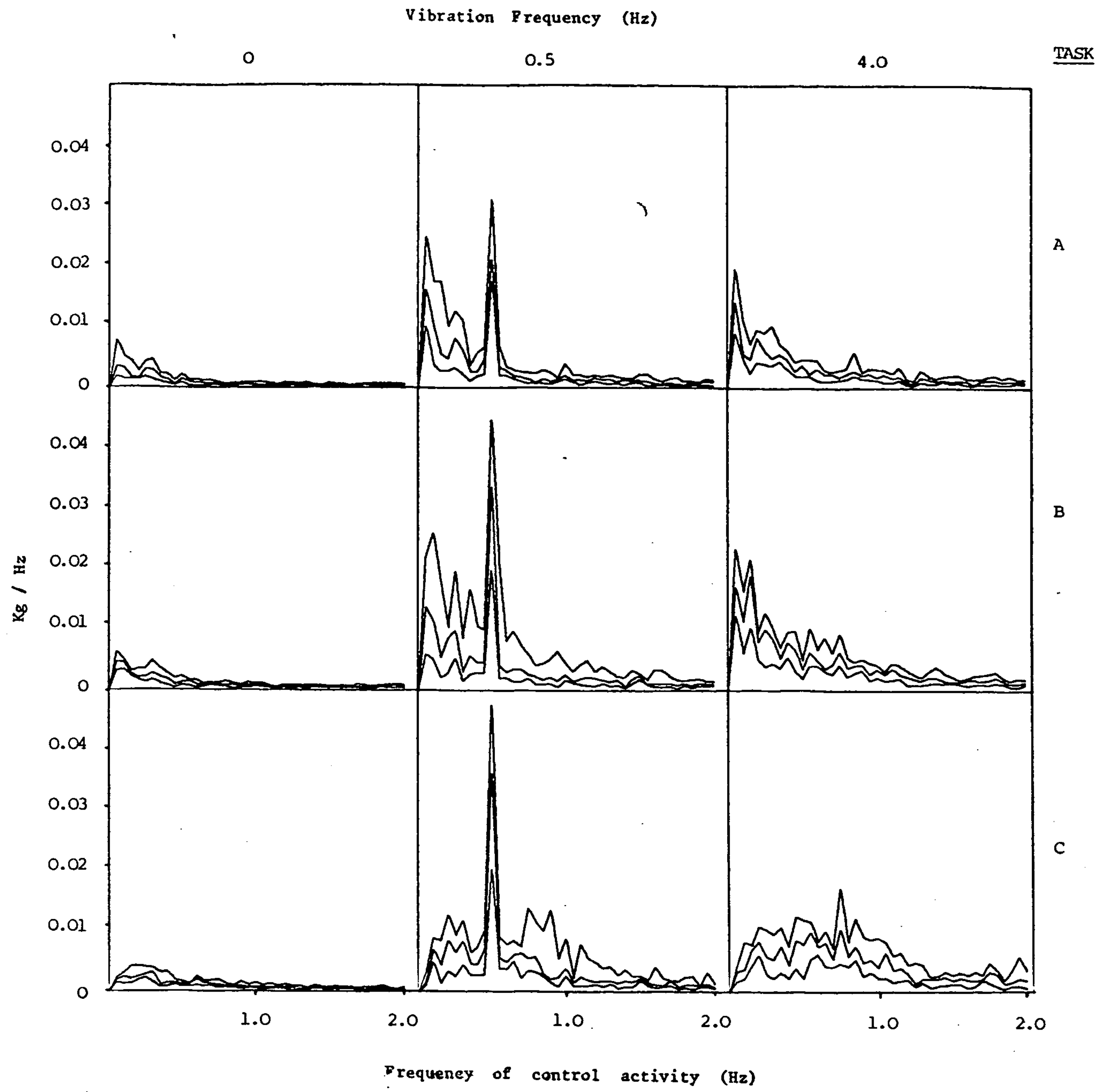


Figure 9.6 Fourier transforms of activity in the fore-and-aft control axis within task and vibration frequency conditions. Median and inter-quartile ranges over 8 subjects. No arm support.

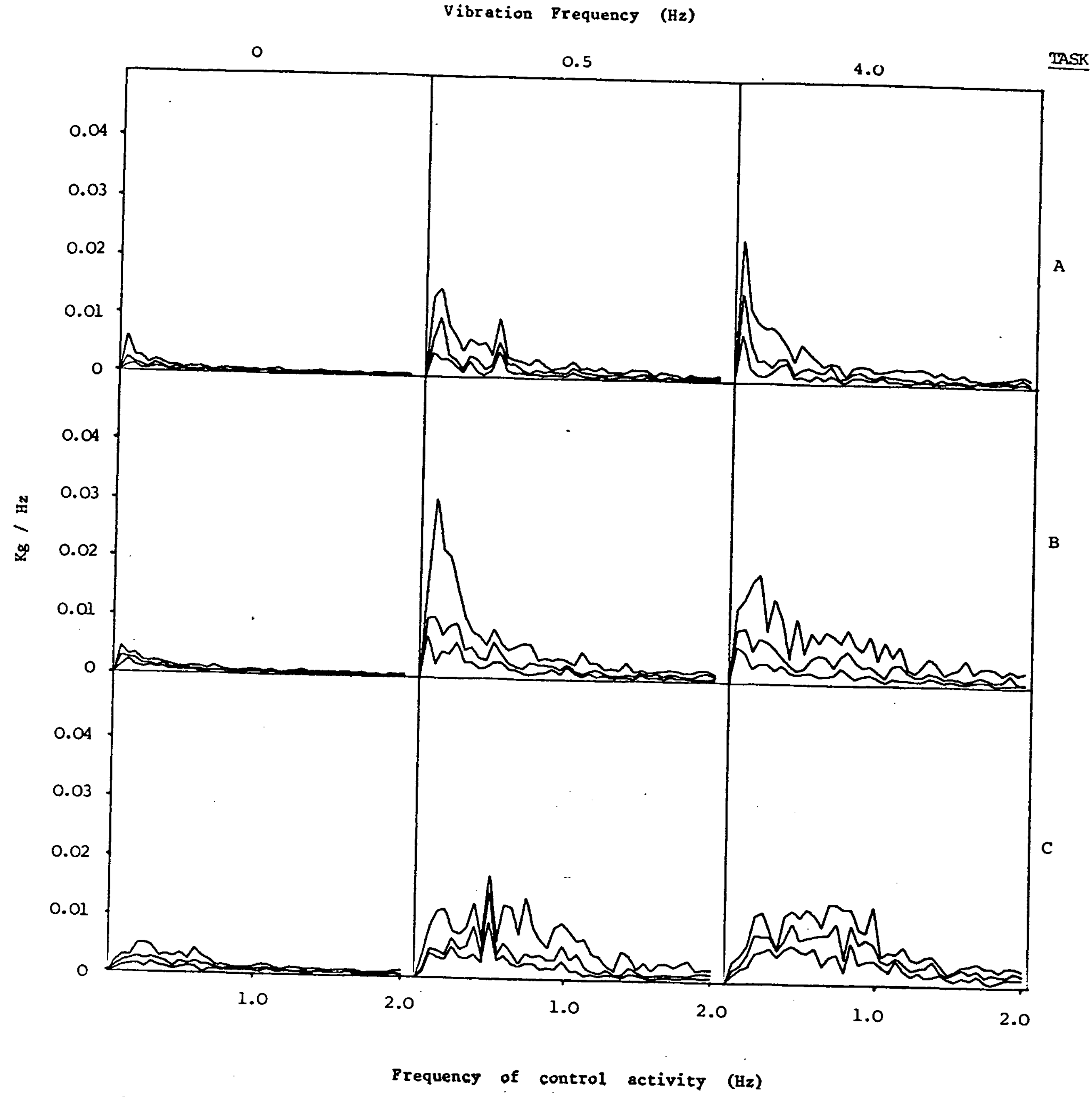


Figure 9.7 Fourier transforms of activity in the side-to-side control axis within task and vibration frequency conditions. Medians and inter-quartile ranges over 8 subjects. Arm support.

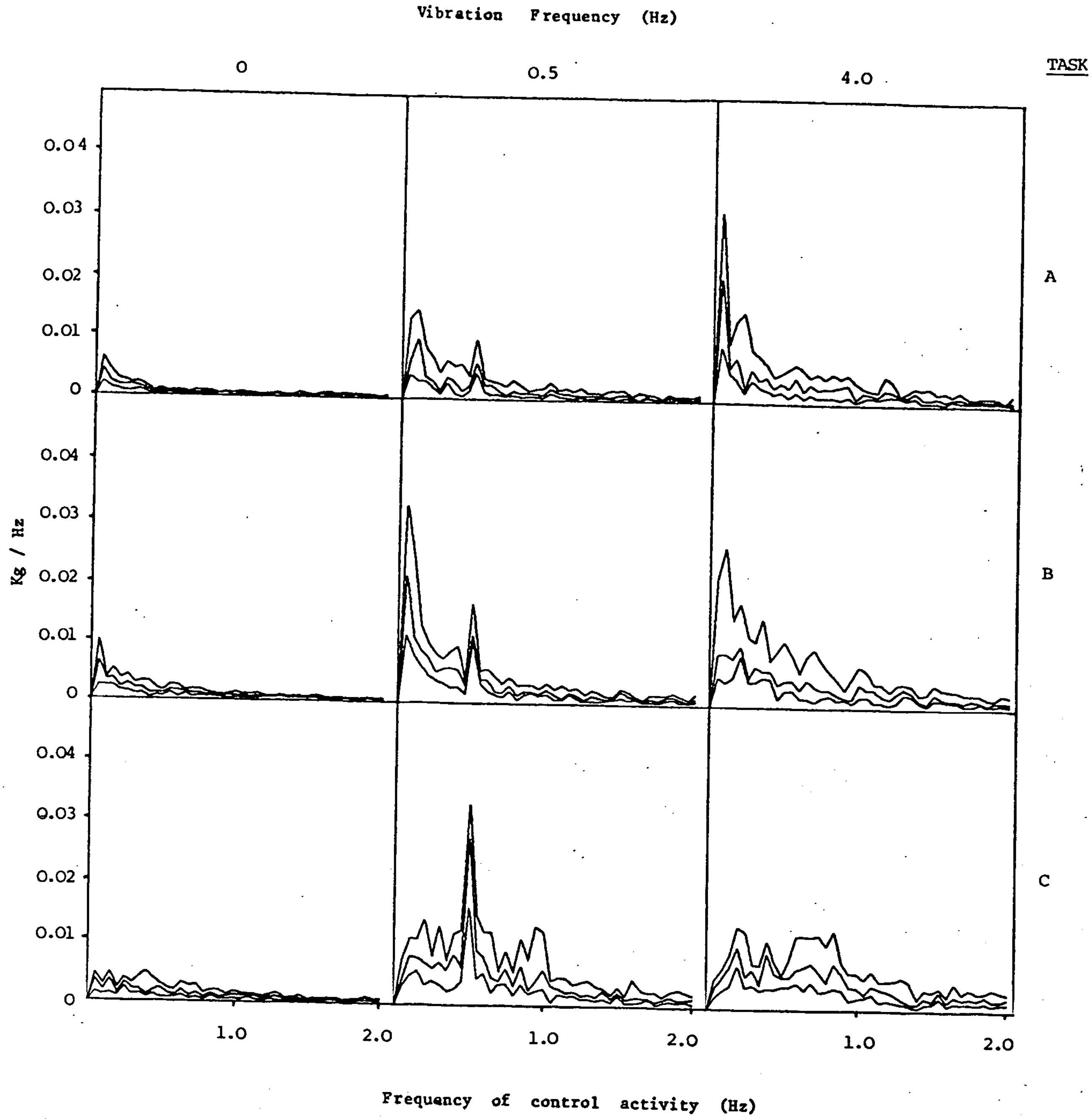


Figure 9.8 Fourier transforms of activity in the fore-and-aft control axis within task and vibration conditions. Medians and inter-quartile ranges for 8 subjects. Arm support.

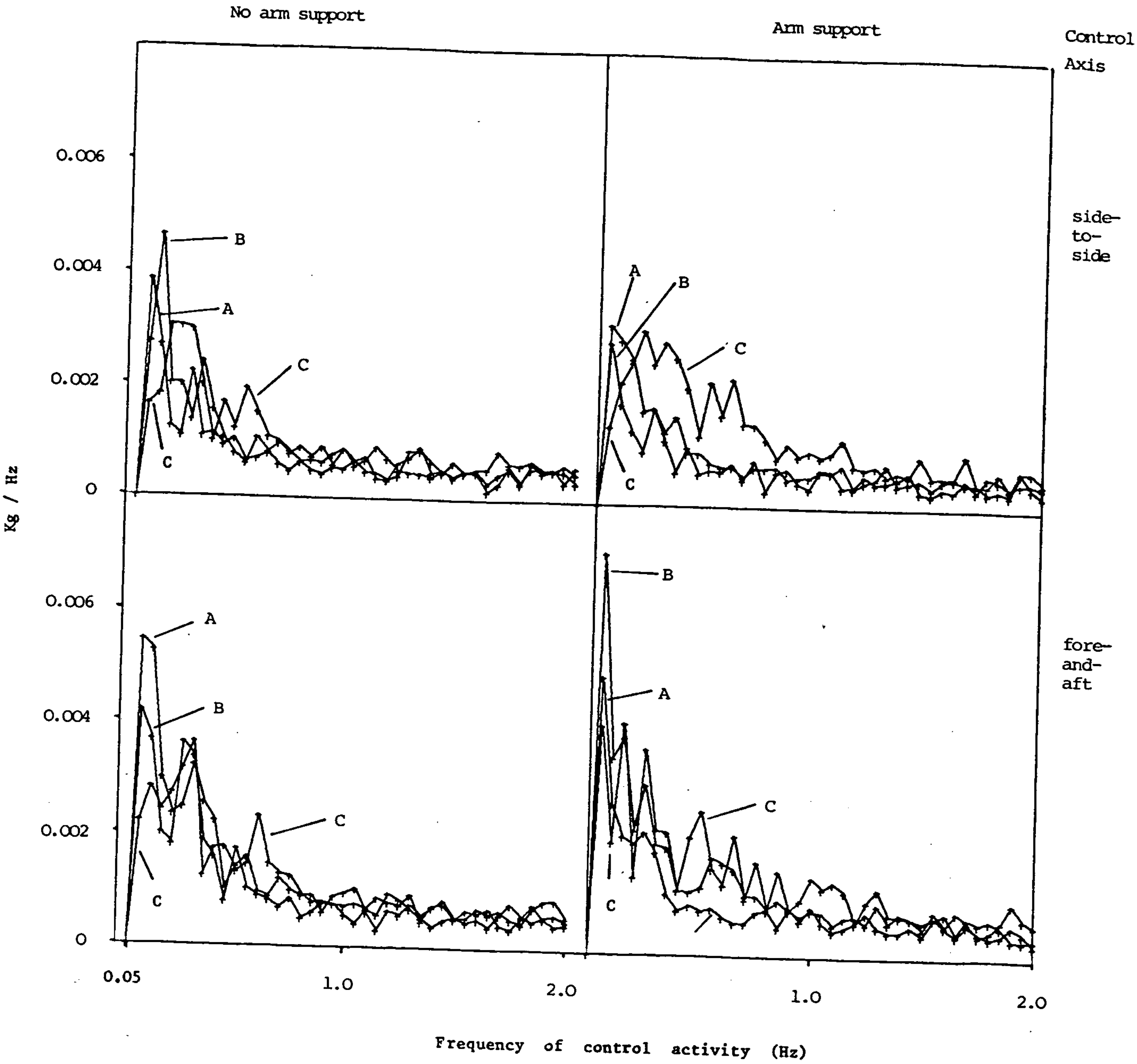


Figure 9.9 Median Fourier transforms of control activity with tasks A, B and C for both arm support conditions and within each control axis. 0 Hz vibration. N = 8.

the control. (Because the time-histories were normalised to remove DC offsets, this effect does not appear at 0.05 Hz).

With the arm support, the data also show less activity at 0.1 Hz with task C than with tasks A or B. The dominant feature however is the increased activity in the side-to-side control axis from about 0.2 to about 1.0 Hz with task C compared with tasks A and B. This increase was significant at 0.2, 0.25, 0.3, 0.35, 0.5, 0.55 and 0.6 Hz ($p < 0.01$). Subjects may have found the arm support uncomfortable and moved their hand and arm to reduce this discomfort. The effect of these movements of the arm on the output of the system (ie., at the controlled element on the display) may only have been apparent to the subjects in task C, and could have led to an increase in intentional control activity to try to compensate for the induced movement. There were no consistently significant effects of the arm support however.

<u>With 0.5 Hz Vibration</u>

Figure 9.10 compares the data for the 3 tasks during exposure to 0.5 Hz vibration. The overall level of activity was greater than without vibration (note the different scales on Figures 9.9 and 9.10). Figure 9.10 again shows the reduction in activity with task C at 0.1 Hz compared with tasks A and B.

Although Figure 9.10 indicates that the arm support reduced the magnitude of 0.5 Hz breakthrough with all 3 tasks, the reduction only reached statistical significance with task B ($p < 0.05$). These data suggest that the arm support generally reduced the magnitude of breakthrough during exposure to vibration at 0.5 Hz. There were no other significant differences between the two arm support conditions. In all cases, the greatest magnitude of breakthrough occurred with task C, suggesting an interaction between the type of task and the transmission of vibration to the

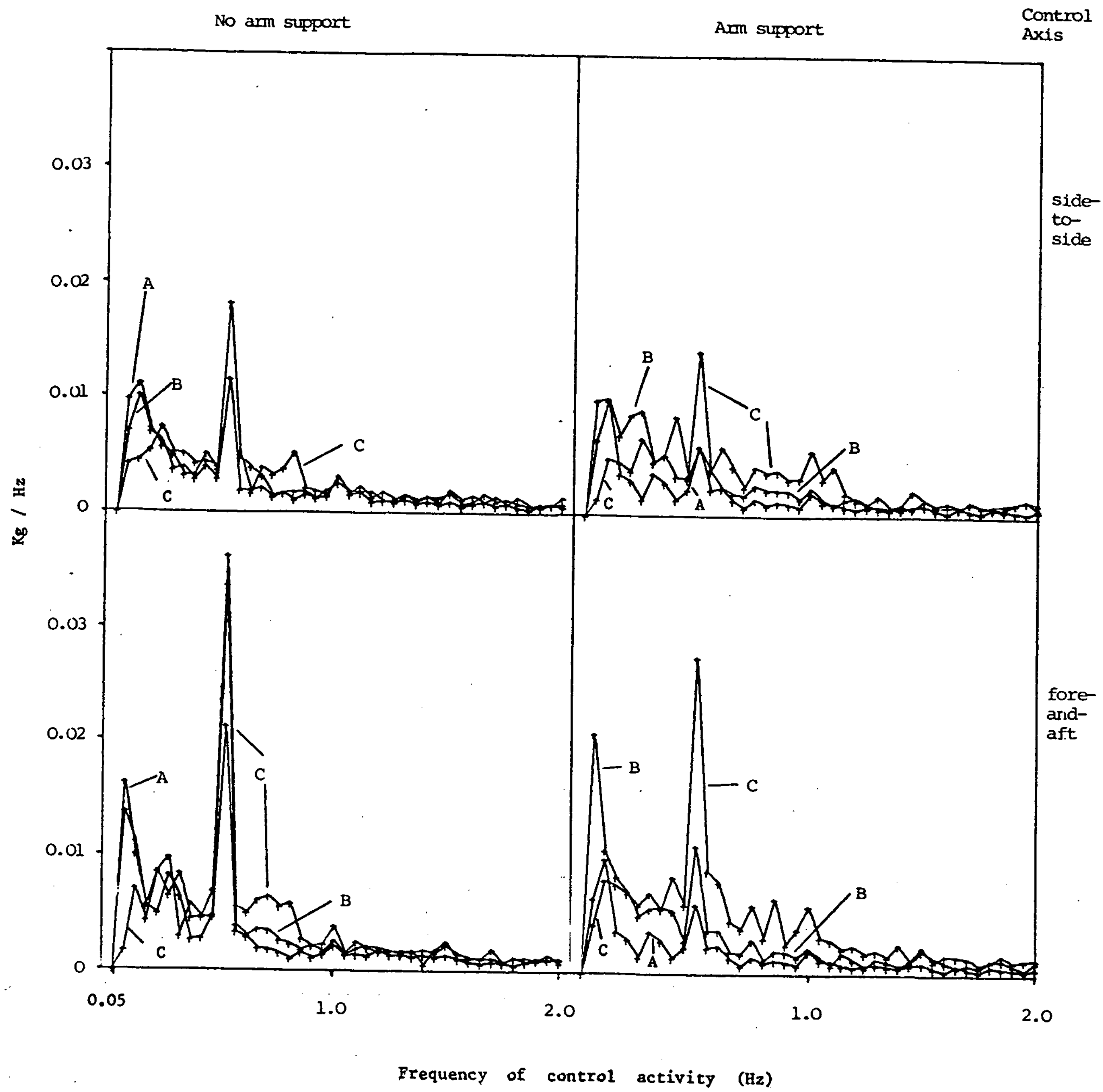


Figure 9.10 Median Fourier transforms of control activity with tasks A, B and C for both arm support conditions and within each control axis. 0.5 Hz vibration, N = 8.

control.

With 4.0 Hz Vibration

Results obtained during 4.0 Hz vibration exposure are shown on Figure 9.11. The results of the Wilcoxon tests comparing control activity at frequencies up to 1.0 Hz are shown on Table 9.2. These results again demonstrate the significant reduction in activity at 0.1 Hz with task C compared with tasks A and B. They also show significantly more activity with task C compared with task A from about 0.5 to about 1.0 Hz. Task B also shows more activity at these frequencies compared with task A, although this only reached statistical significance at frequencies from 0.6 to 0.85 Hz in the side-to-side control axis with the arm support.

There were no significant differences in the magnitude of 4.0 Hz vibration breakthrough with the 3 tasks, and the arm support significantly reduced the magnitude of breakthrough in all conditions. There were no other differences between the two arm support conditions.

3.2 The Effect of Vibration Frequency Within Tasks

Figure 9.12 compares control activity with task A at each vibration frequency. Both 0.5 and 4.0 Hz vibration significantly increased activity at nearly all frequencies below 1 Hz in both axes of the control and both with and without the arm support compared to the condition without vibration ($p<0.02$). The only significant differences between the 0.5 and 4.0 Hz vibration conditions were due to vibration breakthrough.

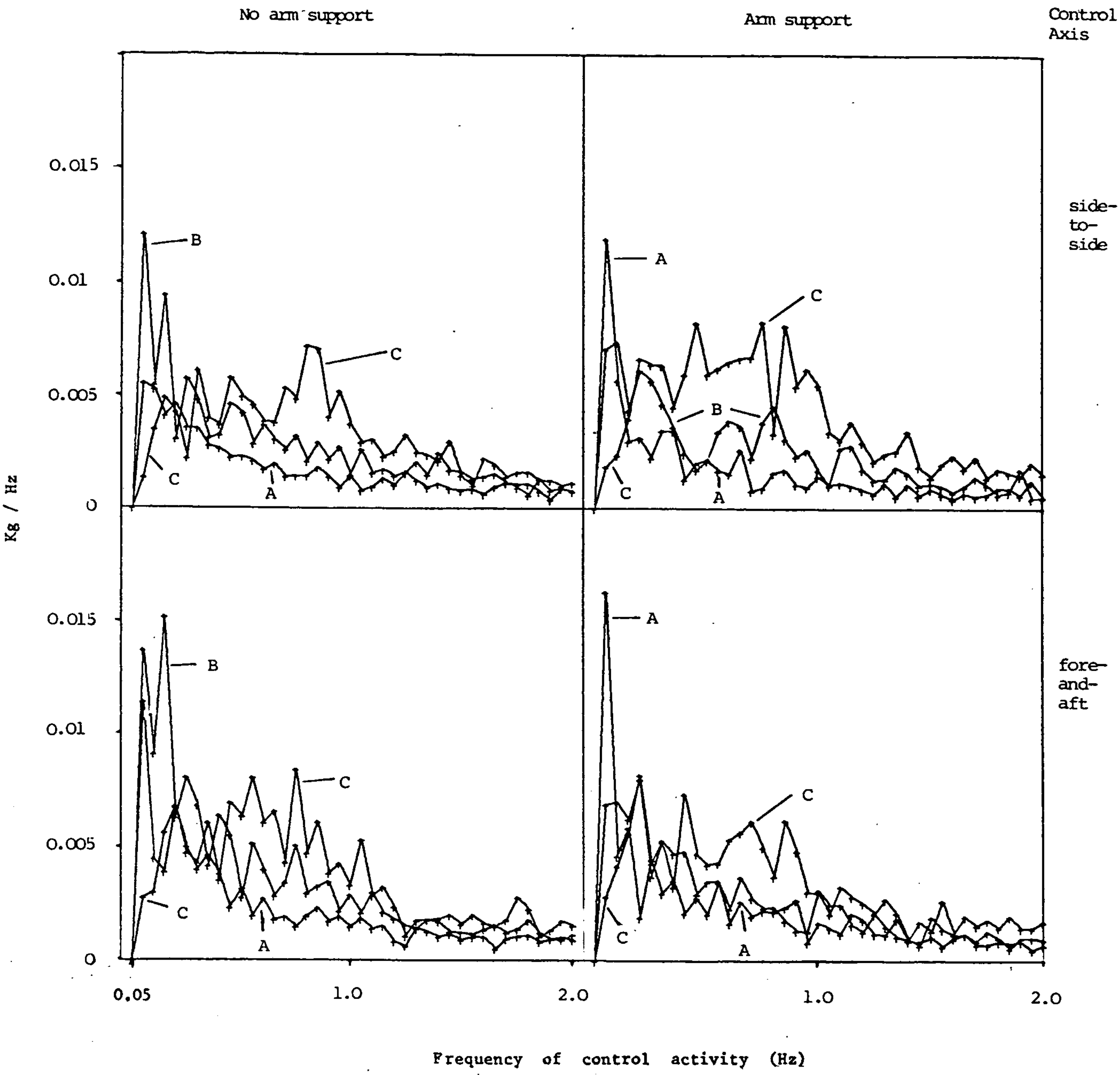


Figure 9.11 Median Fourier transforms of control activity with tasks A, B and C for both arm support conditions and within each control axis. 4.0 Hz vibration, N = 8.

Table 9.2 Results of Wilcoxon tests for differences between the three tasks at each frequency of control activity during 4.0 Hz vibration

1. No Arm Support

Frequency of Control Activity (Hz)

Control Axis	Comparison of tasks	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1.0
side-to-side	A Vs B	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	A Vs C	**	NS	NS	NS	NS	NS	NS	NS	***	NS	*	NS	*	***	**	***	***	*	***	NS
	B Vs C	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	*	**	NS	NS
fore-and-aft	A Vs B	NS	NS	***	***	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS	***	NS	NS
	A Vs C	***	NS	NS	NS	NS	NS	NS	NS	*	*	***	*	**	**	***	**	**	**	*	*
	B Vs C	***	*	***	NS	NS	NS	NS	**	NS	*	NS	*	NS	NS	NS	NS	NS	NS	*	NS

Table 9.2 (continued)

2. Arm Support

Frequency of Control activity (Hz)

Control axis		0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1.0
side-to-side	A Vs B	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS	*	*	NS	**	***	*	NS	NS	NS
	A Vs C	***	NS	NS	*	NS	NS	NS	***	**	**	***	***	*	***	NS	***	**	***	**	**
	A Vs C	***	*	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS	NS	***	*	NS	*
fore-and-aft	A Vs B	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
	A Vs C	***	NS	NS	NS	NS	NS	NS	***	NS	NS	NS	**	*	**	*	NS	*	NS	*	NS
	B Vs C	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	***	NS	NS

(2-tailed tests)

* = $p < 0.05$

** = $p < 0.02$

*** = $p < 0.01$

NS = Not significant

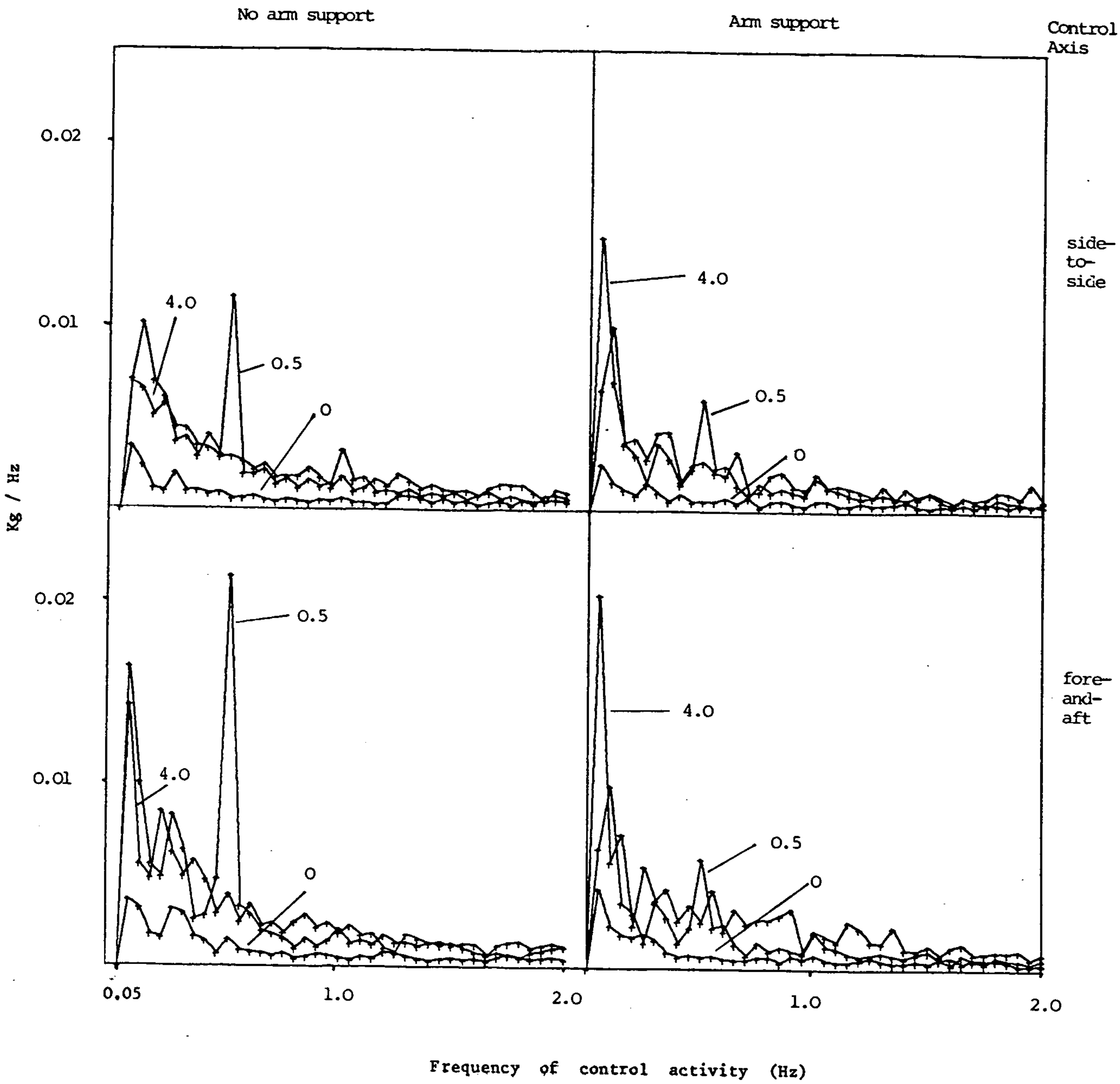


Figure 9.12 Median Fourier transforms of control activity at each vibration frequency for both arm support conditions and within control axis. Task A. N = 8.

Results for tasks B and C are shown on Figures 9.13 and 9.14 respectively. An identical pattern of results occurred for task B as for task A. The same general effects also occurred for task C, although with this task, there was a tendency for more activity to occur at frequencies from about 0.4 to 1.0 Hz in the side-to-side axis of the control during vibration at 4.0 Hz than at 0.5 Hz (with the exception of vibration breakthrough at 0.5 Hz). These differences did not reach statistical significance however.

There were no significant differences between the two arm support conditions, apart from those due to vibration breakthrough.

4.0 Discussion

The discussion of the results will refer to the simple models presented in the introduction to this chapter (Figures 9.1 and 9.3). The likelihood of each of the indicated sources of control activity being responsible for the increased activity observed during vibration exposure will be considered separately for each of the tasks.

Task A

In task A, subjects attempted to hold the control without applying any directional forces. The small amount of activity which occurred was confined mainly to frequencies below about

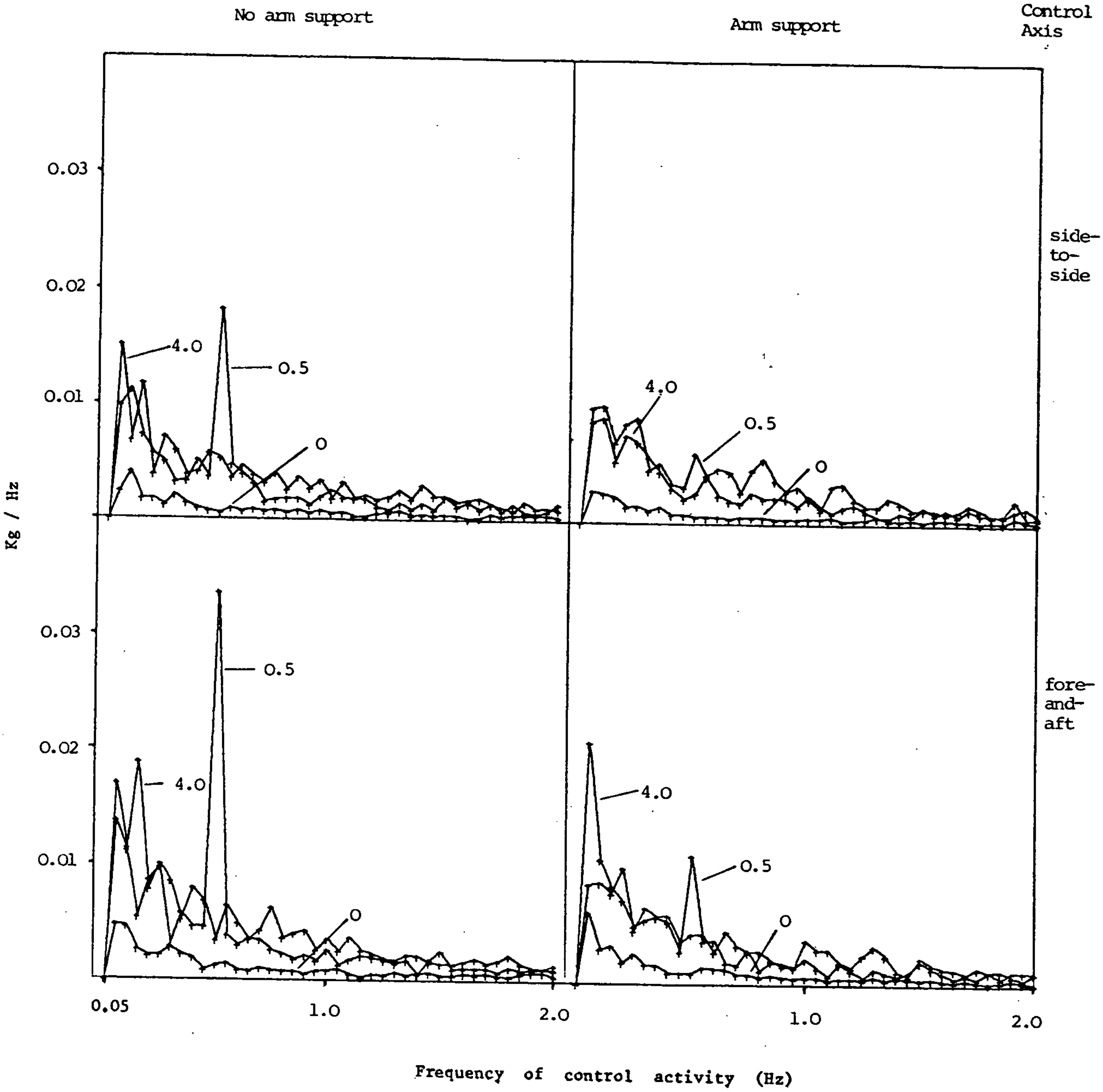


Figure 9.13 Median Fourier transforms of control activity at each vibration frequency for both arm support conditions and within control axis. Task B. N = 8.

(NB. different scale from Figure 9.12).

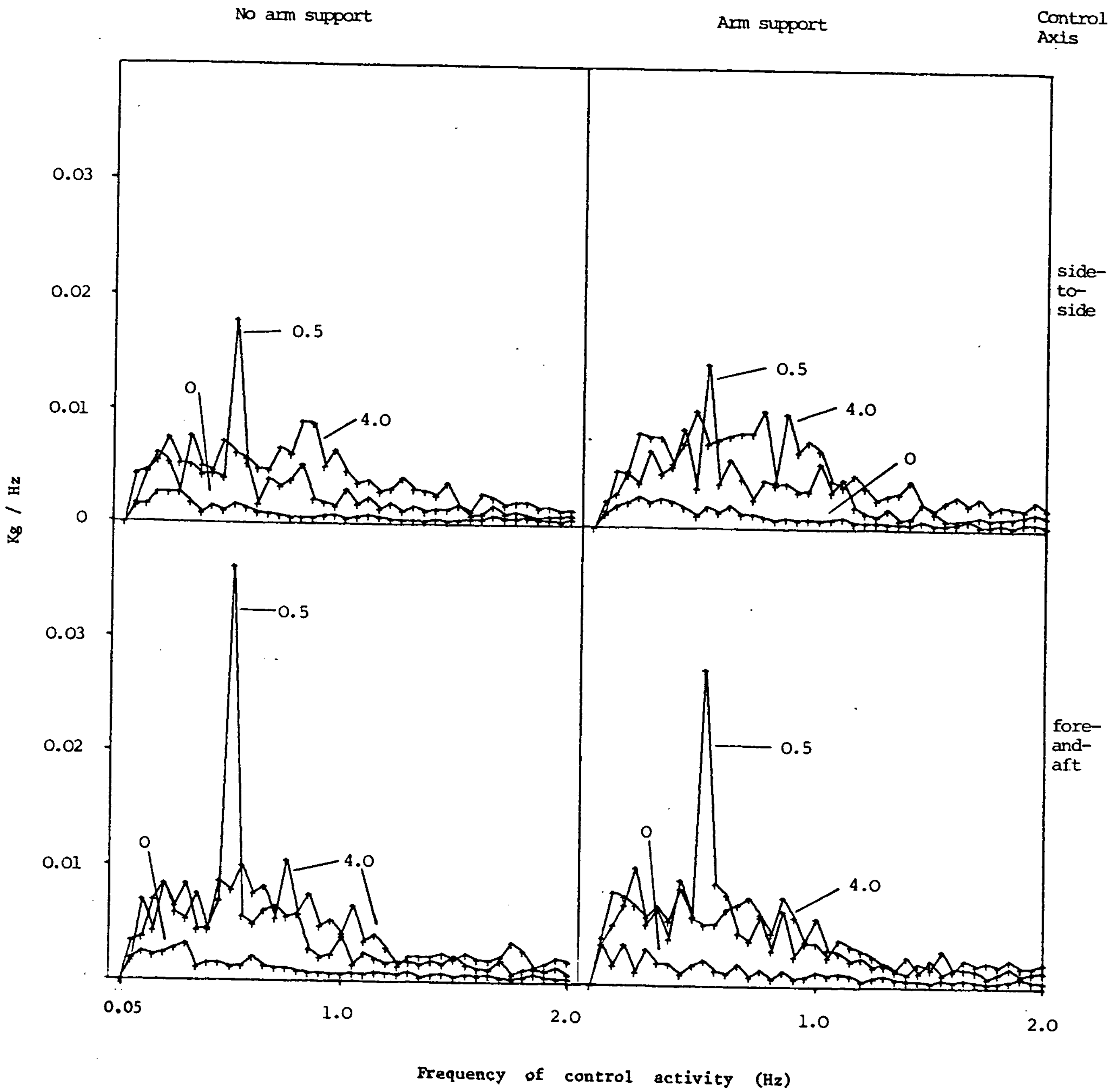


Figure 9.14 Median Fourier transforms of control activity at each vibration frequency for both arm support conditions and within control axis. Task C. N = 8.

(NB. different scale from Figure 9.12)

0.5 Hz (Figure 9.12). This can be attributed to unintentional activity ('noise') arising from both central and neuro-muscular sources (C_n and M_n on Figure 9.1).

During vibration exposure, vibration-correlated activity (breakthrough) occurred at both 0.5 and 4.0 Hz. There were increases in the magnitude of activity at all control frequencies up to about 1.0 Hz during vibration exposure compared to the activity without vibration. Similar increases in magnitude occurred with both vibration frequencies. While vibration breakthrough accounts for control activity at the vibration frequency, it does not explain the general increase in activity at control frequencies up to about 1.0 Hz.

Referring to Figure 9.1b, control activity in response to perceived motion of the body (C_V) could be expected to show a frequency dependence, probably occurring mainly up to about 0.5 to 1.0 Hz. Furthermore, such activity would be expected to be more effective in compensating for movement of the body during vibration at 0.5 Hz than at 4.0 Hz. The lack of a difference in the results with 0.5 and 4.0 Hz vibration suggests that the general increase in control activity during vibration exposure was not due to C_V.

With task A therefore, the general increase in control activity during vibration exposure seems likely to have arisen from central or neuro-muscular noise sources (C_n and M_n on Figure 9.1). Increased neuro-muscular noise may arise either from direct stimulation of muscles by vibration, or by increases in muscle tension. There is evidence that vibration at frequencies as low as 2 Hz can directly stimulate mammalian muscle in some conditions (see section 4.3 of the Literature Review in chapter 2). This is thought to arise from stimulation of end organs when muscle is stretched during relative movement between body parts (Gail et al, 1966). It seems reasonable to assume, therefore, that direct muscle stimulation would produce more activity at 4.0 Hz, which is in the region of major body resonances, than at 0.5 Hz, where the body behaves more like a mass. The lack of a difference in the results with vibration at 0.5 and 4.0 Hz therefore suggests that direct muscle stimulation was not the source of the increased activity.

It seems unlikely also whether changes in central 'noise' due to such things as fidgeting or changes in posture and the grip on the control would produce the general increase in activity observed in this study.

The most likely explanation for the general increase in activity with task A, therefore, is an increase in muscular activity arising from a change in muscle tension. During exposure to vibration at both 0.5 and 4.0 Hz, subjects may have either generally tensed their body, or gripped the control more tightly. Either of these would increase the tension of muscles in the controlling limb and, probably, increase the transmission of muscular activity to the control. Changing muscle tension is not necessarily under voluntary control however. It may reflect a reflex response intended to protect the body from damage..

Task B

In task B, subjects were provided with visual feedback, although the target was not displayed. The results were similar to task A both with and without vibration. It was expected that subjects would use the available visual feedback to detect low frequency drifting, and induce intentional activity, C_i, to compensate for it. While there was some indication both of reduced low frequency drifting and increased activity at frequencies from about 0.5 to 1.0 Hz compared with task A, the effects were not consistent and did not reach statistical significance.

The main effect with task B during vibration exposure was the same as with task A: a general increase in the magnitude of control activity at all frequencies up to about 1 Hz. It therefore seems likely that, as with task A, the effects observed with task B could be attributed to a neuro-muscular effect; specifically, to increased muscle tension.

Task C

In task C, subjects attempted to keep the controlled element in the centre of the stationary target at all times. The presence of the target enabled subjects to detect and compensate for small movements of the controlled element: low frequency drifting was therefore reduced, and intentional activity (C_i on Figure 9.3) was induced at frequencies between about 0.2 and 1.0 Hz. These features are seen most clearly during exposure to vibration at 4.0 Hz (Figure 9.14).

During vibration exposure, task C showed a different pattern of results from tasks A and B. As before, the amount of activity increased at all control frequencies up to about 1 Hz. With task C however, the increase was greater in both vibration conditions at control frequencies from about 0.4 to 1.0 Hz compared with tasks A and B (Figure 9.11). Furthermore, with task C there was more activity in the side-to-side control axis at these frequencies during vibration at 4.0 Hz than at 0.5 Hz.

As with tasks A and B, the general increase in activity with task C at control frequencies below about 1.0 Hz during vibration compared to without vibration is probably attributable to increased neuro-muscular noise. However, because subjects could detect small amplitude movements of the controlled element, they introduced more intentional control activity (C_i) than with tasks A or B: C_i appears as the increased control activity at frequencies between about 0.4 and 1.0 Hz.

The larger magnitude of high frequency activity in the side-to-side control axis during vibration at 4.0 Hz than at 0.5 Hz with task C may indicate a greater effect with 4.0 Hz vibration. The difference is not likely to be due to a visual effect for two reasons. First, any visual effect would be expected to be greater in the fore-and-aft axis of the control, corresponding to the vertical axis of the display. Experiment 4 (chapter 8) showed that visual effects were greater in the vertical than in the horizontal display axis. Second, because the display was collimated, visual effects were not expected to be important at 4.0 Hz (chapter 8).

Arm Support

Providing an arm support caused a reduction in the magnitude of vibration breakthrough, particularly during 4.0 Hz vibration. Apart from this effect on breakthrough, the results with the arm support show the same effects as without the support. The same explanation of the mechanisms involved is therefore suggested in both cases.

The effect of the arm support in reducing the magnitude of breakthrough supports the results obtained in experiment one (chapter 5). In the present study, the reduction occurred in both axes of the control. In experiment one however, the reduction was only significant in the side-to-side axis. There is no obvious reason why this difference should occur between these two studies when the same equipment, control gain and subjects were used in each case. The difference may be due to random variability.

5.0 Conclusions

This experiment set out to investigate the extent to which central or neuro-muscular mechanisms might be important in disrupting manual control performance during exposure to whole-body vibration. The study also investigated whether secondary effects, such as changes in the way a task is performed, would be important.

By eliminating other reasonable explanations, increases in control activity during vibration exposure were interpreted as arising principally through neuro-muscular interference: it was concluded that vibration induced random muscle activity, possibly through an increase in muscle tension. Changes in muscle tension could have either a voluntary or an involuntary basis. When subjects performed a task which allowed fine discrimination of movement of the controlled element on the display (task C), they tried to compensate for controlled element activity introduced through neuro-muscular interference by inducing voluntary compensating control activity, principally at frequencies between 0.4 and 1.0 Hz.

The results during exposure to vibration at both 0.5 and 4.0 Hz were interpreted as showing evidence of the same neuro-muscular mechanism. This suggests an effect which does not depend on the frequency of vibration: that is, an 'all-or-none' response to the sensation of motion.

In experiments 2 (chapter 6) and 4 (chapter 8), similar magnitudes of performance disruption occurred at vibration frequencies between 0.5 and about 2.0 Hz. Effects between 2.0 and 10.0 Hz were attributed to visual interference. The results of the present experiment suggest that the disruption at vibration frequencies below 2 Hz may have arisen from neuro-muscular interference. Although the same effect was seen at 4.0 Hz in this study, experiment 4 indicated that performance disruption with sinusoidal vibration at frequencies above 2.5 Hz could be attributed to visual effects alone. This suggests that at low vibration frequencies (below 2 Hz), other, possibly central, effects may become important when a tracking task is performed. Further research is required to determine both the contribution that the effect demonstrated in this experiment makes to performance disruption, and any other mechanism which could become important when more complex tasks are performed.

CHAPTER TEN

EXPERIMENT SIX: THE EFFECT OF EXPOSURE DURATION ON COMPLEX TASK PERFORMANCE

1.0 Introduction

The current International Standard on human response to vibration (ISO 2631, 1985), defines a time-dependent relationship between vibration exposure and performance. Published data provide little support for any single simple relationship however and the recent British Standard (BSI, 1986) does not include a time-dependence for effects on performance.

Guignard et al, (1976) found that exposures which equal the ISO 2631 'fatigue-decreased-proficiency' (FDP) boundary did not impair performance on a variety of tasks for durations up to 8 hours compared with performance for the same duration without vibration. Whether or not effects of vibration on task performance are affected by the exposure duration may depend upon the precise details of the task, including the complexity of the skill involved, the physical effort required and the extent to which subjects are motivated by the task.

Studies by Wilkinson and Gray (1974), Khalil and Ayoub (1979), and Dudek et al (1971) suggested that vibration may be beneficial over extended durations by arousing subjects when motivation is low. (Section 5 of the Literature Review in chapter 2 reviews the experimental investigations of effects of vibration exposure duration on performance).

The effects of vibration on the combined continuous and discrete tracking task observed in previous chapters occurred with exposure durations of less than 3 minutes for each run. The experiment reported in this chapter had two main aims; first, to establish whether performance of the complex task would be time dependent for durations up to 3.5 hours, and second, to investigate whether exposure to whole-body vibration at a magnitude considerably above the ISO 2631 FDP boundary would alter any duration dependence.

Lewis and Griffin (1979) investigated continuous performance of a single-axis, zero-order tracking task for 60 minutes both with and without exposure to 4 Hz sinusoidal vibration. Their subjects had considerable difficulty maintaining arousal and attention to the task for more than about 15 minutes. It was hoped that the more complex nature of the task investigated in this thesis, combined with a performance dependent payment structure, would help subjects to maintain motivation throughout the exposures.

Pre-experimental data collection

To test the suitability of the task, 2 trained subjects performed for 3.5 hours on two separate occasions each: once without vibration and once during exposure to 4 Hz sinusoidal whole-body vibration at a magnitude of 1.1 ms^{-2} rms. Both subjects felt the task to be sufficiently motivating for performance over the extended duration. For both subjects, the data indicated that performance improved on the second session compared with the first, irrespective of whether the vibration occurred on the first or second session. Data obtained by Seidel et al (1980) demonstrated that with visual and acoustic target identification tasks, the effect of 3 hour vibration exposures reduced with repeated exposures. The greatest improvement occurred in the first 100 minutes of each exposure and the improvement continued until the fourth replication.

This experiment also tested the hypothesis that subjects would adapt to performing over the extended duration if the entire exposure was presented on more than one occasion. Subjects performed for the extended duration on 2 occasions. It was expected that any time dependent impairment in performance would be smaller on the second occasion than on the first.

2.0 Method

2.1. Subjects

It was originally intended to use 18 subjects. However, 2 subjects were unavailable and 2 subjects did not complete the experiment. The final sample size was therefore 14. To avoid confounding effects of adaptation and vibration exposure, these 14 subjects were randomly assigned to 2 independent groups of 7 subjects in each. One group were exposed to vibration on all sessions. The other group received no vibration exposure. All subjects had previously taken part in experiment 4, and were therefore highly trained in performing the combined continuous and discrete tracking task with the simplified dynamics.

2.2 Control Gain and Viewing Conditions

The 2 subjects exposed prior to the experiment commented that the control gain (which, for these subjects, was the same as in experiment 4) induced excessive fatigue in the controlling limb. The control gain was therefore slightly increased for the experiment (see Table 10.1). Subjects viewed the display through a collimating lens. Details of the viewing conditions were therefore

Table 10.1 Details of Experiment 6

Independent Variables	:	Duration; vibration exposure; session.
Dependent Variables	:	- p(on) and p(press/on) - rms angular error and its components - closed-loop system transfer function - subjective ratings and comments
Subjects	:	14 right-handed males in 2 independent groups of 7 ('vibration' and 'no vibration').
Tasks	:	- combined continuous and discrete tracking task - memory reaction-time task (before and after exposures)
Duration	:	2 sessions of 202.5 minutes each. Vibration exposures began after 11.25 minutes and ended after 191.25 minutes. Analysed in 18 successive periods of 11.25 minutes each.
Forcing Function	:	Random time-histories low pass filtered at 0.01 and 0.2 Hz with -12 dB/octave thereafter. 18, 11.25 minutes forcing function with similar rms values joined on end (see text for details).
System Dynamics	:	De-coupled pitch and roll axes of aircraft model. First-order.

Table 10.1 (continued)

Control	:	Isometric side-stick. No arm support.
Control Gain	:	2.5 v/kg fore-and-aft = 1.325 ^{o}/s/kg (vertical) 0.51 v/kg side-to-side = 1.5 ^{o}/s/kg (horizontal)
Display	:	Collimated (viewing conditions as in Table 7.1 for 'Lens' group).
Vibrator	:	Derritron VP180LS. Electro-dynamic. z-axis.
Seat	:	Hard, flat simulated helicopter seat with backrest and 5-point harness. 20 mm thick leather cushion.
Vibration Exposure	:	One octave-band random whole-body z-axis vibration centred on 4 Hz. Acceleration magnitude = 1.46 ms^{-2} rms Weighted acceleration magnitude = 1.4 ms^{-2} rms (ISO 2631 FDP boundary: = 0.7 ms^{-2} rms for 2.5 hours, = 0.53 ms^{-2} rms for 4 hours). Crest Factor = 4.13 (Vibration Dose Value (BSI, 1986) = 19.98).
Procedure	:	3 sessions per subject. Session A - 60 minutes (training) Session 1 - 202.5 minutes Session 2 - 202.5 minutes 'Vibration' group received vibration on all 3 sessions. 'No vibration' group received no vibration (see text for other details).

the same as in the 'lens' condition in experiment 4, except that the display remained stationary in the present experiment.

2.3 Forcing Functions

To avoid systematic effects associated with differences in the difficulty of the task, eighteen independent forcing functions, lasting for 11.25 minutes each, were generated. The procedure for generating each forcing function is described in chapter 8, and details are given on Table 10.1. The first and last 2 seconds of each 11.25 minute time history were shaped using a cosine weighting, so that each section started and finished in the centre of the display.

Eighteen different 202.5 minute time-histories were created by joining the 11.25 minute sections on end using a Latin square procedure. Different 202.5 minute forcing functions were used for each subject in each axis of the display within a session, and no subject received the same complete forcing functions on both sessions. In this way it was hoped to balance differences in the difficulty of the task across groups and sessions.

2.4 Vibration and Seating

One-octave-band random, z-axis, whole-body vibration centred on 4 Hz was presented for 180 minutes by means of a Derritron VP180LS electro-dynamic vibrator. Vibration time-histories were generated on a DEC PDP 11/34 digital computer.

The digital acceleration time-history had an rms magnitude of 1.46 ms^{-2} and a crest factor of 4.13. When the time-history was weighted according to the procedures defined in ISO 2631 (1985), the weighted acceleration magnitude was 1.4 ms^{-2} rms. This exposure is twice the recommended ISO 2631 FDP limit for 2.5 hour exposures, and nearly 3 times the FDP limit for 4 hour exposures. Using the procedures defined in the recent British Standard (BSI, 1986), the motion had a Vibration Dose Value of 19.98.

The magnitude of vibration at the seat will be partly dependent on the weight of each subject. The actual vibration experienced may therefore have varied slightly from a weighted magnitude of 1.4 ms^{-2} rms. The seat acceleration was acquired directly to the digital computer for 60 minutes with 2 subjects. (The analogue-to-digital sampling rate was 64 samples per second, with anti-aliase filtering at 16 Hz). For these 2 subjects, the seat acceleration was measured as 1.43 and 1.47 ms^{-2} rms respectively. The magnitude of seat acceleration was continuously displayed on an rms meter during each 202.5 minute run.

Subjects sat on the rigid simulated helicopter seat with a backrest and 5-point harness as used in previous experiments. A thin (20 mm) leather cushion was provided to reduce the discomfort of the seat. This did not alter the transmission of vibration to the subjects. The display and the subjects' feet were not vibrated. In the group not exposed to vibration, the vibrator was switched on to provide a similar level of background acoustic noise to the vibration-exposed group.

2.5 Data Recording and Acquisition

The vibration and task forcing function time-histories were recorded on an FM tape recorder for replay during the experiment.

During recording, the tape speed was 30 inches per second (ips). The digital to analogue (D-to-A) conversion rate was 4096 samples per second (sps) for the vibration time-history, and 409.6 sps for the forcing functions.

During the experiment, the forcing functions and system response (ie., controlled element position in both display axis and the button state) were recorded on the FM tape recorder at a speed of 15/16 ips.

After completion of the experiment, the results for each subject were acquired to the digital computer for analysis. During data acquisition, the tape recorder was replayed at 15 ips. The data were anti-aliase filtered, (except for the button state channel, as in previous studies) at 25 Hz, and then acquired by D-to-A conversion at 102.4 sps. This is equivalent, in real time (ie., at a tape speed of 15/16 ips), to D-to-A conversion at 6.4 sps after anti-aliase filtering at 1.56 Hz. Time delays introduced by the position of the replay heads on the tape recorder were compensated for after the data were acquired.

2.6 Choice Reaction-time task and Questionnaires

In addition to the combined tracking task, two additional measures were taken. Subjects completed questionnaires both before and after each of the 202.5 minute exposures and at least 3 days after completing the final session. These questionnaires investigated:

(i) Subjects feelings of physical and mental well-being before and after each exposure;

(ii) subjective ratings of how their motivation and performance varied during each exposure; and

(iii) subjective ratings of any changes in performance and motivation between the 2 experimental sessions and possible reasons for these changes.

Appendix F provides examples of these questionnaires.

Subjects also performed a mental reaction-time task before and after each exposure. The task presented was based on one devised by Sternberg (1966) and used to investigate effects of vibration on cognitive performance by Shoenberger (1974). Subjects viewed sequences of 2, 4 or 6 letters displayed in a tachistoscope for 1.5 seconds. After a 0.5 second delay a single letter appeared. Subjects were asked to decide as quickly and accurately as possible whether the single letter had appeared in the sequence of 2, 4 or 6 letters presented previously. Twenty four response were made for each sequence of letters. This task is considered to measure both the total time for perceiving and responding to the test letter and the time to mentally process each digit of the sequence. It was hoped that this task would show evidence of mental fatigue by comparing results before and after each session. Training on this task was provided before and after the 60 minute pre-experimental session (see section 2.7).

2.7 Procedure

Subjects attended the laboratory on 3 separate occasions, In the first session, subjects performed the task continuously for 60 minutes, with or without vibration exposure according to their experimental group. This session allowed for any re-training necessary and gave subjects experience of continuous performance over an extended duration.

In the experimental sessions, subjects performed the task for 202.5 minutes with 15 second rests, during which the target was stationary, after 11.25 and 191.25 minutes. In the vibration exposed group, the 180 minutes of vibration exposure began during the first 15 second rest and ended during the second 15 second rest.

The two experimental sessions began at either 0900 or 1300 hours. Subjects performed both sessions at the same time of day, one week apart. In the vibration exposed group, 3 subjects performed in the morning session, and 4 in the afternoon. In the group without vibration, 4 subjects performed in the morning and 3 in the afternoon. Subjects were asked to have a good nights sleep on the evening before each session, to ensure they had breakfast or lunch, as appropriate, and to refrain from taking part in sporting activity on the morning of the experiment. Subjects were encouraged to use the toilet immediately before attending the laboratory.

On arrival at the laboratory, subjects completed a consent form and the pre-exposure questionnaire. After performing the choice reaction-time task, they removed their watches, mounted the vibrator and read the following instructions:

> Your task is to keep the centre of the aircraft symbol (cross) in the centre of the target (circle) at all times, and to keep the button pressed while on target. You will earn 2 points for every instant the aircraft symbol is on target and you will lose 1 point for every instant off target. You earn a further 2 points for every instant the button is pressed while on target and you lose 1 point for every instant the button is pressed while off target. The

amount of money you earn is directly related to the number of points you accumulate.

The scoring remains the same throughout the duration of the run. Please try to perform as well as you can at all times.

The target will stop moving for a short period on two separate occasions. The first will be near the start of the run, and the second will be near the end of the run. You will be told when the run is complete.

Please adopt a comfortable upright posture and try to maintain it throughout the run.

You are free to end the experiment at any time if you should so wish.

Do you have any questions?

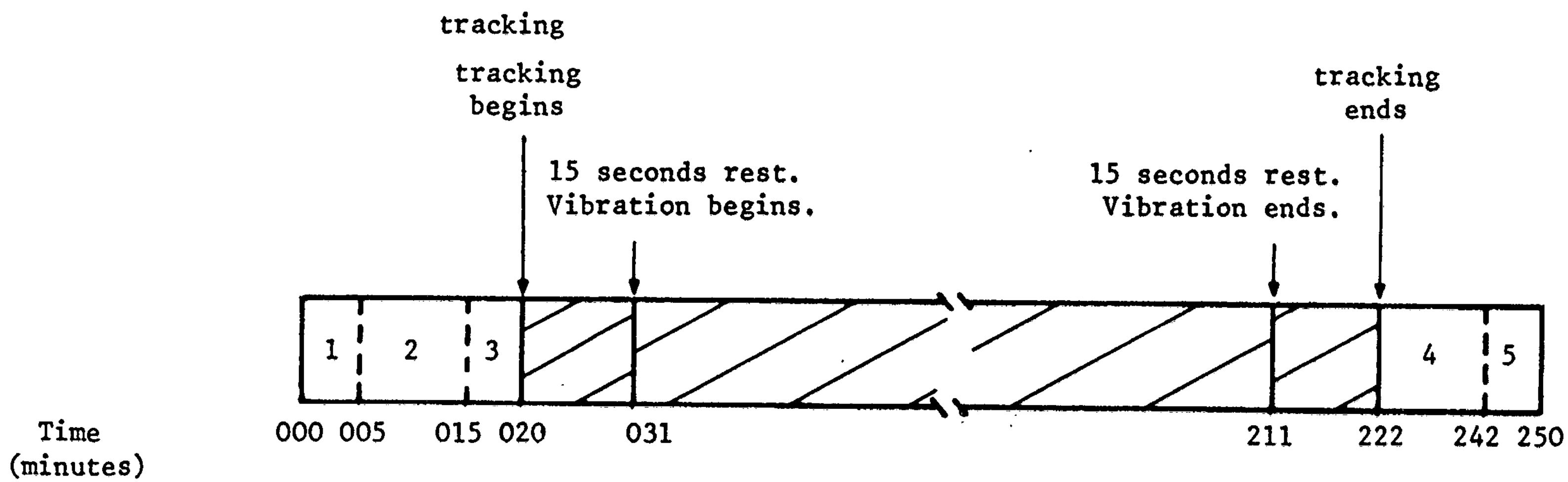
They then performed a 'warm-up' run of about 2 minutes. The 202.5 minute exposures began when the subject felt settled and ready to begin. Exposures were presented in a semi-darkened laboratory. The display was adjusted to give a comfortable brightness for each subject. Table 10.2 illustrates the sequence of events from the time the subject arrived at the laboratory.

The noise level and temperature approximately 10 cms from the subjects' head and in line with the ear was recorded every 10 minutes for one subject during vibration exposure. The noise level varied from 61.3 to 62.5 dB(A). Temperature slowly increased from 25.2 to 25.5°C.

3.0 Results

The results will be presented in 3 sections: the first

Table 10.2 Illustration of procedure from the time the subject entered the laboratory.



2. Choice reaction-time task.

4. Choice reaction-time task.

1. Subject completes consent form and Questionnaire A.

3. Subject mounts vibrator and performs 2 minute 'warm up' run.

5. Subject completes Questionnaires A and B.

section considers the performance data and the second section considers the information from the questionnaire. Results from the choice reaction-time task are considered in the third section.

3.1 Performance Data

The total duration was divided into successive 11.25 minute periods for analysis. These coincided with the periods of the 18 forcing functions.

The main objective of this study was to investigate whether vibration exposure would alter any time-dependent changes in performance; ie., whether there would be an interaction between vibration exposure and duration. The experiment used independent groups of subjects who performed either with or without vibration exposure. The statistical analysis therefore used split-plot Analyses of variance. In the terminology adopted by Kirk (1968), the experimental design can be designated SPF - p.qr, with p representing the vibration condition, q representing the duration and r being the session (p is a between-block treatment and q and r are both within-block treatments). For the probability and rms error data, the Analyses of variance were carried out on the percentage change in performance in successive 11.25 minute periods compared with the first 11.25 minute period. These analyses were performed using the GENSTAT statistical software package.

3.1.1 Probability Data

Figure 10.1 shows the probability of being on target - p(on) - as a function of duration for the individual subjects. This figure shows the results on both sessions for the 2 vibration groups. In most cases these data show a consistent and relatively smooth decline in performance over the course of each run. Nearly all subjects show an improvement in period 18, which they knew to be approaching the end. Figure 10.2 shows the medians of these data. This figure shows a clear improvement in p(on) on session 2 compared with session one for both groups of subjects. In the group without vibration, this improvement appears after period 6 (after 67.5 minutes).

Figure 10.3 shows the percentage change in p(on) at each time period compared with period one for the individual subjects. The median percentage change data are shown on Figure 10.4. The Analysis of Variance summary table for these data is shown on Table 10.3. There were significant effects of both session ($F_{1,396}$ = 164.104, $p<0.01$) and duration ($F_{16,396} \doteqdot 15.57$, $p<0.01$). Both of these main effects can be seen on Figure 10.4. There was no significant main effect of vibration exposure and there were no significant interactions.

It was demonstrated in experiment 2 (chapter 4) that the probabilities of pressing the button while on target - p(hit)- and while off target - p(FA) - were dependent on p(on). In this experiment, these two measures again reflected the effects of session and duration seen with p(on). Figure 10.5 shows the median probability of pressing the button as a proportion of p(on) - p (press/on). The Analysis of variance on these data again showed significant effects of both session ($F_{1,396}$ = 58.28, $p<0.01$) and duration $F_{16,396}$ = 5.42, $p<0.01$). There was also a significant interaction between vibration condition and session ($F_{1,396}$ = 43.34, $p<0.01$).

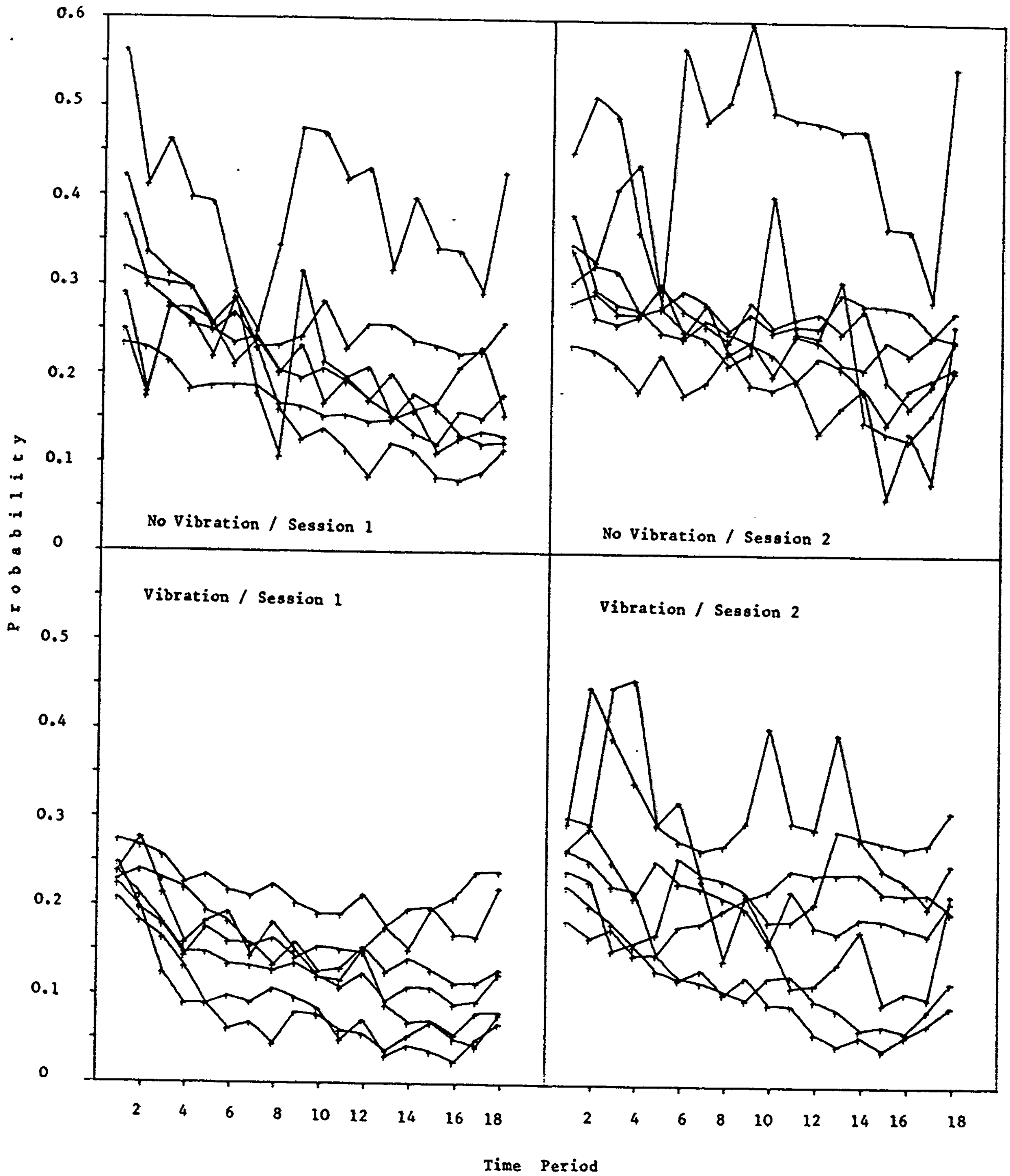


Figure 10.1 The probability of being on target - p(on) - as a function of time for 2 groups of 7 subjects (with or without vibration exposure) on 2 sessions.

(Each time period = 11.25 minutes, period 1 = pre-vibration, period 18 = post-vibration)

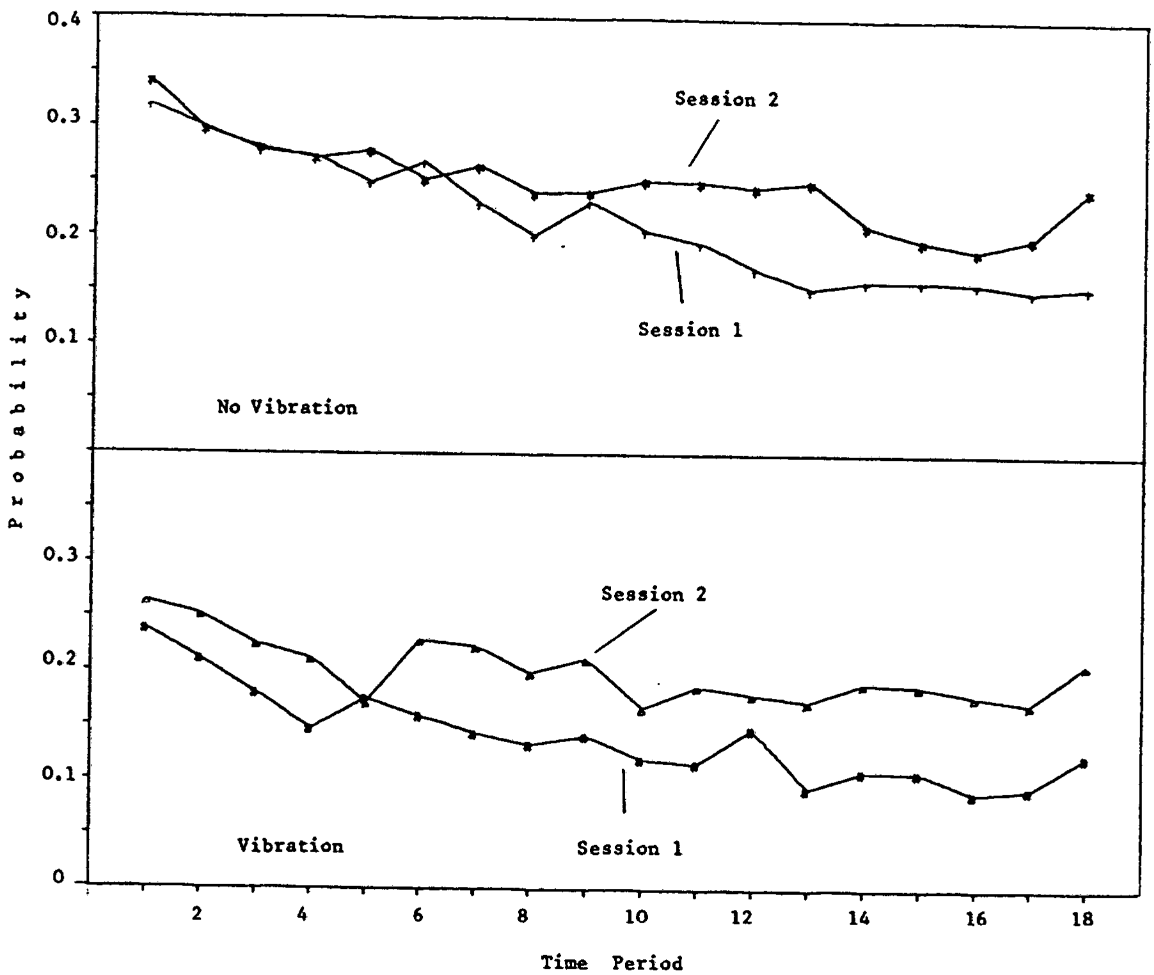


Figure 10.2 Median probability of being on target - p(on) - as a function of time on 2 sessions with or without vibration exposure (N = 7).

(Each time period = 11.25 minutes, Period 1 = pre-vibration, Period 18 = post-vibration)

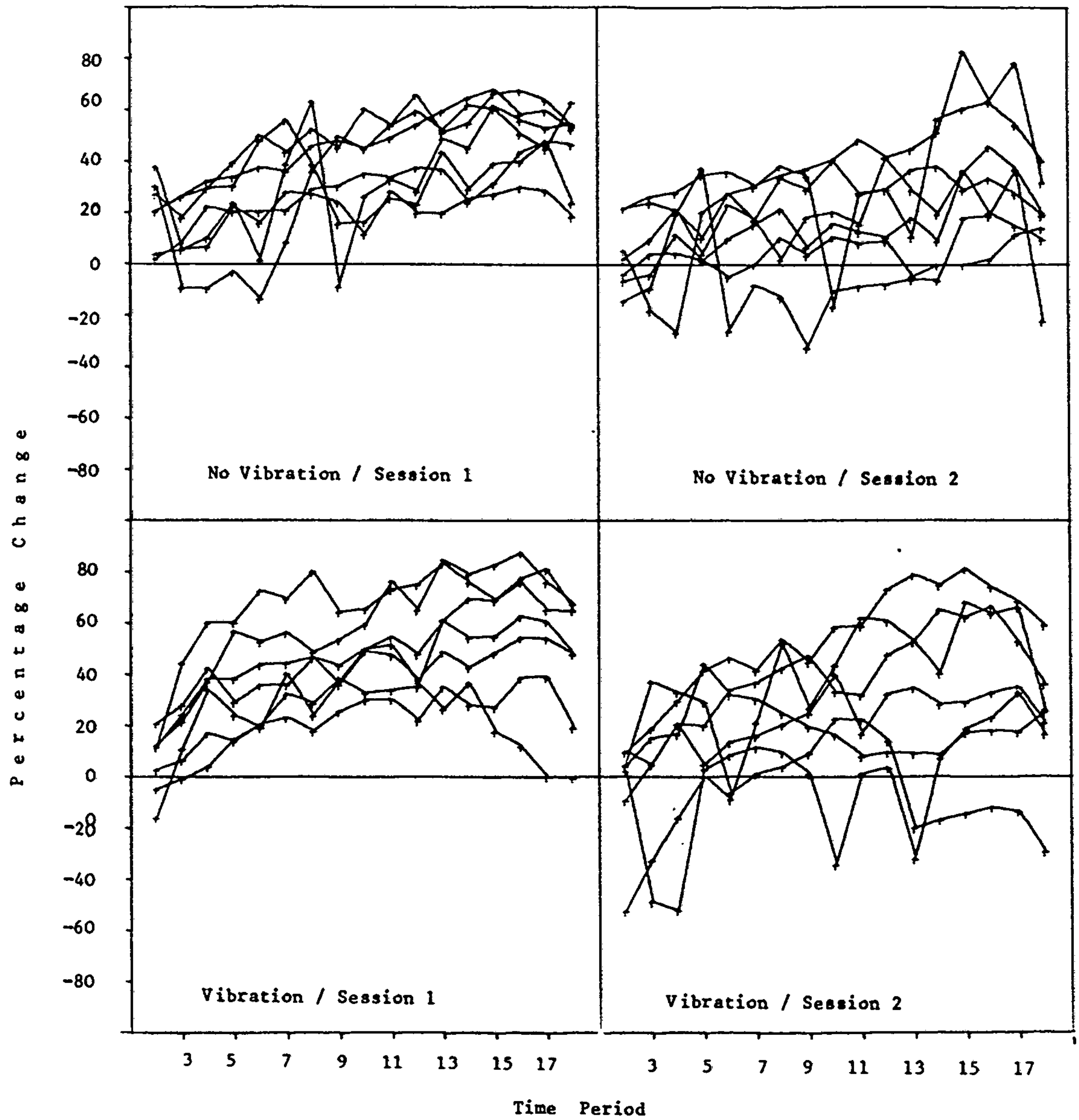


Figure 10.3 Percentage change in p(on) as a function of time for 2 groups of 7 subjects (with or without vibration) compared with period 1 on 2 sessions.

(Each time period = 11.25 minutes. Period 18 = post-vibration)

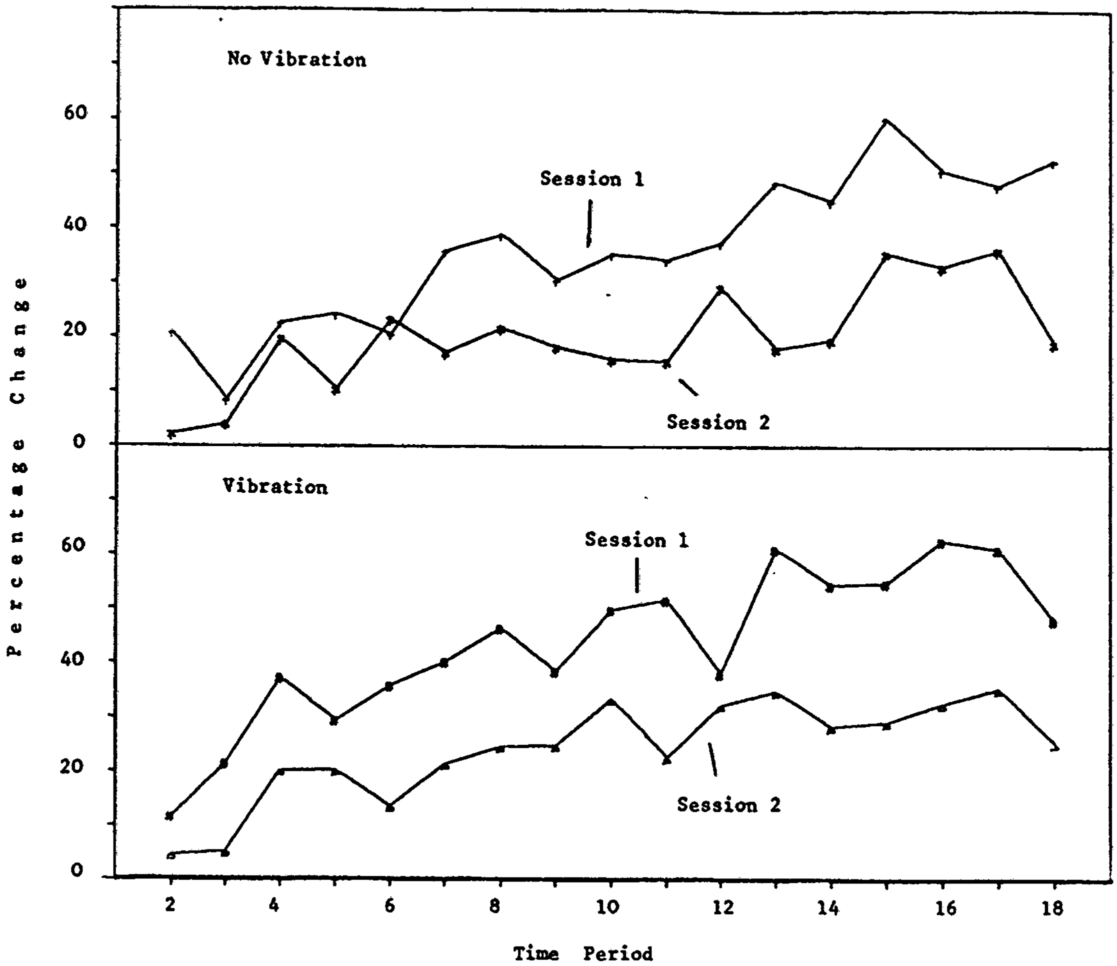


Figure 10.4 Median percentage change in the probability of being 'on' target - p(on) - as a function of time on 2 sessions with or without vibration exposure compared with time period 1 (N = 7).

(Each time period = 11.25 minutes.
Period 18 = post-vibration)

Table 10.3 Analysis of Variance Summary table for the Percentage Change in the probability of being on target - p(on)

Source	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	p <
Between Subjects					
Groups (vibration)	1	4297.2	4297.8	0.558	
Residual	12	92469.2	7705.8		
Total	13	96766.4	7443.6		
Within Subjects					
Session	1	38207.2	38207.2	164.104	0.01
Duration	16	58745.4	3671.6	15.77	0.01
Group x Session	1	274.0	274.0	1.177	
Group x Time	16	3770.9	235.7	1.012	
Session x Time	16	2642.4	165.2	0.709	
Group x Session x Time	16	1726.7	107.9	0.464	
Residual	396	92198.2	232.8		
Total	462	197564.6	427.6		
Grand Total	475	294330.9			

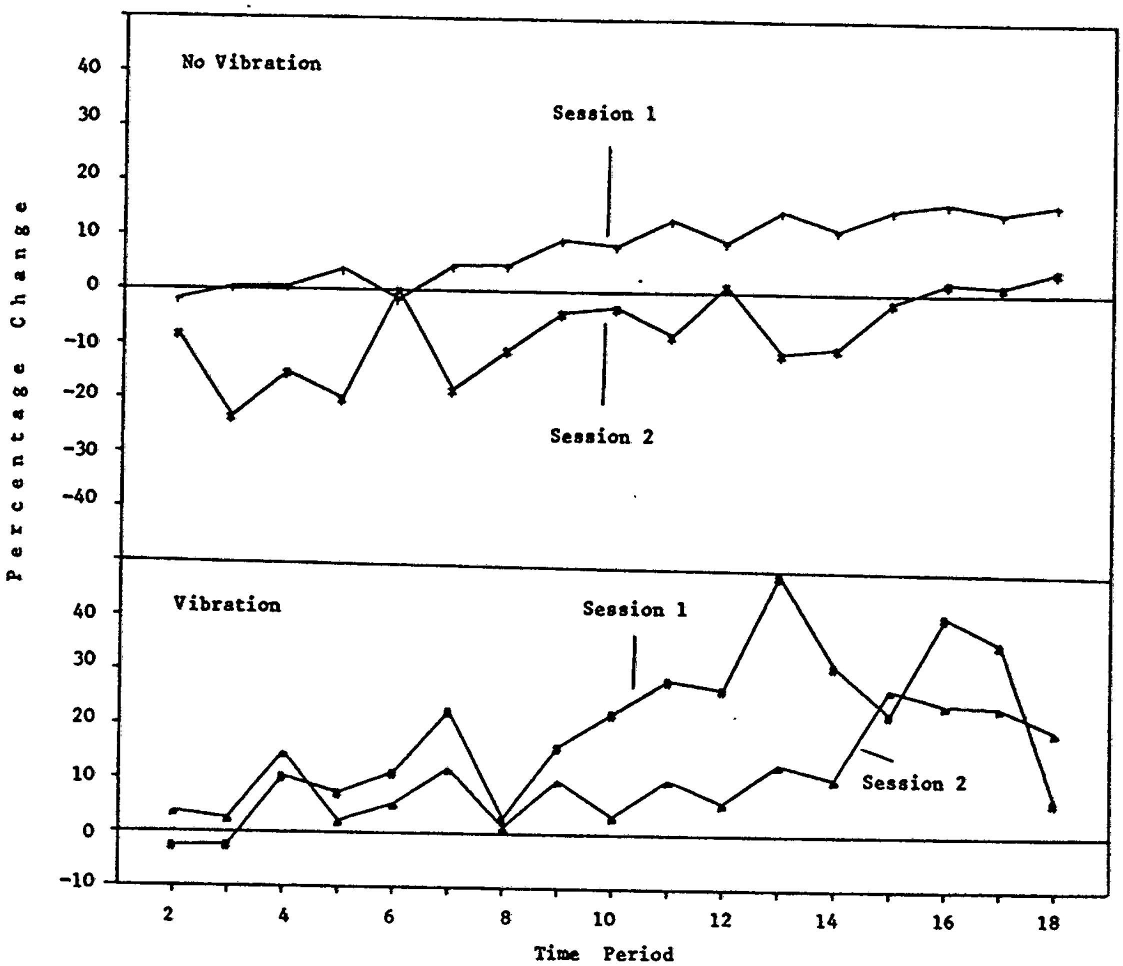


Figure 10.5 Median percentage change in the probability of pressing the button as a proportion of the probability of being on target - p(press/on) - as a function of time on 2 sessions with or without vibration exposure compared with time period 1 (N = 7).

(Each time period = 11.25 minutes.
Period 18 = post-vibration).

(i) No vibration
(ii) Vibration

For the group not exposed to vibration, the negative percentage change in p(press/on) up to period 15 on session 2 is attributable to a reduction in button pressing activity in the first period compared with the next 14 periods, and with period one from session one. This occurred for 6 of the 7 subjects in this group and for 1 subject in the vibration-exposed group. On this session, these subjects may have felt that the task did not properly begin until after the target stopped for the first time. The lack of a similar effect in the vibration group is probably attributable to the different subject populations rather than to any effect of vibration: indeed, vibration would seem more likely to arouse subjects in the second and successive periods and therefore to produce precisely the effect observed with the group who did not receive vibration,

Although Figure 10.5 suggests an interaction between session and duration for the vibration-exposed group - with an effect of session occurring mainly between about periods 8 (90 minutes) and 15 (168.75 minutes) - this did not approach significance.

3.1.2 RMS Error

It was shown in chapter 8 that vibration-correlated activity of the controlled element on the display (ie., vibration breakthrough) was not an important mechanism of disruption by vibration with vibration frequencies above 0.5 Hz at an acceleration magnitude of 2.1 ms^{-2} rms. In the present study, the vibration was band-limited at 2.8 Hz and was presented at a magnitude of about 1.46 ms^{-2} rms. It can therefore be assumed that vibration breakthrough to the display was not important in this study.

Total root-mean-square (rms) tracking error and its components (input-correlated error and remnant) in the vertical display axis are shown as a function of duration on Figures 10.6 and 10.7 for the two groups of subjects. These figures show the data for the individual subjects. In most cases results were nearly identical in the horizontal display axis. (The spectral estimates used in calculating these data, and the transfer function data in section 3.1.3, had a resolution of 0.025 Hz and 65 degrees of freedom).

Figures 10.8 and 10.9 show the median rms error data in each axis of the display. These figures reflect the trends for the individual subjects: input-correlated error accounts for the greatest proportion of total error at the start of each session. Changes in total error with time are accompanied by changes in both input-correlated error and remnant, although remnant generally shows greater increases.

Statistical analysis showed main effects of session and duration for all 3 measures ($p < 0.01$ in all cases). There was no significant effect of vibration, and there were no significant interactions.

3.1.3 Transfer Functions

Closed-loop system transfer functions between the movement of the target and the response of the system were calculated to determine the nature of changes in linear behaviour indicated by the input-correlated error results. Figures 10.10 to 10.14 show median transfer functions in the vertical display axis without vibration

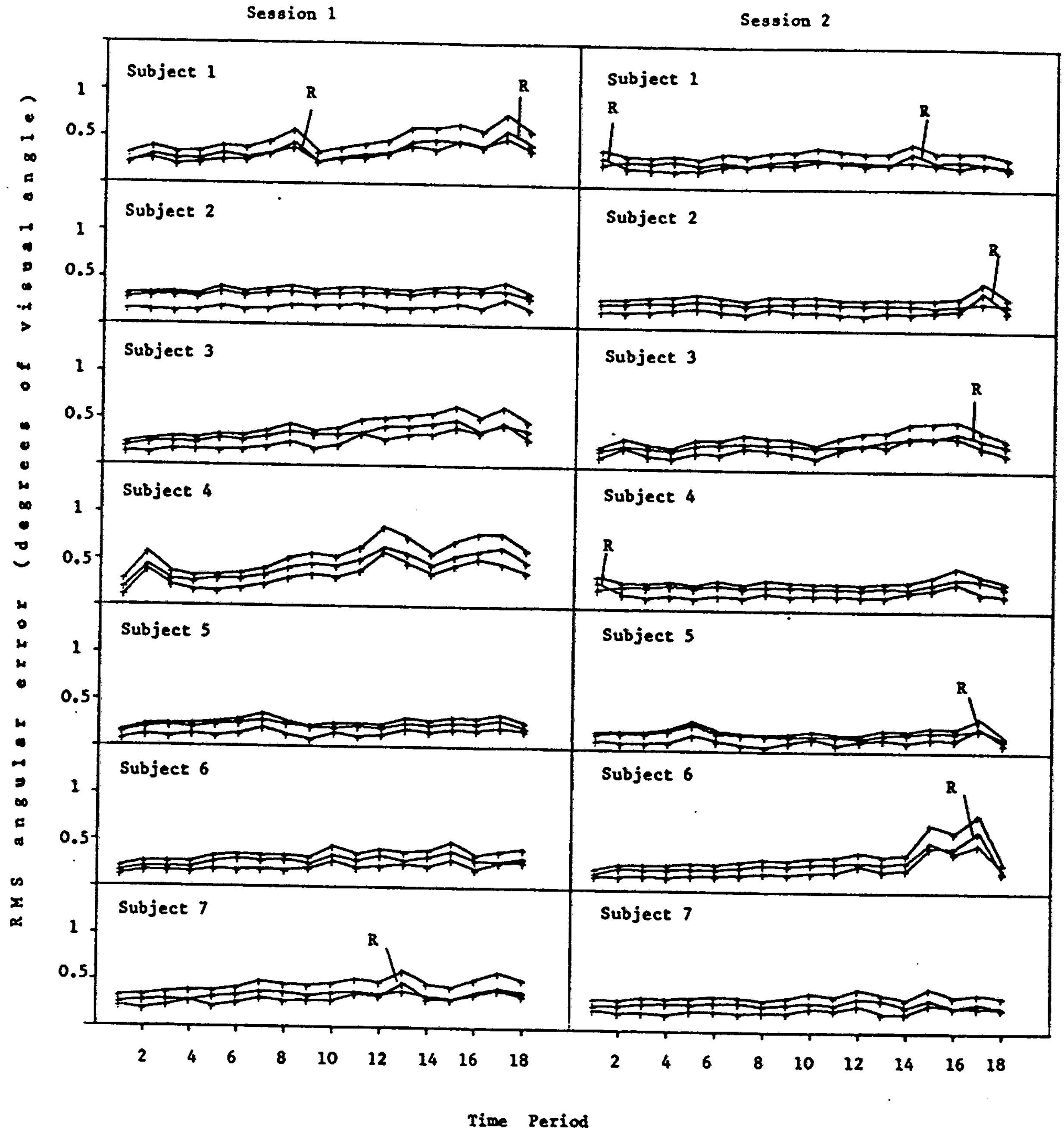


Figure 10.6 RMS angular error and its components (remnant and input-correlated error) in the vertical display axis as a function of time for 7 subjects on 2 sessions without vibration. (Remnant is at the bottom in all cases except where indicated by R. Each time period = 11.25 minutes. S1 = subject 1, etc).

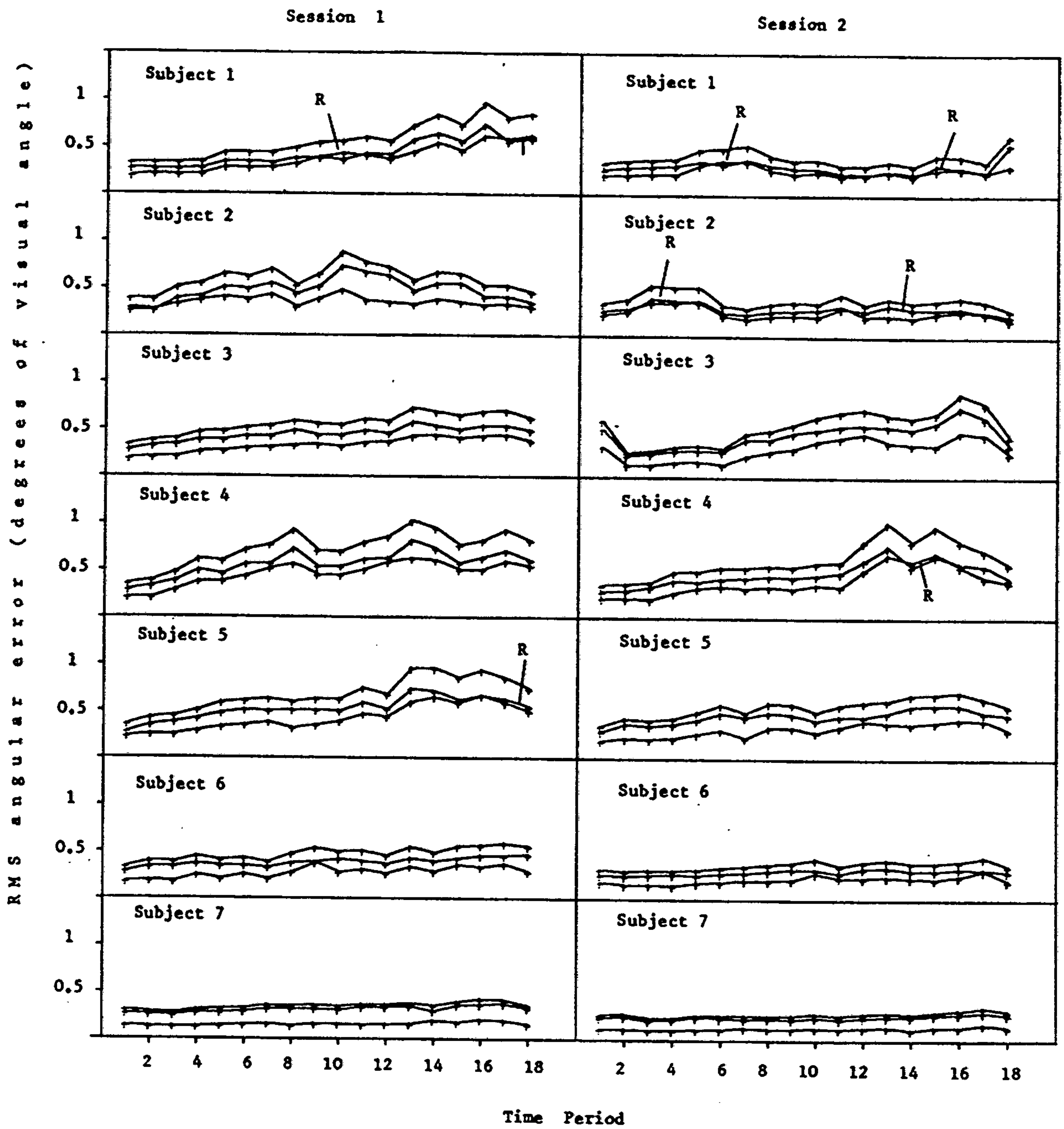


Figure 10.7 RMS angular error and its components (remnant and input-correlated error) in the vertical display axis as a function of time for 7 subjects on 2 sessions during vibration exposure. (Remnant is at the bottom in all cases except where indicated by R. Each time period = 11.25 minutes. Period 1 = pre-vibration, Period 18 = post-vibration. S1 = subject 1, etc).

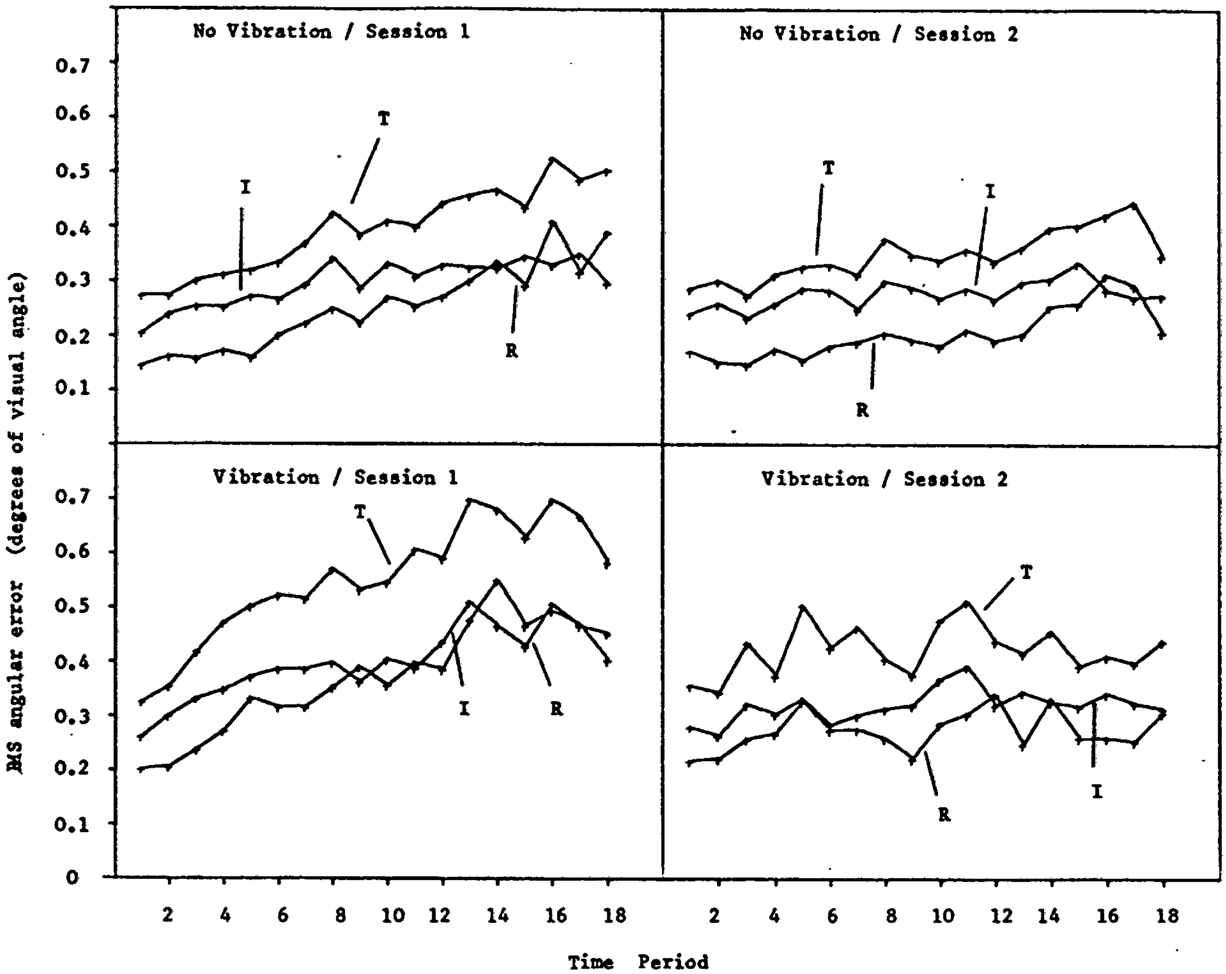


Figure 10.8 Median RMS angular error and its components in the horizontal display axis as a function of time on 2 sessions with and without vibration exposure.

(T = total error, I = input-correlated error, R = remnant error. Each time period = 11.25 minutes).

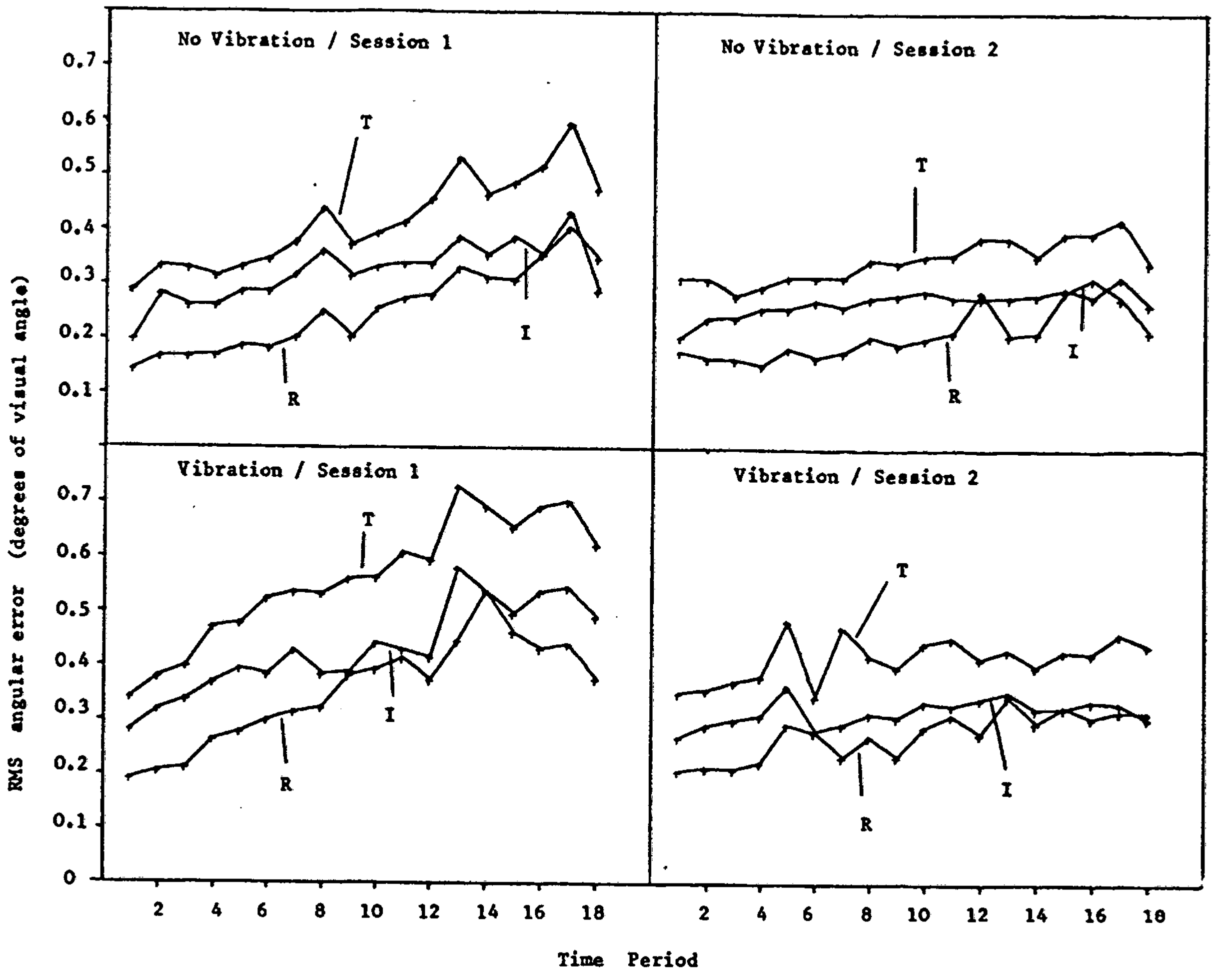


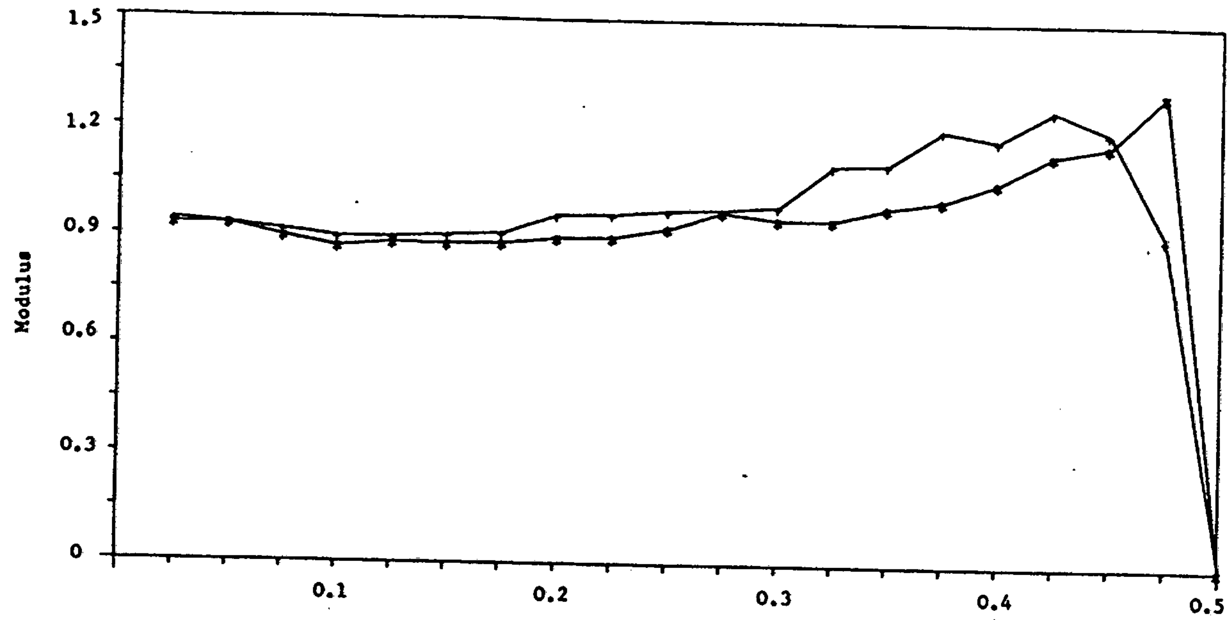
Figure 10.9 Median RMS angular error and its components in the vertical display axis as a function of time. With and without vibration exposure on 2 sessions.

(T = total rms error, I = input-correlated error, R = remnant error. Each time period = 11.25 minutes. Period 1 = pre-vibration, period 18 = post-vibration) during periods 2, 5, 11, 17 and 18 compared, in each case, with period 1. (The coherency for these data was greater than 0.5 at frequencies below about 0.35 Hz). These figures indicate a reduction in the modulus and an increase in the phase lag at most transfer function frequencies below about 0.35 Hz up to period 17. The general results were the same in the vibration exposed group.

Figures 10.15 and 10.16 show, respectively, the median moduli and phase in the vertical display axis at 0.1, 0.2, 0.3, and 0.4 Hz as a function of time. At 0.1 and 0.2 Hz these figures indicate a relatively constant reduction in the modulus up to about period 10, and a slightly greater reduction up to period 17. At 0.3 Hz, the modulus is approximately constant to period 12 and shows a reduction in the later stages. In all cases, the modulus increases again in period 18. This can also be seen on Figure 10.14. At 0.4 Hz, where the coherency is below 0.5, the modulus shows a cyclic pattern with a period of about 4 periods (45 minutes). The modulus at this frequency may partly reflect non-linear activity not removed in the spectral analysis.

The median phase lag (Figure 10.15) shows an approximately constant increase with increasing time at all four transfer function frequencies. The rate of increase is greater at the higher frequencies. In all cases, the phase lag is reduced in the final period, although it is still greater than in period 1.

Statistical analysis of the transfer function results again used split-plot Analyses of variance. Transfer function frequency was included as an additional within-subjects factor. (Because of limitations in the amount of data which GENSTAT could handle, transfer functions were only analysed at 0.1, 0.2, 0.3, 0.4 and 0.5 Hz). Results showed significant main effects of session, duration and frequency for both modulus and phase in both axes of the display ($p < 0.01$) and for both the vibration and the no vibration groups. Table 10.4 shows the Analysis of Variance Summary table



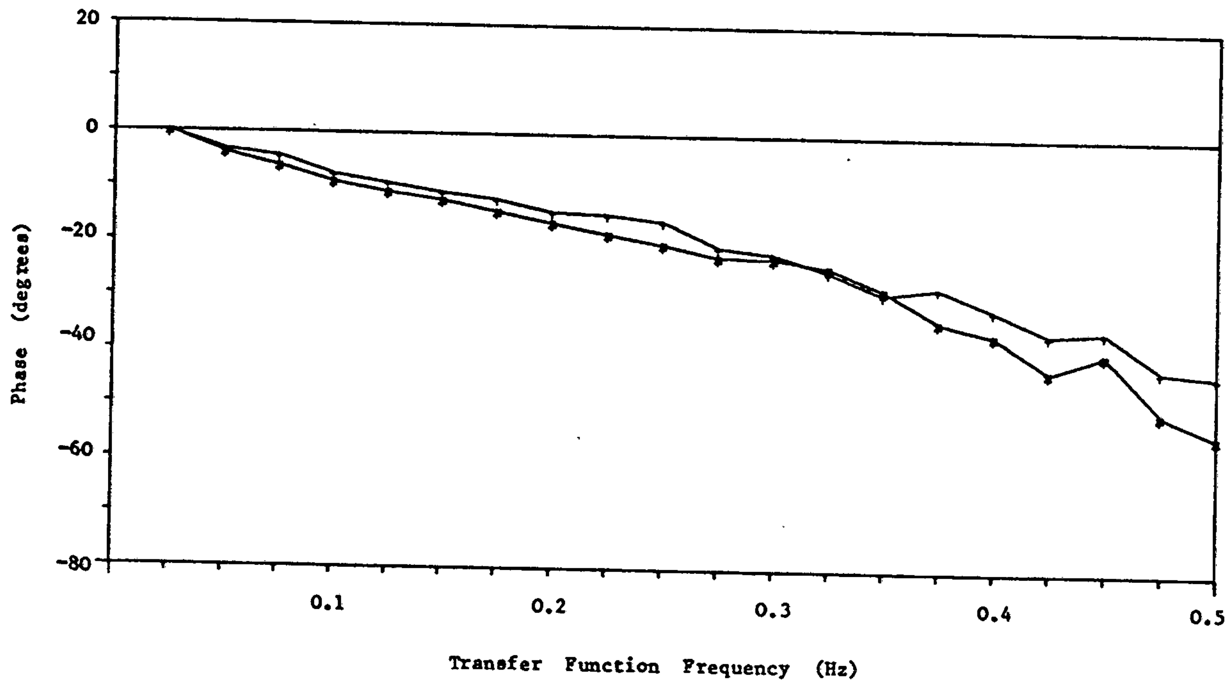


Figure 10.10 Comparison of median closed-loop system transfer functions in the vertical display axis during time periods 1 and 2. Session 2, no vibration (N = 7), 72 degrees of freedom.

+ = time period 1 (0-11.25 minutes)
* = time period 2 (11.25-22.5 minutes)

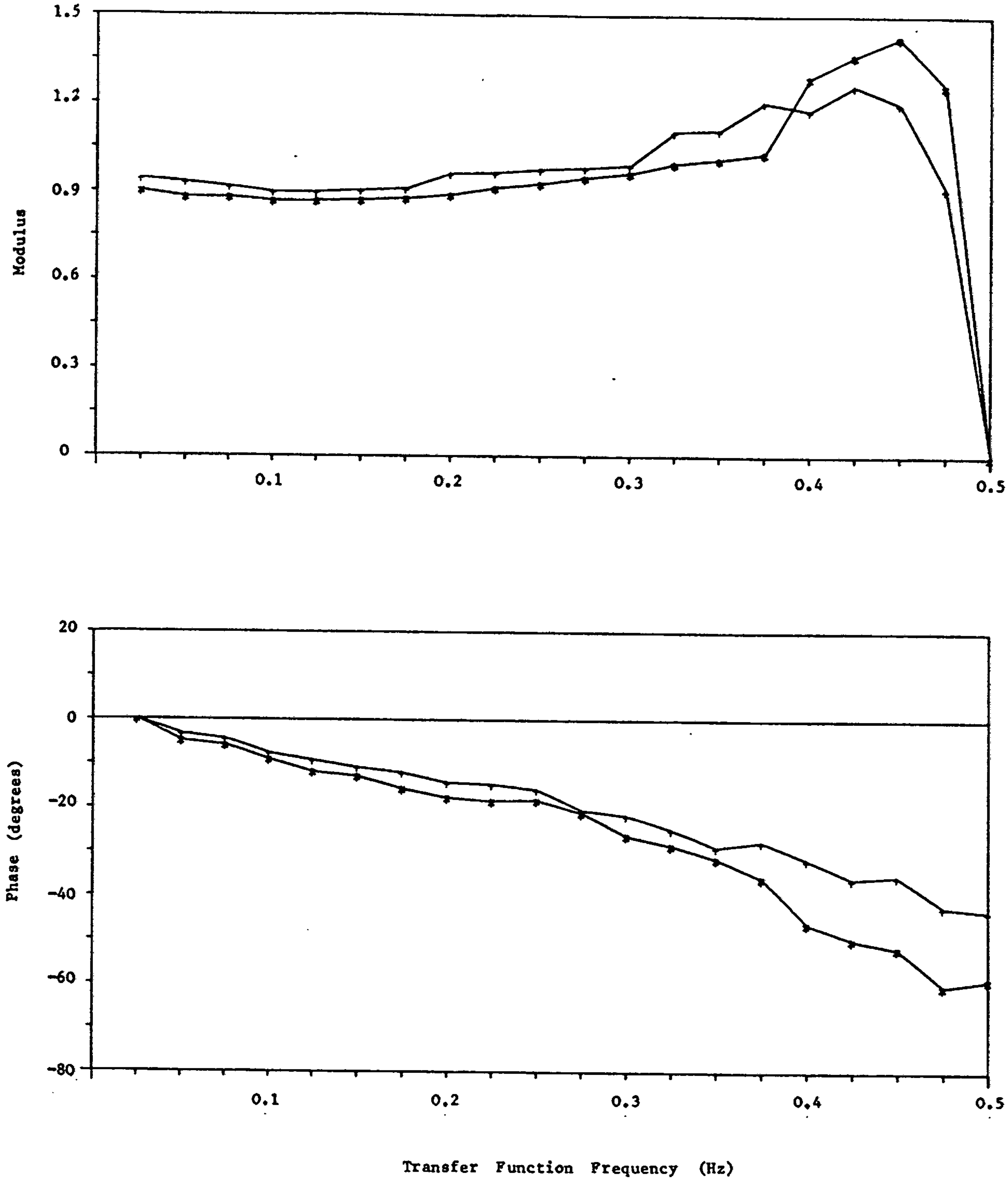


Figure 10.11 Comparison of median closed-loop system transfer functions in the vertical display axis during time periods 1 and 5. Session 2, no vibration (n = 7). 72 degrees of freedom.

+ = time period 1 (0-11.25 minutes)

* = time period 5 (45-56.25 minutes)

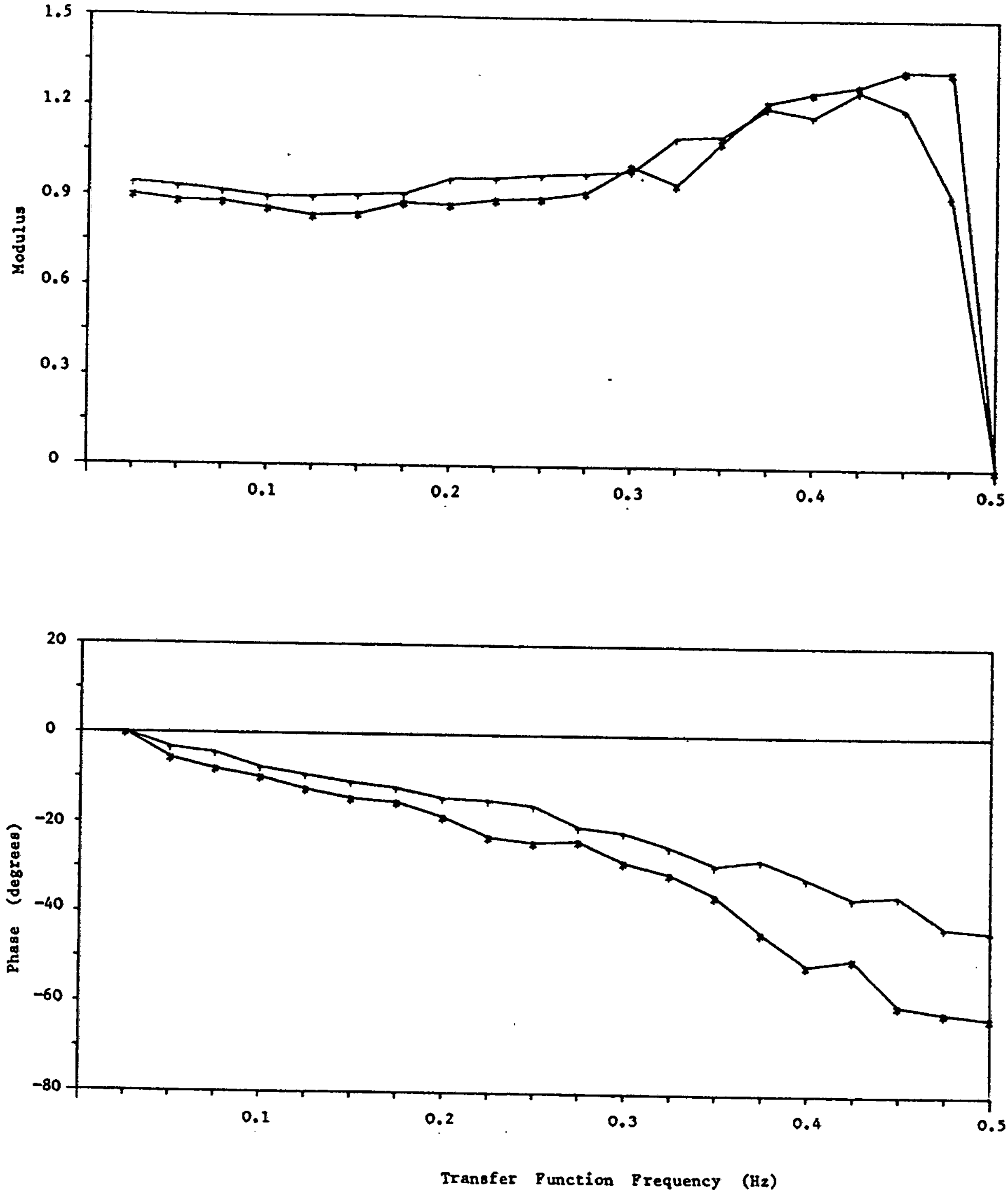


Figure 10.12 Comparison of median closed-loop system transfer functions in the vertical display axis during time periods 1 and 11 (N = 7). Session 2, no vibration.

+ = time period 1 (0-11.25 minutes)

* = time period 11 (112.5-123.75 minutes)

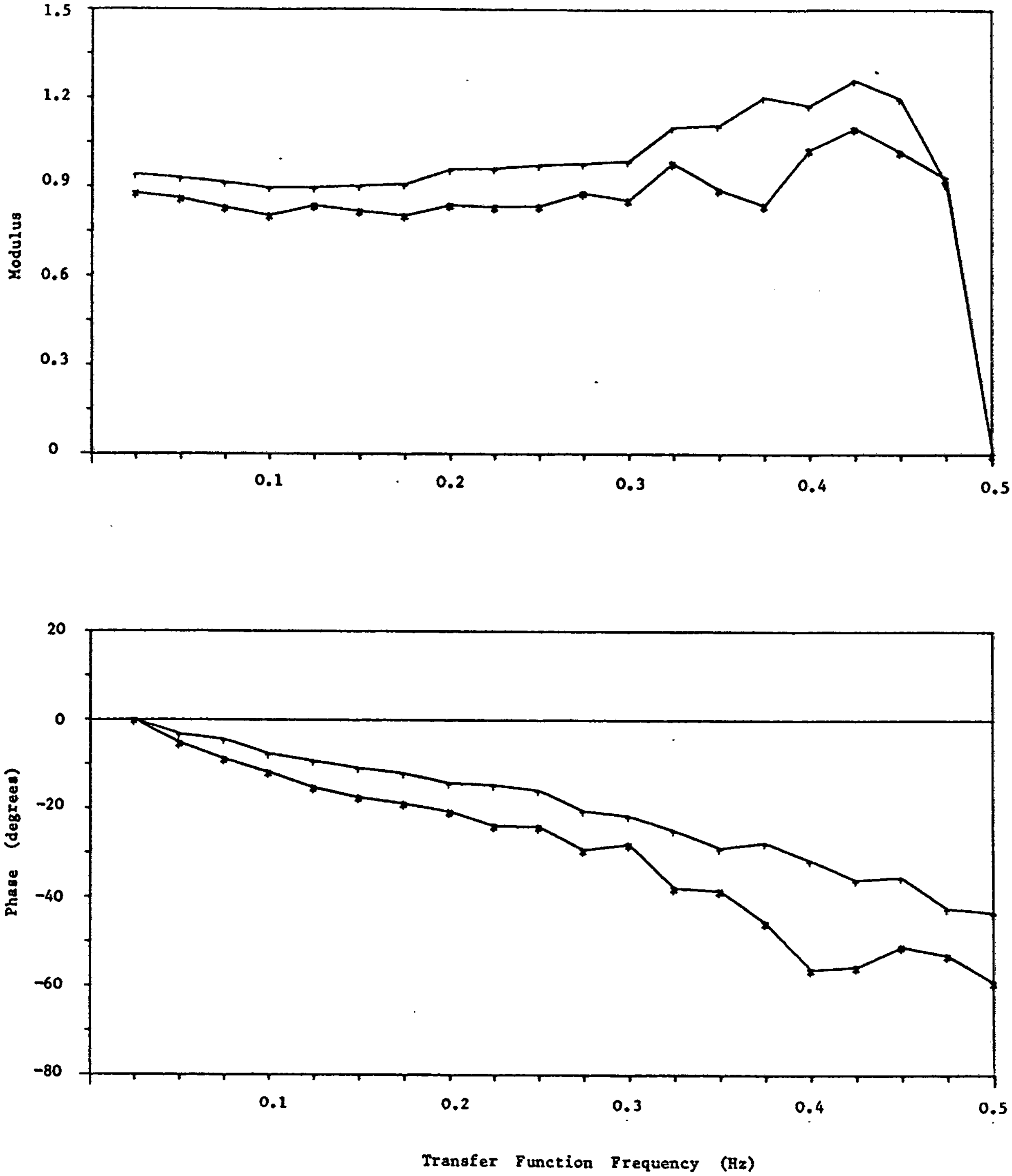


Figure 10.13 Comparison of median closed-loop system transfer functions in the vertical display axis during time periods 1 and 17. (N = 7). Session 2, no vibration.

+ = time period 1 (0-11.25 minutes)
* = time period 17 (180-191.25 minutes)

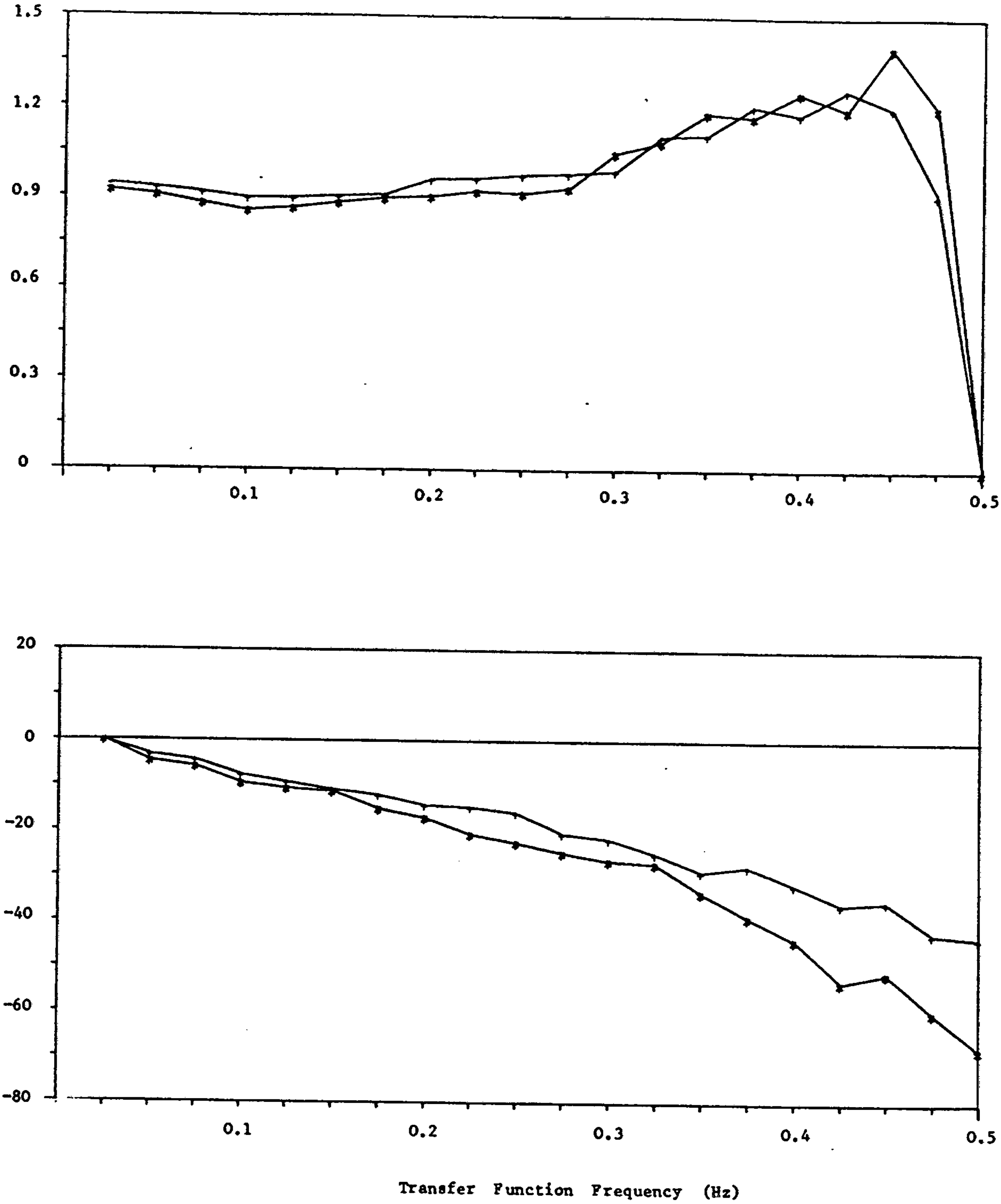


Figure 10.14 Comparison of median closed-loop system transfer functions in the vertical display axis during the first and last time periods (1 and 18). (N = 7). Session 2, no vibration.

+ = Session 1 (0-11.25 minutes)

* = Session 18 (191.25-202.5 minutes)

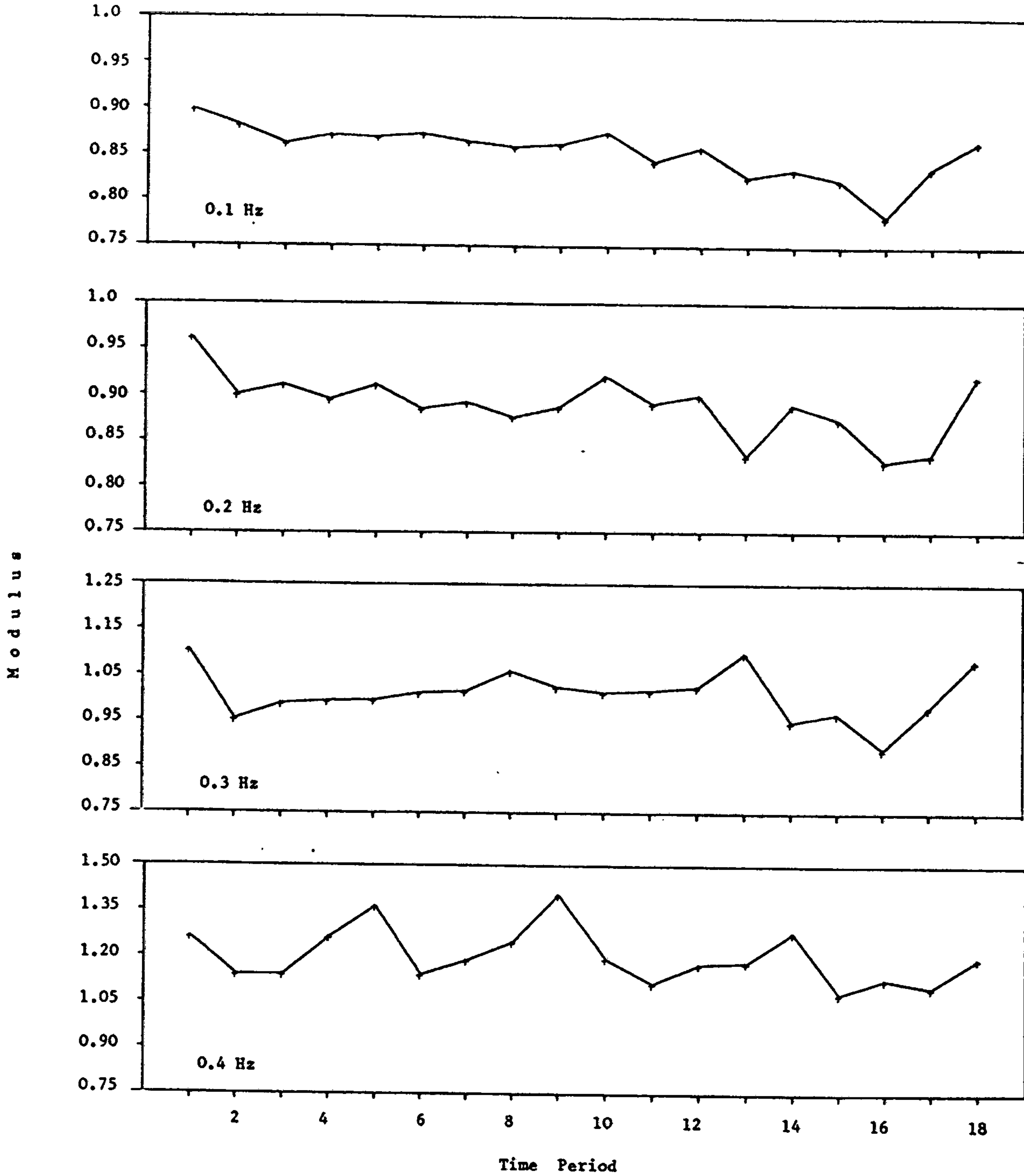


Figure 10.15 Median moduli at 4 closed-loop system transfer function frequencies as a function of time. Session 2, no vibration. (N = 7).

(Note different scales).

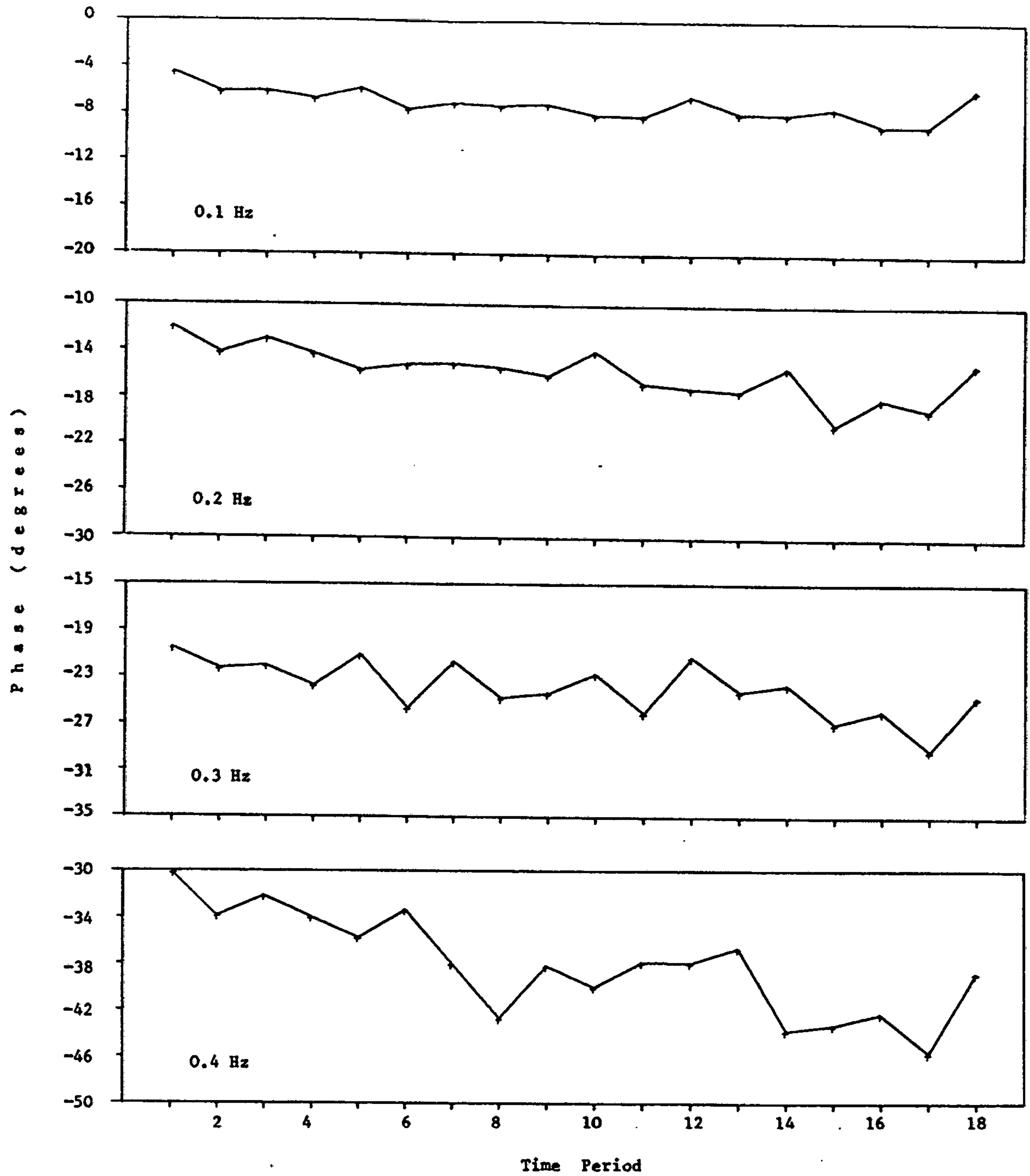


Figure 10.16 Median phase lags at 4 closed-loop system transfer function frequencies as a function of time. Session 2, no vibration. (N = 7).

Table 10.4 Analysis of Variance Summary table for the phase of the closed-loop system transfer functions in the vertical axis of the display

Subjects	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Ration	p <
Between Subjects					
Group	1	1.47049	1.47049	0.385	
Residual	12	45.81444	3.81787		
Total	13	47.28493	3.63730		
Within Subjects					
Session	1	23566.5	23566.5	61.535	.01
Time	17	35297.4	2076.3	5.422	.01
Frequency	4	914765.4	228691.3	597.144	.01
Group x Session	1	8232.0	8232.0	21.495	.01
Group x Time	17	6500.4	382.4	0.998	
Session x Time	17	10060.3	591.8	1.545	
Group x Frequency	4	2788.2	697.06	1.820	
Session x Frequency	4	2175.44	543.86	1.420	
Time x Frequency	68	21808.3	320.7	0.837	
Group x Session x Time	17	7225.6	425.0	1.110	
Group x Session x Frequency	4	2625.9	656.5	1.714	
Group x Time x Frequency	68	20428.0	300.4	0.784	
Session x Time x Frequency	68	22859.5	336.2	0.878	
Residual	2216	848672.3	383.0		
Total	2506	1163200.24	524.91		
Grand Total	2519	1163242.29			

for the phase of the transfer functions in the vertical axis of the display. On the second session, both groups of subjects showed smaller changes in both modulus and phase over time compared with the first session.

There was a significant interaction between vibration exposure and session for the phase lag in both axes of the display ($p < 0.01$). This is attributable to a greater reduction in phase lag on session one for the group who did not receive vibration than for the vibration-exposed group. There was no difference between the two groups on the second session.

3.1.4 Error Spectra

Figure 10.17 illustrates the median power spectral densities of the total error and of the remnant error in the vertical display axis at each time period. Most of the error occurs at frequencies below about 0.25 Hz, which coincides with the bandwidth of the forcing function. For most of the duration, remnant forms only a small proportion of the error at these frequencies.

Above about 0.3 to 0.35 Hz, most of the error is attributable to remnant. The reduction in performance over time is accompanied by increases in the spectra of both total error and remnant at frequencies below about 0.25 Hz. The increase in remnant occurs principally below about 0.1-0.2 Hz.

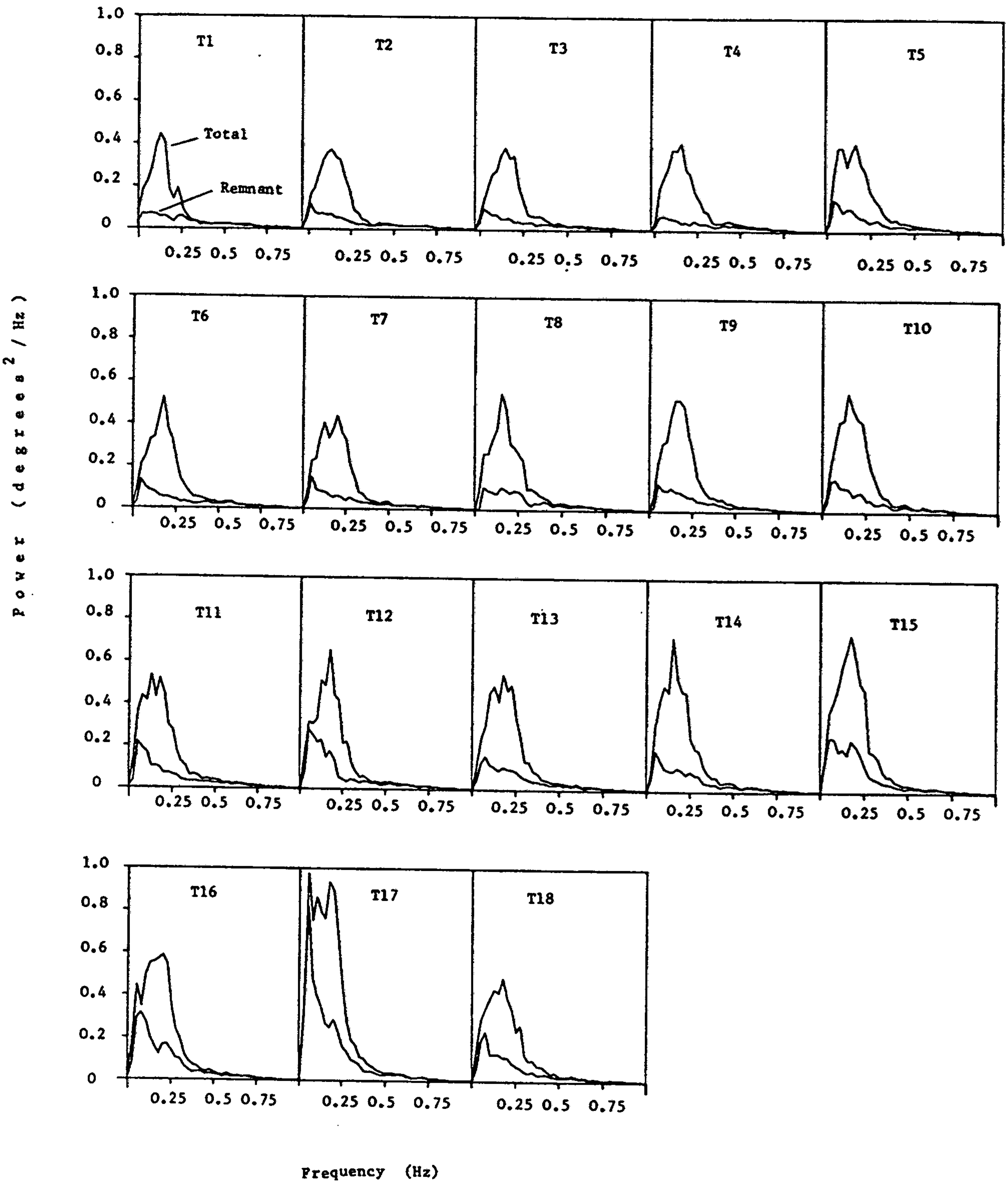


Figure 10.17 Median Power Spectral densities of total error and remnant error in the vertical display axis in each time period (N = 7). Session 2, no vibration.

(T_1 = time period 1, etc)

3.2 Questionnaire Results

This section summarises the information obtained through the questionnaires. Questionnaires A and B asked subjects to rate their physical and mental well being immediately before (A) and after (B) each of the 202.5 minute runs. Questions 1 to 4 were identical on these 2 questionnaires. Questionnaire C investigated differences betwen the 2 sessions.

3.2.1 Questionnaires A and B

Table 10.5 summarises the results of questions 1, 2, 3 and 4 on questionnaires A and B (see Appendix F for details of the questions asked). The table summarises changes in subjects' ratings of their physical and mental fatigue over each of the exposures. The ratings are very similar on both sessions and for both groups of subjects.

The median ratings show increases in overall physical and mental fatigue on both sessions. All subjects identified fatigue in the right hand and arm (which was used to operate the control). There was also fatigue in the eyes, and buttocks and, to a lesser extent, in the back and neck. Fatigue in the buttocks, back and neck was probably due to the hard seat, and the restricted movement allowed by the restraining harness. Fatigue in the eyes will be more complex, and may be dependent on the brightness of the display and its contrast with the background. Visually pursuing the target for the extended duration could also contribute to fatigue in the eyes.

Table 10.5 Summary of responses to questions 1, 2, 3 and 4 on Questionnaire A. (The values indicate the magnitude of change in rating. A +ve value means the rating was higher (closer to 'extremely tired') after the session. S_1 = Session 1; S2 = Session 2)

1. Group 1 : Without vibration

	SUBJECT															
	1		2		3		4		5		6		7		Median	
QUESTION	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
1. (How physically tired overall?)	+3	+1	+2	+3	+2	+2	+1	+3	+1	+2	+3	+3	+1	O	+2	+2
2. (How mentally tired overall?)	+3	+3	+1	+2	+3	+2	+4	+3	O	+1	+4	+5	+1	O	+3	+2
3. (How tired are your muscles in:																
thighs	+1	-1	-1	O	+3	+1	-3	+4	+1	O	O	+1	-3	O	O	O
calves	O	+1	+1	+1	+3	+1	-3	+2	+1	O	O	+1	-1	O	O	+1
buttocks	+1	+1	+3	+3	+4	+2	-3	+3	+4	+4	+3	+3	O	+2	+3	+3
back	+2	-1	+1	+2	+2	+2	-1	+1	+1	+2	+2	+2	+3	+3	+2	+2
neck	+3	O	O	+2	+4	+2	+3	+2	+2	+2	O	+3	+2	+1	+2	+2
eyes	+4	+3	+2	+3	+4	+4	+6	+3	+2	+2	+1	+3	+5	+4	+4	+3
head	+4	+1	-1	+2	+2	+2	O	O	+1	+1	+2	+2	+4	-1	+2	+1
hand R	+5	+2	+2	+3	+6	+5	+6	+4	+4	+2	+3	+4	+5	+5	+5	+4
hand L	+2	+1	+1	+1	+1	O	O	+1	+1	O	O	+1	-1	O	+1	+1

Table 10.5 (continued)

1. Group 1 : Without Vibration

	SUBJECT 1		2		3		4		5		6		7		Median	
QUESTION	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
3. (How tired are your muscles in?):																
lower arm R	+5	+1	+2	+2	+5	+5	+1	+1	+2	+2	+1	+3	+2	+1	+2	+2
lower arm L	+2	0	0	+1	+1	0	0	+1	+1	0	0	0	-3	-3	0	0
upper arm R	+3	+1	+2	+2	+5	+3	+5	+4	+1	+2	+1	+1	+1	+2	+2	+2
upper arm L	+1	+1	+1	0	+1	0	0	0	-1	0	-1	-1	-1	0	0	0
4. Any other condition? (After only)	Sore thumb (RH)		Sore thumb (RH)		R. hand fingers sore		Cough	Sore thumb (RH)	Sore thumb (RH)	Sore thumb (RH)			Eye strain	Sore thumb (RH)		

Table 10.5 (continued)

2. Group 2 : Vibration

	SUBJECT 1		2		3		4		5		6		7		Median	
QUESTION	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
1. (How physically tired overall?)	+1	+3	+3	+3	+4	+2	+1	+3	+4	+2	+1	0	+1	0	+1	+2
2. (How mentally tired overall?)	0	+1	+2	+3	+1	0	0	+3	+1	+1	+2	0	+4	+3	+1	+1
3. (How tired are muscules?):																
thighs	0	0	0	+2	+1	+1	+1	+1	0	+1	0	0	+1	+1	0	+1
calves	0	0	0	+1	0	+1	+1	0	0	+1	0	0	+1	-1	0	0
buttocks	+1	+1	+2	+3	+2	+3	+3	+2	+2	+3	0	0	+1	+3	+2	+3
back	+4	0	+1	+1	+3	+2	0	+1	-1	0	+1	0	+1	+3	+1	+1
neck	0	0	+1	+1	+1	+2	-1	0	+1	0	+1	+1	+1	+1	+1	+1
eyes	+2	+2	+2	+3	+2	+4	0	+1	+2	+2	+3	0	+2	+4	+2	+2
head	0	0	+1	+1	+1	+2	0	+1	+2	+1	+2	0	+2	+2	+1	+1
hand R	+6	+5	+4	+3	+4	+4	+6	+1	+4	+3	+6	+2	+5	+3	+5	+3
hand L	0	0	0	0	0	+1	0	0	+1	+1	0	0	+2	+2	0	0
lower arm R	+3	+2	+2	+2	+4	+3	+4	+1	+3	+2	+4	+1	+6	+5	+4	+2
lower arm L	0	0	0	0	0	+1	0	0	+1	-1	0	0	+2	+1	0	0

Table 10.5 (continued)

Group 2 : Vibration

	SUBJECT 1		2		3		4		5		6		7		Median	
QUESTION	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
3. (How tired are muscles?): (continued)																
upper arm R	+4	+5	+2	+1	+3	+3	+3	0	0	-1	+2	0	+3	+1	+3	+1
upper arm L	0	0	0	0	0	+1	0	0	-2	-1	0	0	+1	0	0	0
4. Any other Condition? (After only)	Sore fingers, palm, thumb (RH)	Sore thumb and fingers (RH)	—	—	Sore wrist and shoulder (RH)	Sore wrist (RH)	—	—	Sore thumb (RH)	Sore thumb (RH)	Sore wrist, fingers and thumb (RH)	Sore thumb (RH)	Fed up	Worn out and depressed		

3.2.2 Questionnaire B

This section summarises the responses to the remainder of questionnaire B, which was completed after each exposure. Figure 10.18 shows tracings of subjects' estimates of their performance (time-on-target) and motivation on session 2 (questions 6 and 7). Most subjects felt their performance declined over time although there was considerable variation in the pattern of perceived performance. A number of subjects felt their performance periodically improved, and 2 subjects felt they performed better in the middle than at the start.

Estimates of motivation also show a general decline over time. While the variability is considerable, most subjects felt they maintained a fairly high level of motivation for most of the run. The group who were not exposed to vibration show more consistently high levels of motivation than the vibration group. This suggests that vibration did not notably arouse the subjects.

For most of the subjects there is a clear correspondence between their estimates of performance and motivation. This may be an artefact of the way the data were collected. However, it does seem likely that changes in motivation provide a major contribution to changes in performance.

In response to question 8, most of the subjects cited boredom, tiredness and a loss of concentration as reasons for their perceived changes in performance and motivation. Physical fatigue in the controlling limb, and distraction due to discomfort caused by the seat were also commonly mentioned. On session 1, 6 subjects commented that their motivation reduced through not knowing how long the run would last.

In addition to discomfort caused by the seat, 6 subjects commented that the control was 'a bit stiff' and 'sluggish'.

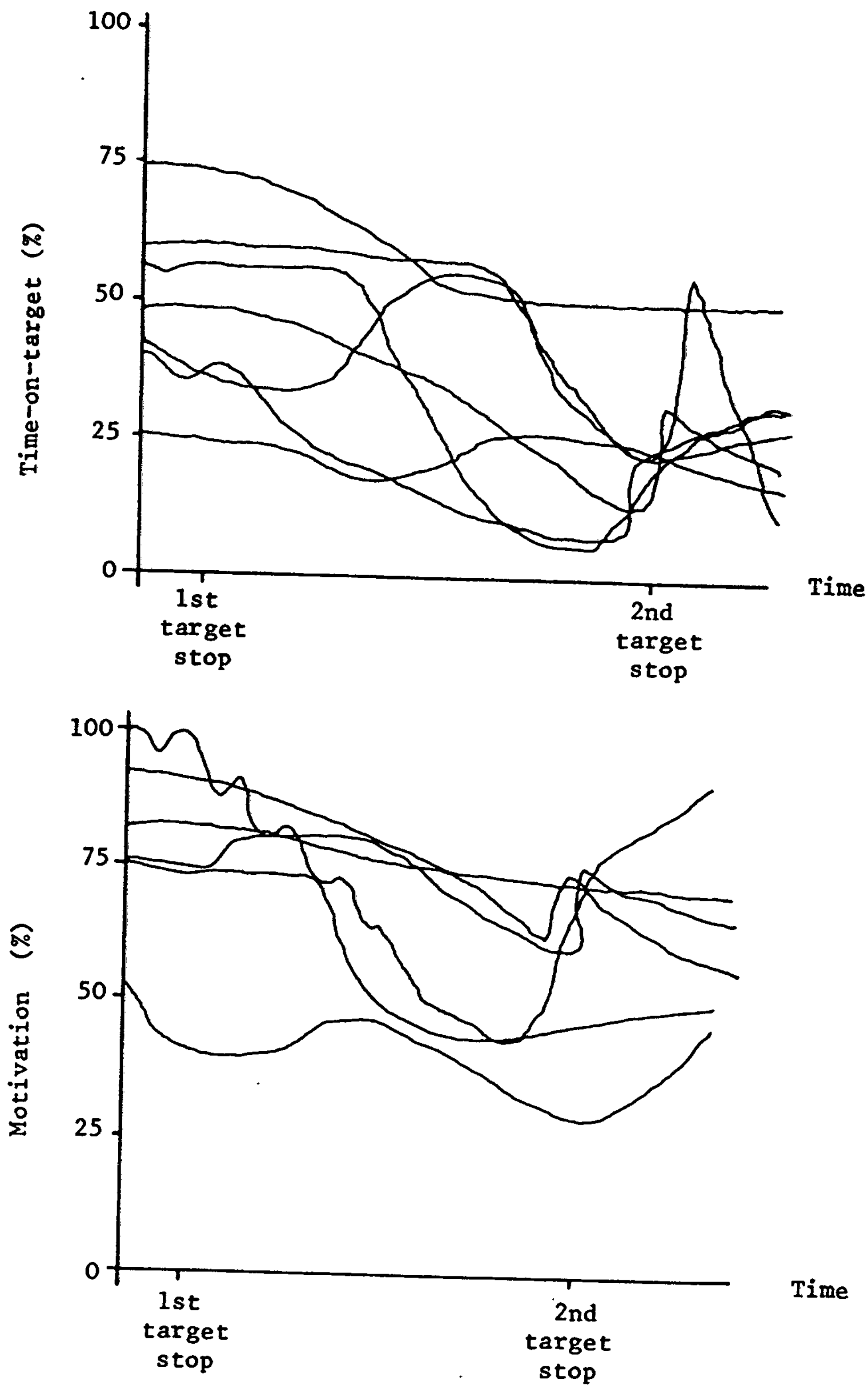
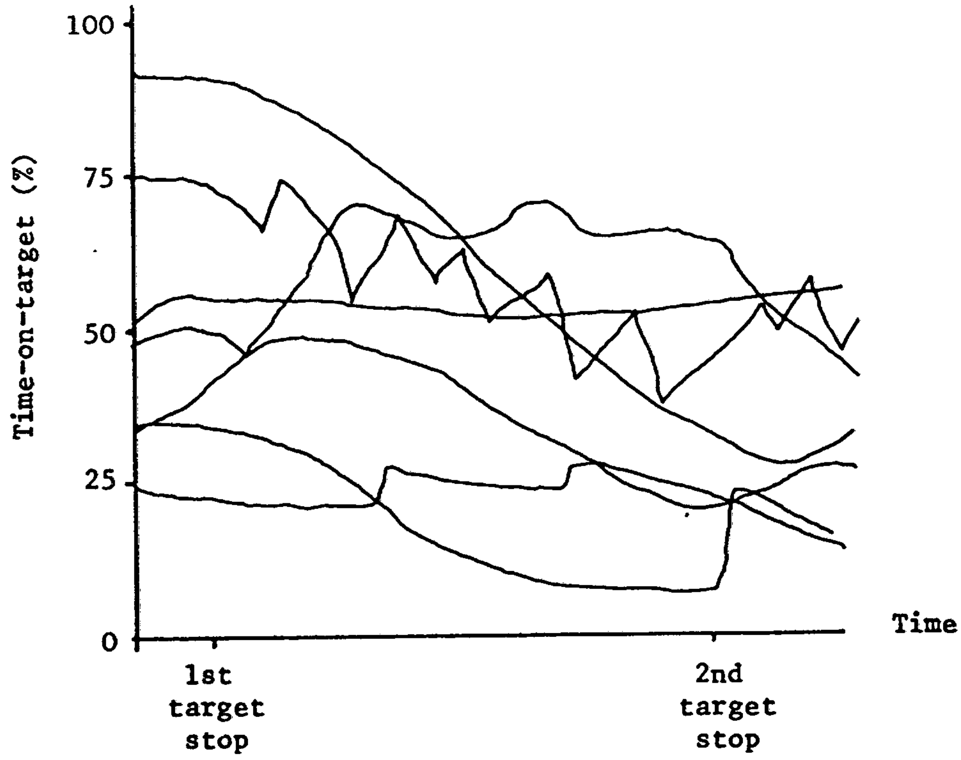


Figure 10.18 Subjects estimates of their performance and motivation on Session 2. No vibration group.



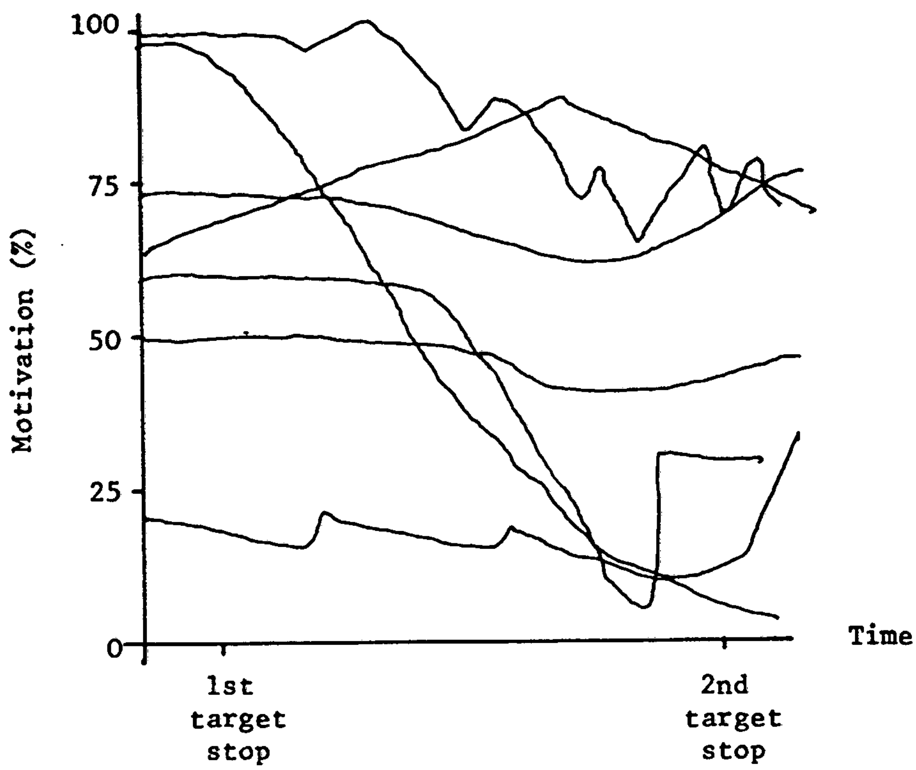


Figure 10.18 (continued) Vibration group.

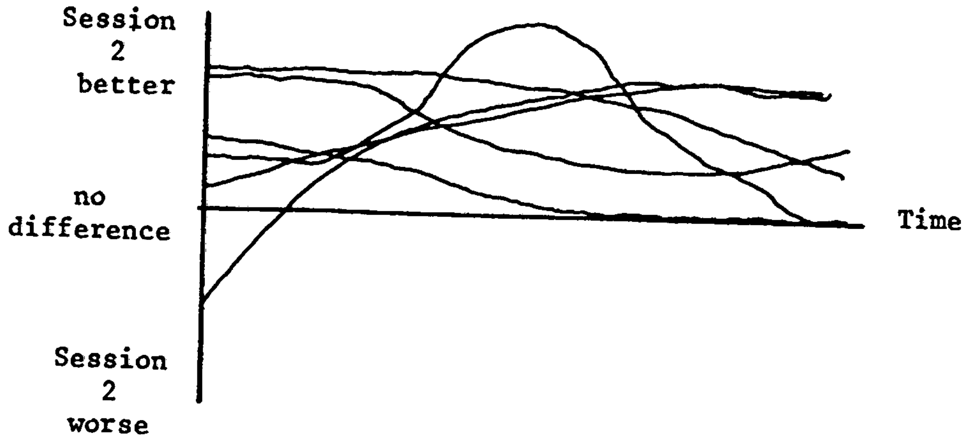
However, 4 subjects commented that the control was 'OK', although it became sweaty. The remaining 4 subjects made no comment on the control. Four subjects said that they were 'irritated' by background noise. One of these said the noise was 'too much - fatiguing'. Background noise was measured at a constant 62 dB(A) for one run during vibration exposure. There were also occasional brief noises from an adjoining laboratory. There were no other comments on the equipment, although a few subjects felt that the laboratory became 'a bit hot and stuffy'.

Under question 11 (other information), 2 subjects noted that when their eyes became tired they experienced brief periods of loss of focus. One subject commented that he feld 'fed up' and 'irritated' on both sessions. Other comments related to fatigue and loss of concentration.

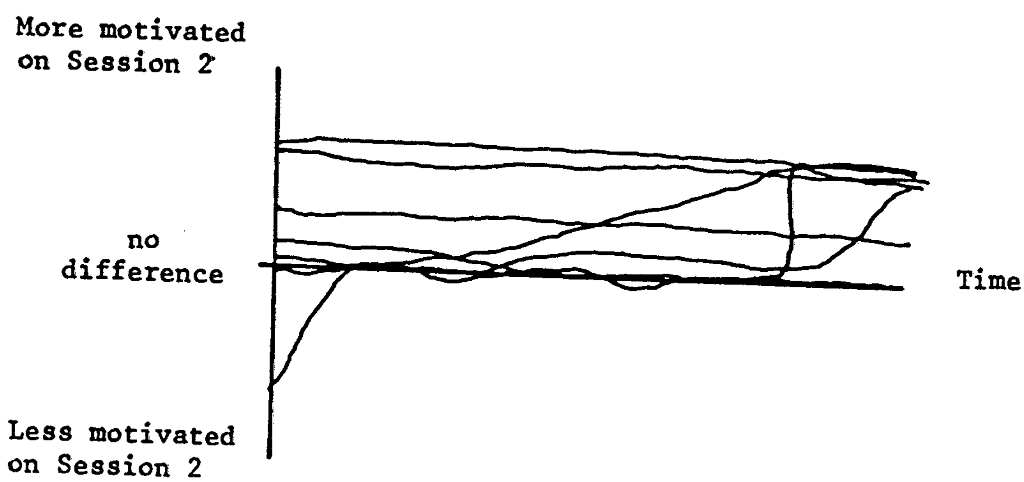
3.2.3 Questionnaire C

Questionnaire C was completed at least 3 days after completion of session 2. Eight subjects felt that session 1 had been of a longer duration than session 2 while two subjects felt the sessions were of the same duration. Ten subjects thought the task was easier on session 2, and 4 thought there was no difference in task difficulty.

Figure 10.19 shows tracings of subjects' perception of differences in their performance and motiviation on session 2 compared with session 1. All but one subject felt they generally performed better and were more motivated on session 2. Six subjects felt the difference in performance increased with increasing duration while 3 thought it reduced. Half of the

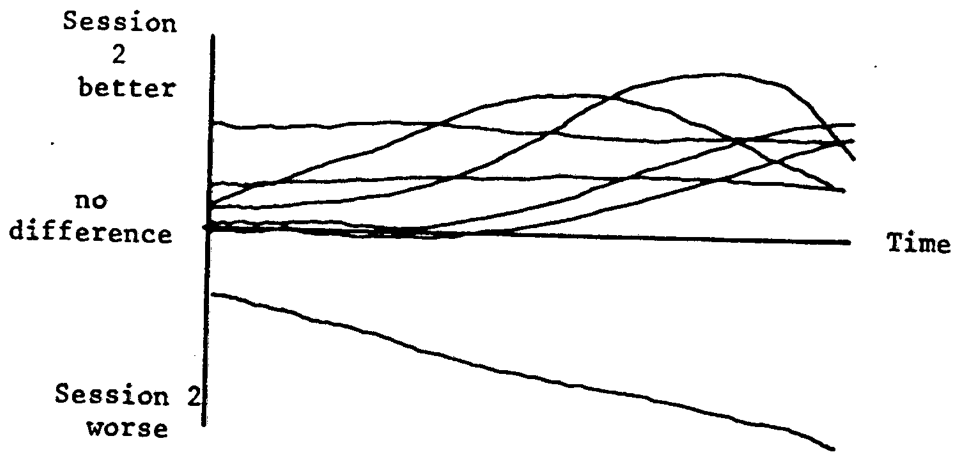


a) Time-on-target

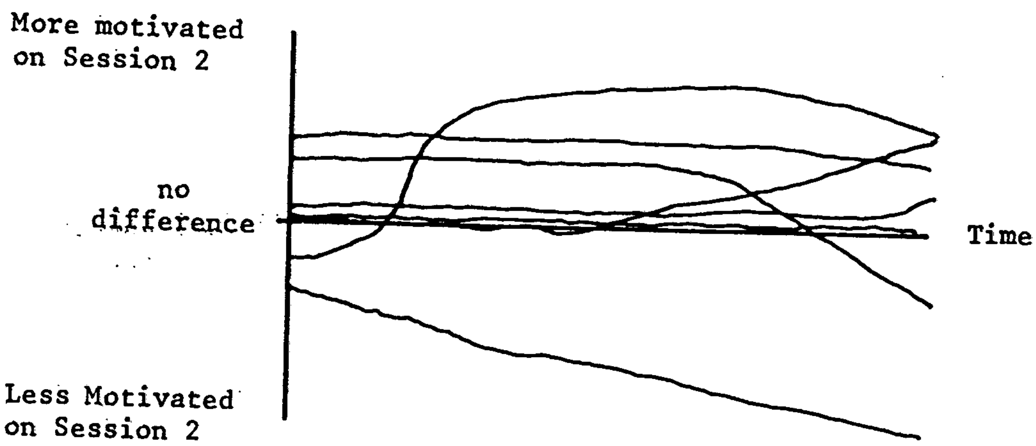


b) Motivation

Figure 10.19 Subjects' estimates of differences in a) Time-on-target and b) Motivation between the two 202.5 minute sessions. No Vibration group.



a) Time-on-target



b) Motivation

Figure 10.19 (continued) Vibration group.

subjects felt more motivated on session 2 by a constant amount throughout the duration.

Nine of the subjects noted that they either knew what to expect on session 2, or that they could prepare for it better beforehand. Improved motivation, or reduced anxiety through knowing what to expect was reported by 4 subjects.

Most of the subjects reported fatigue in the evenings following the two sessions and some reported soreness in the right thumb, hand and arm. Before being paid, 10 of the subjects said they would be prepared to repeat the experiment.

3.3 Choice Reaction-time task

Figure 10.20 compares the median reaction time for each size of character set before and after each exposure. As expected, there was a significant increase in reaction time with increasing size of character set (Friedman, $p < 0.01$). There were no significant differences between performance before and after each exposure although there was a significant improvement for most set sizes on session 2 compared with session 1.

The difference between the sessions may reflect the better preparation for the second session than for the first observed in the other measures. It probably also reflects insufficient training on the task. The lack of an improvement in performance after each session compared with before may reflect effects of fatigue counteracting the effect of increasing training. On the basis of these data however, it is not possible to distinguish these various effects.

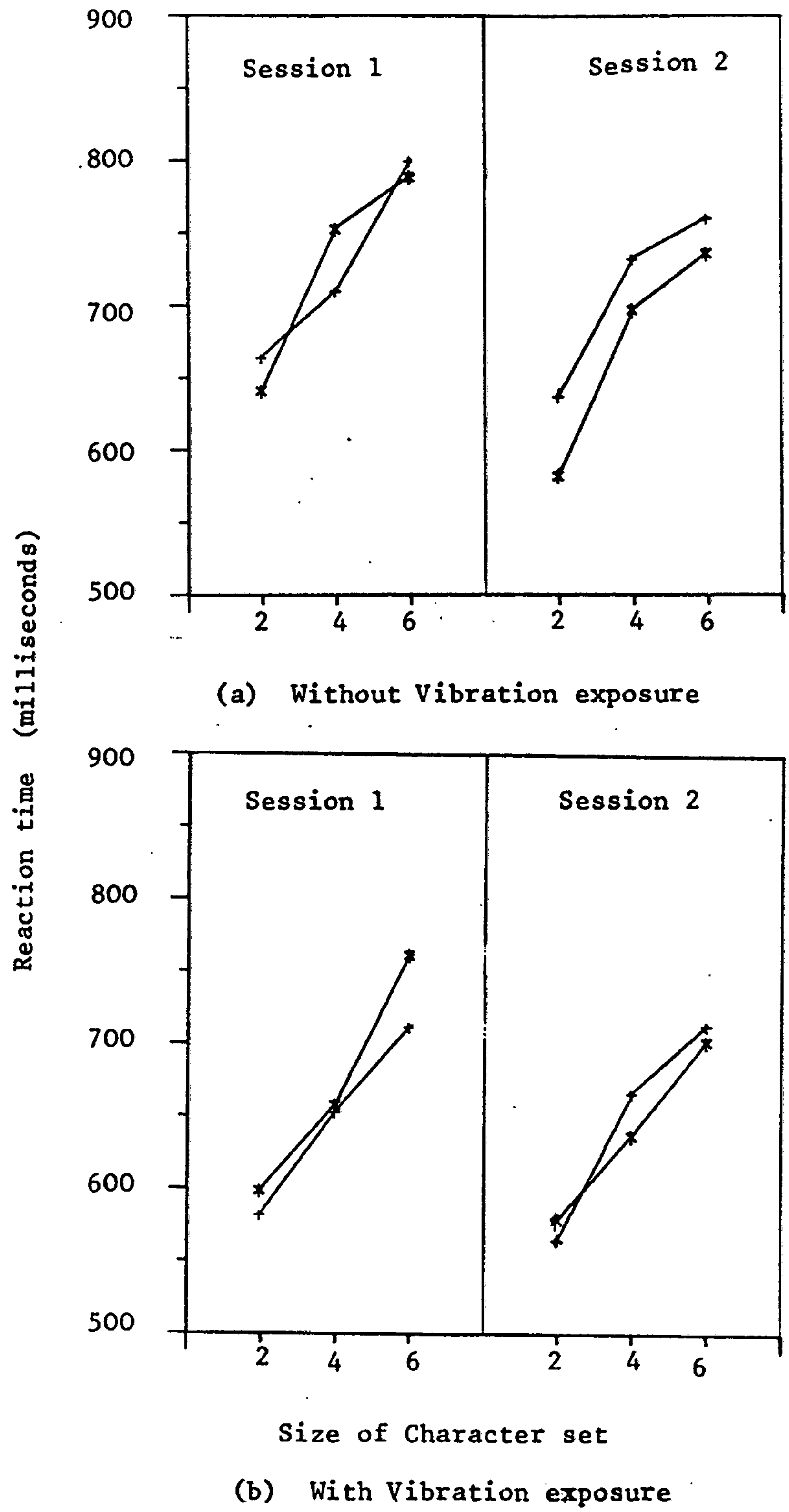


Figure 10.20 Results of Choice reaction-time task for both groups of subjects on both sessions as a function of character set size.

+ = Before 202.5 minute exposures

* = After 202.5 minute exposures.

In most cases, the reaction times for the vibration-exposed group were faster than the group not exposed to vibration. The difference occurred both before and after each exposure. It can therefore be attributed to a difference between the subject groups, rather than to an effect of vibration exposure.

This task therefore failed to demonstrate an effect of mental fatigue on choice reaction time. This may be due to the way in which the task was presented rather than to the lack of mental fatigue. For example, if the time for which each character set was displayed is reduced (from 1500 msecs), effects of fatigue may have been reflected in an inability to visually acquire the displayed information in the available time. There are a number of similar factors, combined with insufficient training, which could have contributed to the lack of a fatigue-induced decrement in performance of this task.

4.0 Discussion

4.1 Effect of Duration

Performance of the continuous tracking task declined at an approximately constant rate up to the final period. This decline was attributable to fatigue in the controlling limb combined with reduced arousal and loss of concentration, partly due to discomfort.

There were increases in both input-correlated error and remnant with increasing duration. System transfer functions showed increased phase lags and reduced moduli over time. It seems reasonable that with fatigue in the controlling limb and reduced motivation, subjects would respond to target movements more slowly, producing increased phase lags. The reduced moduli may reflect an unwillingness to exert the forces required to follow the full amplitude of target motions. Furthermore, with an increasing delay between target movements and the system response, subjects would observe changes in the direction of target motion before the controlled element reached the target. They may therefore not complete the movement, contributing to a reduction in modulus.

Increases in remnant predominantly occurred at frequencies below 0.2 Hz. Lewis and Griffin (1976) observed increased remnant at frequencies above the highest frequency in the forcing function. Remnant at these high frequencies probably reflects voluntary non-linear behaviour, which may be ballistic. High frequency activity will require more effort and attention than low frequency activity.

The increases in low frequency remnant could reflect a lack of responding. For example, due to fatigue or loss of motivation, subjects may have confined their activities to the central area of the display. Tracking low frequency, high amplitude target motions requires the application of sustained forces on the control. With fatigue in the controlling limb, subjects would have been unwilling to exert the effort required. This strategy would tend to minimise the effort required and would contribute both to increases in remnant and reductions in moduli.

Fatigue in the controlling limb indicates that the control was not sufficiently sensitive for performance over the extended duration. The control sensitivity (or gain) was slightly greater than that considered optimal for 3 minute runs. If the control had been very much more sensitive, error would be expected to be greater at the start of the run, principally due to increases in high frequency remnant (Lewis and Griffin, 1977). Effects of duration would be difficult to predict. If the amount of high frequency remnant reduced, overall performance may improve over time despite duration effects. However, overall performance could also remain constant or decline depending on the nature of other duration effects. For real-world tasks, the duration of performance needs to be considered in setting appropriate control sensitivities.

The discrete task showed a reduction in the probability of pressing the button as a proportion of the time-on-target - ie, in p(press/on). Most subjects reported soreness in the button pressing thumb. The reduction in p(press/on) probably reflects a reluctance to press the button with a sore thumb. There may also however be a component due to an inability to concentrate on both aspects of the task: subjects may have attended to the continuous task at the expense of the discrete task.

4.2 Vibration

Vibration did not alter the effect of duration on performance. The magnitude of vibration was considerably above the 'fatigue-decreased-proficiency' boundary defined in ISO 2631 (1985). This suggests, as have a number of other studies, that this limit is excessively conservative. In principal, it seems reasonable that there would be some magnitude of vibration above which time-dependent effects of vibration would occur. The present results suggest that, for this task, such a limit would be above the magnitudes of vibration which commonly occur in many real world environments. Time-dependent effects of vibration may be more likely to occur if the vibration environment is sufficiently severe to produce instantaneous disruption to performance.

This study presented random vibration centred on 4 Hz. At frequencies above about 30 Hz, vibration applied directly to muscle tissue has been demonstrated to produce reflex muscle contraction. This has been termed the Tonic Vibration reflex (TVR) and has been shown to be most sensitive to vibration in the region around 150 Hz (Gail et al, 1966). If exposure to high frequency whole-body vibration also induced the TVR, muscles would be likely to fatigue with extended exposures due to the sustained contraction. Time-dependent effects of vibration on performance may therefore be more likely to occur at higher vibration frequencies. Although the experiment reported in Chapter 9 suggested a direct affect of 0.5 and 4.0 Hz vibration on neuro-muscular processes, the lower acceleration magnitude used in this experiment would not necessarily induce the same effect.

Time-dependent effects of vibration may be highly task dependent. In particular, vibration has been suggested to reduce time-dependent impairments in tasks which are not inherently motivating. The subjective responses obtained suggested that, although it reduced over time, motivation remained relatively high for most subjects. Indeed, although the data were not suitable for statistical analysis, there was a suggestion that the group not exposed to vibration showed more consistent motivation over time than the vibration exposed group. These responses provide no evidence that vibration exposure increased motivation, possibly because the task was itself sufficiently motivating.

4.3 Effect of Session

The effect of duration on performance was smaller on the second session than on the first. Questionnaire C indicated that subjects felt generally better prepared and more motivated on the second session. They had some idea of the duration and may have felt more confident and less anxious. Reporting a similar finding with a vibration dependent duration effect, Seidel et al (1980) noted that subjects felt the vibration to be less stressful with repeated exposures of 3 hours.

Adaptation to the duration of performance has important implications for the design of experiments investigating time-dependent effects on performance (or, presumably, on other aspects of human behaviour). In repeated-measures designs, the effects of adaptation may be balanced by suitable randomisation. However the effects of session on performance in this study were large, and may therefore obscure systematic treatment effects by contributing to 'random' variability. For this type of study, independent groups of subjects should be used with each group receiving only one level of a treatment condition on more than one occasion.

Further research may determine the number of exposures required to remove the effects of adaptation for a particular duration. Seidel et al (1980) found that adaptation continued over 4 replications of 3 hours; the effect of vibration reduced with repeated exposures. It is not clear to what extent time-dependent effects of vibration reported in the literature could be attributed to an interaction between vibration and a lack of adaptation to the task duration.

5.0 Conclusions

This experiment provides 3 main conclusions:

(i) Performance of the continuous tracking task was dependent on the duration of performance up to 202.5 minutes. Muscular fatigue due to the sensitivity of the control combined with a decrease in motivation to produce an approximately constant rate of decline in performance.

(ii) The time-dependence for effects of vibration on performance incorporated in ISO 2631 (1985) is considerably more conservative than required for this task. Vibration did not alter the effect of duration on task performance.

(iii) Experiments investigating time-dependent effects of performance should expose subjects to the full duration on more than one occasion. Subjects may adapt to the length of performance and can show smaller time-dependent effects on a second, and possibly subsequent, exposure than on the first.

CHAPTER ELEVEN

CONCLUSIONS AND RECOMMENDATIONS

1.0 Summary of Results and Main Conclusions

1.1 Effects of Vibration on Performance

The experimental programme demonstrated that:

(i) performance of the continuous manual control task was sensitive to disruption by z-axis whole-body vibration at frequencies from 0.5 to 10.0 Hz at acceleration magnitudes above 2.0 ms^{-2} rms. Greatest disruption occurred at frequencies between about 5 and 8 Hz. The magnitude of disruption was approximately constant at frequencies from 0.5 to about 2 Hz;

(ii) the discrete task was not affected independently from the effects on the continuous task;

(iii) performance of the continuous task was time-dependent; and

(iv) exposure to whole-body vibration at a magnitude considerably above the limit recommended by the current International Standard (ISO 2631, 1985) did not alter the time-dependence.

1.2 Mechanisms and the Behavioural Model

Previous research has shown that performance of first-order tracking tasks can be disrupted by exposure to whole-body vibration. However, the mechanisms underlying the disruption have not been clearly identified. The behavioural model presented in Chapter 3 summarised four mechanisms which have been suggested to be important. The experimental programme demonstrated that the impairment in performance which occurred could be attributed principally to two of these mechanisms; visual impairment and interference with neuro-muscular processes.

1.2.1 Visual Impairment

Experiments 3 and 4 (Chapters 7 and 8) demonstrated that at vibration frequencies above about 2 Hz impairments in tracking performance arose through reduced visual ability. This was shown to arise from relative translational movement between subjects' eyes and the display. The evidence of this mechanism came from the use of a collimating lens: collimating the display removed most of the impairment at vibration frequencies above about 2 Hz.

Although some authors have suggested that visual effects could contribute to the disruption of manual control performance during vibration exposure, the importance which this mechanism can have has not previously been demonstrated experimentally. Furthermore, the dominance of translational movements between the eye and the display in producing visual impairments at a viewing distance of less than 1 metre had not been shown.

For the task, viewing conditions and vibration magnitude used in this thesis, the lowest frequency at which visual impairment was important depended on the vibration waveform. With predictable, sinusoidal vibration, there was evidence that subjects were able to actively compensate for movements of the head relative to the display at frequencies up to 2.5 Hz by visually tracking the display. With less predictable, one-third-octave band random vibration, such compensation was not effective at frequencies above 1.6 Hz. Previous studies had not compared effects of sinusoidal and one-third-octave band random vibration at frequencies below 2.5 Hz. The effect of active visual tracking had therefore not previously been observed with this type of task.

1.2.2 Neuro-muscular Interference

The results from experiment 5 (Chapter 9), were interpreted as showing that vibration could interfere with neuro-muscular processes. However, the precise nature of the interference was not clear. Muscle tension may have increased either through a voluntary response to the perception of motion, or through an involuntary, reflex-type mechanism. With increased tension, the signal-to-noise ratio between intentional commands inducing muscle activity for task performance and random muscle activity (such as tremor) would reduce. Subjects could therefore have experienced difficulty in producing the precise forces on the control required in performing the task.

A number of assumptions were made in arriving at the conclusion of neuro-muscular interference. Indeed, the conclusion arose by eliminating other reasonable explanations. It should therefore be considered as a hypothesis which, it is hoped, may stimulate further investigation.

Other authors have suggested that vibration could disrupt performance by interfering with neuro-muscular processes. However, there has previously been no supporting experimental evidence which could not reasonably be attributed to other mechanisms.

1.2.3 Secondary Effects

Vibration has previously been considered either to directly increase the amount of control activity not related to the performance of the task, or to reduce the ability of the operator to perform the task. The ways in which humans could adapt their performance to compensate for these effects have not been considered. The behavioural model emphasises the ability of humans to perform adaptively. The model indicates a number of processes which may be involved in changing the way the task is performed to compensate for, or minimise the influence of, the fundamental mechanisms of disruption. These changes are described as being secondary vibration effects.

In experiment 5 (Chapter 9) the frequency content of control activity was shown to depend on the type of visual feedback provided: when the feedback allowed discrimination of small movements of the controlled element, more control activity occurred at frequencies between 0.4 and 1.0 Hz than when less accurate discrimination was possible. Activity in this frequency range was interpreted as being generated intentionally to compensate for effects of neuro-muscular interference.

In experiment 4 (Chapter 8), changes in total rms tracking error during vibration exposure were accompanied by changes in the proportion of error due to linear operations on the target motion: there were increased phase lags between movements of the target and the response of the system. Subjects may have performed less predictively due either to an inability to quickly detect changes in the rate of target movement (due to visual impairment), or to a reduced capacity to rapidly respond to perceived changes (due to neuro-muscular interference). At vibration frequencies above 2 Hz, collimating the display removed the increased phase lags. Significant changes in the linear parameters of the operators' response during vibration exposure have not previously been observed.

The results of these two experiments indicate secondary effects of vibration; ie., effects which arose as a consequence of the fundamental mechanisms.

1.2.4 Other Effects

As well as indicating visual and neuro-muscular mechanisms and various factors which could be involved in producing secondary effects, the behavioural model shows two additional mechanisms which have been suggested: vibration breakthrough and central effects.

Vibration breakthrough appearing on the display (V_{1b} on the model) was not an important mechanism with the system studied: although breakthrough appeared at the control in experiments 1 and 5 (Chapters 5 and 9; V_{1a} on the model), it was attenuated by the system dynamics such that it did not appear on the display (experiment 4, Chapter 8).

The results obtained in this thesis do not indicate changes in the cognitive state of subjects, (such as arousal or motivation, or changes in perceptual-motor workload) due to vibration exposure. The experiments performed were not specifically designed to detect such changes. Indeed, the measures taken would not be expected to directly indicate such effects. Changes in cognitive state are likely to be difficult to detect, and even more difficult to quantify. However, if they are affected by vibration, the possible effects on performance may be large.

2.0 Recommendations

Recommendations can be made in two areas:

(i) in providing guidance for evaluating effects of vibration through standards; and

(ii) in suggesting areas for future research.

2.1 Standards

Experiments 2 and 4 (chapters 6 and 8) found approximately constant amounts of disruption with vibration at frequencies below about 2 Hz at a constant acceleration magnitude of either 2.0 (experiment 2) or 2.1 (experiment 4) ms^{-2} rms. Experiment 1 observed similar magnitudes of vibration breakthrough to the control at 0.5, 1.0 and 2.0 Hz. These results suggest that, for many tasks, the weighting functions in ISO 2631 (1985) and the proposed British Standard (1986) could reasonably be extended to 0.5 Hz using the

the same weighting value as at 1.0 Hz. However, there may be situations, such as with very high acceleration magnitudes at frequencies below 1 Hz, or with more complex tasks, where low frequency effects may become more pronounced; for example, if large displacements produced feelings of anxiety or fear.

The results do not support the time-dependent relationship between vibration exposure and performance incorporated in ISO 2631 (1985). The literature review also failed to provide support for any single simple relationship. It is suggested that a time-dependent standard should not be defined until experimental results demonstrate a reliable relationship.

2.2 Future Research

There are a number of areas in which further research is required to more fully understand the effects of vibration on manual control performance. Some of the areas considered to be most important include:

2.2.1 Mechanisms

The precise nature of the suggested interference with neuro-muscular processes should be investigated. Such research should investigate whether the effect is indeed neuro-muscular, and should determine whether it has a voluntary or an involuntary basis. This is likely to involve recording muscle activity during vibration. Emphasis should be laid on quantifying the relationship between changes in muscle activity and the ability to produce precise forces at the hand.

Future research should also attempt to determine whether central effects can be important in disrupting performance during vibration. If so, the conditions under which these effects occur and the disruption to performance they produce, should be described and, if possible, quantified.

2.2.2 Secondary Effects

The results obtained in this thesis indicate that further research is necessary to understand the secondary effects which may occur during vibration exposure. These could include changes in strategy and other forms of adaptive behaviour. There is a need for a method of interpreting changes in human operator transfer functions in terms of the underlying changes in behaviour. This should be based on empirical observations.

The types of behaviour underlying the 'linear' and 'non-linear' modes of responding shown in the behavioural model are not clear. By varying the sensitivity of the control, and measuring performance over runs of up to 10 minutes duration, it should be possible to determine the extent to which changes in remnant reflect intentional behaviour. This may help to identify the nature of secondary vibration effects, and indicate the role of tracking strategies not linearly related to the movement of the target.

Although the system dynamics were simplified in experiments 4 and 5, it seems likely that the same mechanisms (visual and neuro-muscular) would have been important with both sets of dynamics. The more complex, cross-coupled, dynamics used in experiments 2 and 3 were assumed to require more complex behaviour than with the un-coupled dynamics. They may have required a greater effort, in terms of attention and concentration, in performing the task. There may therefore have been additional secondary effects, such as increases in perceptual-motor workload, with these dynamics. Further research should investigate whether vibration can produce changes in the operators' workload and, if so, the ways in which these are dependent on the nature of the task and the vibration environment.

2.2.3 Duration

In experiment 6 it was shown that, although performance of the task deteriorated over time, one-octave-band random vibration centred on 4 Hz at an acceleration magnitude of 1.4 ms^{-2} rms did not alter the time-dependence. It was suggested that time-dependent effects could occur with vibration at higher magnitudes or higher frequencies than were presented in this experiment. Effects may be more likely to occur with vibration environments which produce instantaneous effects either on performance or on muscle activity. Future research should consider these vibration conditions.

Experiment 6 also showed that subjects would be less affected by the duration of performance if they performed over the full duration on a second occasion. Experiments investigating time-dependent effects must ensure that subjects are allowed to adapt to the duration of performance. Future research should attempt to determine both the number of repeated exposures for which adaptation will continue, and whether adaptation interacts with any time-dependent effect of vibration; ie., whether the time-dependent vibration effect occurs with fully adapted subjects.

2.3 Philosophical Considerations

With a few notable exceptions, previous research has generally been concerned with describing vibration effects. Experiments have often been concerned with making comparative judgements of the sensitivity of different forms of system variables to disruption by vibration. This approach has yielded some useful information for system designers. However, the emphasis on describing effects has been at the expense of a fundamental understanding of why the effects occur.

Scientific understanding advances through a process of generating hypotheses and testing them. It is suggested that a change in the emphasis of research into effects of vibration on manual control performance is required. Experiments should be directed towards testing hypotheses about the mechanisms producing disruption. This approach is not necessarily incompatible with evaluating different types of equipment and could yield considerable long term benefits for designers by producing generally applicable predictive models. Of particular benefit would be a programme of research evaluating a single complex system under a small number of vibration conditions. Such a programme should progressively test more restrictive hypotheses concerning the mechanisms involved.

3.0 In Conclusion

The human is an exceedingly complex system whether described in physiological, psychological or engineering terms. Unfortunately for the researcher, it is not sufficient to describe human control performance using one of these categories alone. The great variety and flexibility of human behaviour both defines the usefulness of humans as controllers and serves to frustrate simple descriptions of the ways in which they exert control.

An attempt has been made to understand the mechanisms by which vibration can disrupt manual control performance. The experimental programme indicated the mechanisms likely to have been important with the particular control system studied. Further experimental data are required to precisely identify both the conditions under which the major mechanisms contribute to performance disruption, and the type of tasks for which each mechanism is important. A more complete understanding of the ways in which controllers can adapt, and the conditions producing adaptation is also needed. This thesis has indicated the importanceof considering both the fundamental mechanisms by which vibration impairs performance as well as they ways in which humans could adapt their behaviour to compensate for the vibration effects.

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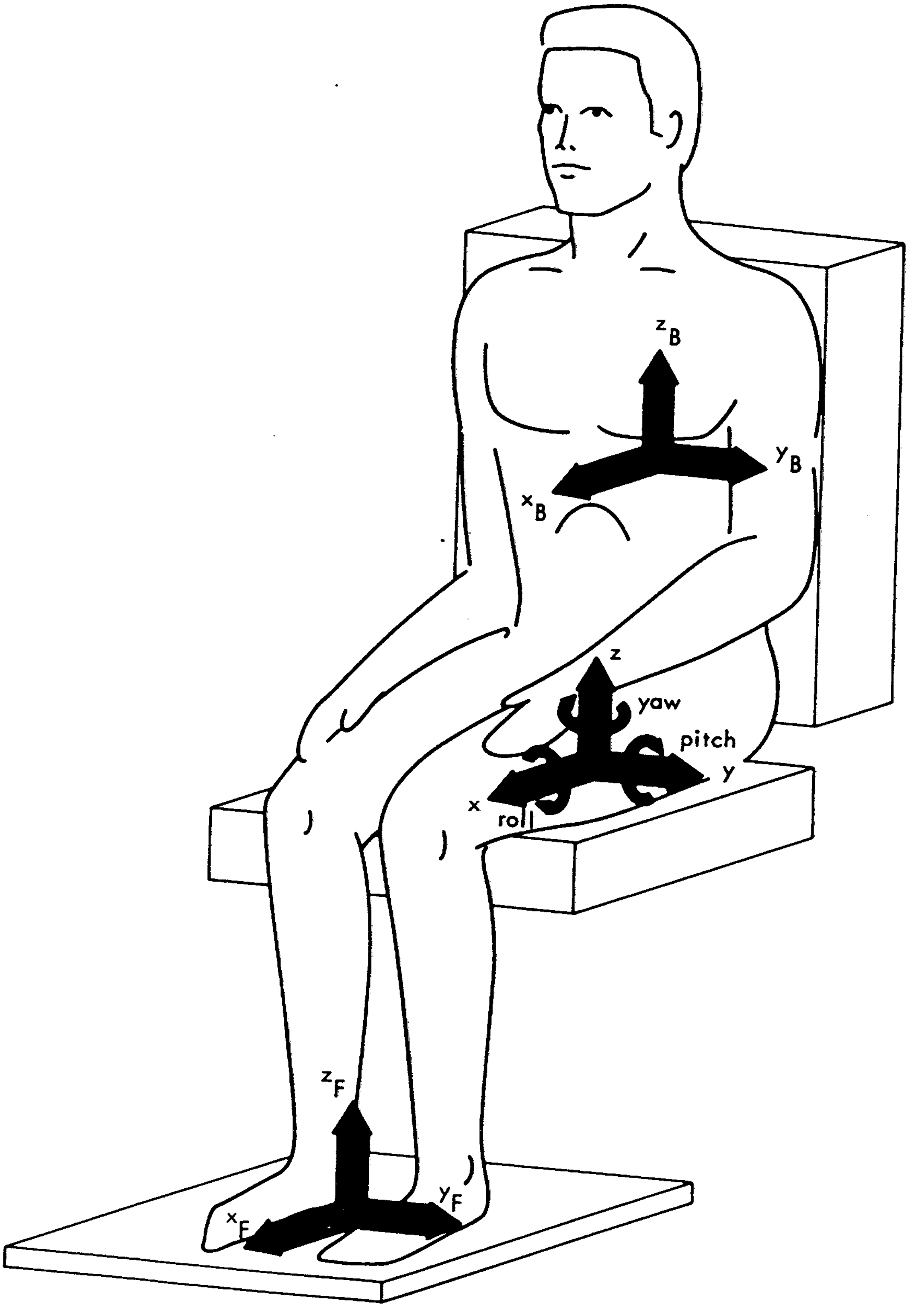
Appendix A: The Co-ordinate System Describing the Axes of Vibration Relative to the Human



APPENDIX B

SUMMARY OF THE LITERATURE

Table B.1. Summary of the Literature of instantaneous vibration effects.

	Authors and Date	Allen, Jex and Magdaleno 1973	Besco 1961
	Independent Variables	Vibration frequency; Vibration axis; Control type	Type of motion; Frequency and Amplitude of task; Replications
	Dependent Variables	rms tracking error and components; Human operator describing functions	rms tracking error
	System Dynamics	First-order, and simulated aircraft dynamics (each with a different vibration axis).	(Simulated aircraft) first-order
	Task	Single axis compensatory	Single axis compensatory
	Forcing Function	0.08 - 1.67 Hz (sum of 5 sinusoids)	1. 0.008 to 0.04 Hz 2. 0.016 to 0.08 Hz 3. 0.032 to 0.16 Hz; 1.5, 3.0 or 4.5 degrees peak displacement
	Task Duration	100 seconds (z-axis) 50 seconds (x- and y-axis)	3 minutes
Control	Type	'spring' and 'stiff'	Aircraft joystick (isotonic)
Control	Gain	0.17 kg/cm ('spring') 14 kg/cm ('stiff')	6 lbs/inch (force/displacement of control. Maximum displacement = 2 inches)
Control	Location	Centre	Centre
Vibration	Axis	x, y, z	z
Vibration	Waveform	Sinusoidal	1. Aircraft response to stick. 2. 1 + low level random gust 3. 1 + high level random gust
Vibration	Frequency (Hz)	x- and y-axes: 0, 1.3, 2, 3, 4.5 7, and 10 Hz z-axis: 0, 2, 4, 6, 8 Hz	Not given (less than 10 Hz)
Vibration	Magnitude	4.0 ms^{-2} rms	2. 2 ft s^{-1} rms 3. 4 ft s^{-1} rms
	Seat	Hard seat with backrest and restraints	Not given
	Number of Subjects	3	4
	Main Effects	i) Vibration frequency: z-axis - greatest 'feedthrough' to control occurred with 4 Hz vibration. Greatest performance disruption at 10, followed by 6 and 2 Hz. x-axis - effects depend on control; with 'spring' control, greatest 'feedthrough' at 3 Hz, performance disruption reduced with increasing vibration frequency. With 'stiff' control, greatest 'feedthrough' at 1.3 and 4.5 Hz, greatest performance disruption at 1.3 and 7 Hz. y-axis - 'feedthrough' and performance disruption greatest at 1.3 Hz, and reduced as the vibration frequency increased. ii) Control type: 'Stiff' stick better without vibration but shows greatest relative increase in error during vibration.	Higher frequency tracking tasks produced more error without vibration. The effect of random gusts was more pronounced with higher frequency tasks. Motion in response to stick displacements alone however significantly improved performance compared with no motion.
	Other Information	Effects of vibration mainly attributed to increased operator-generated 'noise' (or remnant). Suggestion of neuro-muscular lags with 10 Hz vibration. The paper describes a biomechanical model describing the transmission of vibration through the body.	Used a closed-loop system: displacements of control produced motion of cockpit.

Table B.1. (continued)

	Authors and Date	Buckhout 1964	Catterson, Hoover & Ashe 1962	Chaney and Parks 1964
	Independent Variables	Vibration frequency; Vibration magnitude	Vibration frequency; Vibration magnitude	Vibration frequency; Vibration magnitude; Control type; Control force; Task
	Dependent Variables	Tracking error	Integrated absolute error (number of Lights from centre of display)	Adjustment time and error
	System Dynamics	First-order	Zero-order	Zero-order with 2 second delay
	Task	2-axis compensatory tracking	2-axis compensatory	Time to adjust dial indicator. Compensatory tracking on 2 separate displays.
	Forcing Function	Not given	Not given	Not given
	Task Duration	5 minutes	2x5 minutes during 20 mins vibration (error measured over 2 minutes)	Not given
Control	Type	Probably isotonic	Column	Aircraft column & wheel. Horizontal and vertical thumbwheels. Large & small knobs.
	Gain	Not given	Not given	Various
	Location	Side with arm support	Centre	Various
Vibration	Axis	z	z	z
	Waveform	Sinusoidal	Sinusoidal	Sinusoidal
	Frequency (Hz)	5, 7 and 11 Hz	2, 4, 6, 8, 11 and 15 Hz	1 to 27 Hz
	Magnitude	5 Hz; 1.8, 2.2, 2.5 ms^{-2} rms 7 Hz; 2.05, 2.5, 2.9 ms^{-2} rms 11 Hz; 3.9, 4.7, 5.4 ms^{-2} rms	1 and 2.3mm rms	4 subjective reaction levels of equal displacements. Frequencies from 3-8 Hz only presented at 2 lowest levels
	Seat	Ejection seat with wooden "cushion" with harness	Wood and steel chair with backrest	Reinforced aircraft seat
	Number of Subjects	13	5	7
	Main Effects	Greatest disruption occurred in the vertical axis of the display. In both axes least disruption occurred with 7 Hz vibration and increasing acceleration increased the disruption.	Slight improvement in performance with vibration at 1mm rms. At 2.3mm rms all frequencies improved performance with the greatest effect at 8 Hz.	Incomplete results obtained show consistent effects of vibration independent of frequency, magnitude, type of control or control stiffness.
	Other Information	Subjects also performed a pattern matching task and a discrimination reaction-time task. There was no effect on reaction time, but an increased frequency of making an incorrect response in the pattern matching task during vibration.		High workload (performance with added secondary task) increased tracking error without vibration. However increased workload did not further disrupt performance during vibration probably because performance was already poor.

Table B.1. (continued)

	Authors and Date	Coermann, Magid & Lange 1962	Dimasi, Allen & Calcaterra 1972	Forbes 1960
	Independent Variables	Vibration frequency	Isolation of seat or seat & display from vibration platform; Control type	Vibration frequency
	Dependent Variables	Absolute integrated error	Mean square tracking error	Modulus mean error
	System Dynamics	First-order	First- and second-order (horizontal and vertical display axes)	Zero-order
	Task	Compensate for rotations of seat in 2 axes	2-axis compensatory tracking	2-axis compensatory
	Forcing Function	0.05 to 1 Hz	0-0.3 Hz	Not given (sinusoidal)
	Task Duration	1 minute	2 minutes	3 minutes 25 seconds (1 minute of vibration)
Control	Type	Aircraft joystick (isotonic)	Column & wheel (CW) and isotonic joystick. CW not isolated from platform vibration	Miniature isotonic joystick
Control	Gain	Not given	Not given	Not given
Control	Location	Centre	CW - Centre joystick - side	Side (with arm support)
Vibration	Axis	z	z	z
Vibration	Waveform	Sinusoidal	Broad-band random	Sinusoidal
Vibration	Frequency (Hz)	24 frequencies between 2 & 20 Hz	1 to >50 Hz (peaks around 5 & 20 Hz)	1, 2, 3, 4, 5 Hz
Vibration	Magnitude	1/3 short-time tolerances. Approx. 3.5 ms^{-2} rms from 4 to 8 Hz	<1.5 g rms	± 0.25 inch
	Seat	Ejection seat with wooden seat pan	Active vehicle isolation seat (AVIS)	Aircraft seat with 4 inch thick foam cushion; full harness
	Number of Subjects	15	Not given	5
	Main Effects	Maximum sensitivity (angular error per unit acceleration) at vibration frequencies between 6 and 8 Hz. Decreasing effect outside this region. No effect above 12 Hz.	Vibration effects largely removed by isolation of the human, control and display from the vibration. Performance was not improved if the display was not isolated from the platform motion.	Greater error in pitch (vertical axis than in (horizontal). Significant impairment at 2, 3, 4 and 5 Hz in pitch and at 3, 4 and 5 Hz in roll. Greatest disruption at 4 Hz in pitch.
	Other Information	Disruption remained 1 minute after vibration ended.	Seat isolation dramatically improved subjective comfort.	Author concludes effects due to visual impairment and involuntary movement of the hand and arm.

Table B.1. (continued)

	Authors and Date	Fraser, Hoover & Ashe 1961	Harris and Shoenberger 1965	Hornick 1962
	Independent Variables	Vibration magnitude, Vibration axis, Vibration of display	Vibration frequency, Vibration magnitude.	Vibration axis; Vibration frequency; Vibration magnitude Duration
	Dependent Variables	Integrated absolute error	Integrated absolute error	Integrated absolute error
	System Dynamics	Zero-order	First order	Zero-order
	Task	2-axis compensatory	2-axis compensatory	Single-axis compensatory
	Forcing Function	Not given (random)	0.02 to 0.27 Hz (vertical), 0.02 to 0.5 Hz (horizontal). With 11 Hz both axis 0.02 to 0.5 Hz	Not given
	Task Duration	58.5 seconds	3 minutes	4 x 15 minute periods (continuous)
Control	Type	Joystick	Not given	Steering wheel
	Gain	Not given	Not given	Not given
	Location	Centre	Side (with arm support)	Centre
Vibration	Axis	x, y, z	z	x, y, z (presented in different experiments)
	Waveform	Sinusoidal	Sinusoidal	Sinusoidal
	Frequency (Hz)	2, 4, 7, 12 Hz	5, 7, 11 Hz	1.5, 2.5, 3.5, 4.5 and 5.5 Hz
	Magnitude	± 1/16, 1/8, 3/16, 1/4 inch	5 Hz: 0.7,1.0,1.4,1.8 ms^{-2} rms, 9 Hz: 1.0, 1.4,1.8,2.0 ms^{-2}. 11 Hz: 1.8,2.6,3.4,4.3 ms^{-2} rms	1.5, 2.5 and 3.5 ms^{-2} rms
	Seat	Hard wooden contoured seat. No restraints.	Wooden seat with backrest and harness	Rigid wooden chair with back support
	Number of Subjects	4	30 (10 at each frequency)	10 to 20
	Main Effects	z-axis; Interaction between frequency and amplitude - above 1/16 inch, 7 & 12 Hz more disruptive than 2 or 4 Hz. x-axis; No effect on performance y-axis; No frequency dependence. 3/16 and 1/4 inch displacement caused greatest disruption. z-axis vibration caused most disruption in the fore-and-aft control axis. y-axis vibration worstin the side-to-side control axis.	Minimum acceleration producing a significant decrement was 1.4 ms^{-2} rms at 5 Hz, 1.8 ms^{-2} rms at 7 Hz, and 2.6 ms^{-2} rms at 11 Hz	Limited results are presented. More disruption occurred with y-axis motion at 1.5 Hz than in any other condition. Disruption was said to increase with acceleration magnitude. Frequency dependencies were not discussed.
	Other Information	Display consisted of a matrix of lights 1 inch apart. Resolution of error would therefore be 1 inch.		Subjects also performed choice reaction time, foot pressure constancy peripheral vision and visual acuity tasks. Peripheral vision was slightly affected by vibration in the y-axis. Significant time-dependent effects occurred.

Table B.1. (continued)

	Authors and Date	Levison and Houck 1975 (also Levison 1975)	Levison 1976	Levison & Harrah 1977
	Independent Variables	Vibration; Control location; control spring gradient	Vibration waveform; Vibration magnitude; Control stiffness.	Vibration axis; Control stiffness
	Dependent Variables	rms tracking error & rms control activity. Human-operator transfer function. Remnant spectrum	rms tracking error & control activity. Human operator transfer function.	rms tracking error and control activity
	System Dynamics	First-order	First-order	First-order
	Task	Single-axis compensatory	Single-axis compensatory	Single-axis compensatory
	Forcing Function	Flat to 0.3 Hz, with -6 dB/octave thereafter	Flat to 0.3 Hz with -6dB /octave thereafter	Sum of sinusoids at 0.08, 0.2, 0.48, 1 & 1.66 Hz with -6 dB/octave above 0.31 Hz
	Task Duration	2 minutes	2 minutes	100 seconds
Control	Type	Spring-centred	'spring' or 'stiff'	'spring' and 'stiff'
Control	Gain	2-600 lbs/inch (force/displacement of control)	7.5 lbs/inch ('spring') or 130 lbs/inch ('stiff') (force/displacement of control)	7.0 lbs/inch ('spring') and 130 lbs/inch ('stiff') (force/displacement of control)
Control	Location	Centre or side	Centre	Side
Vibration	Axis	z	z	z, roll, pitch, yaw, x + pitch, y + roll
Vibration	Waveform	Multi-frequency	1. Sinusoidal 2. Sum-of-sines 3. Random	Multi-frequency
Vibration	Frequency (Hz)	Sinusoidal components at 2, 3.3, 5, 7 and 10 Hz	1. 2, 3.3, 7, 10 Hz 2. Components at 2, 3.3, 5, 7, 10 Hz. 3. 2 - 10 Hz	Sinusoidal components at 2, 3.3, 5, 7, 10 Hz
Vibration	Magnitude	3 ms^{-2} rms	Nominally 1.5 & 3.0 ms^{-2} rms Also 2.0 ms^{-2} rms with the random motion	Less than 2.5 ms^{-2} rms
	Seat	Not given	Not given	Not given
	Number of Subjects	7	7	12
	Main Effects	No effect of stick location. Vibration exposure consistently impaired performance, but the amount of increase in error depended on the control stiffness. Stiffest sticks produced best performance without vibration, but allowed greatest 'feedthrough' of vibration. Overall effect on rms error was similar with each control stiffness.	Both rms error and control activity increased approximately linearly with increasing acceleration magnitude. Greatest increase in control activity occurred with the stiff control. Without vibration, rms error was less with the stiff control, but the difference reduced as the vibration magnitude increased.	'Feedthrough' greatest with stiff stick. Some effects of vibration on rms tracking error with the 'stiff' stick. No effects with the 'spring' stick. Effects on control activity with both sticks.
	Other Information	Data are also presented showing the transmission of vibration to the shoulder, elbow and head. Design guidance is prepared based on adaptation of the optimal control model of pilot behaviour. Effects attributed to increased operator-generated noise (remnant).	Also presents data for transmission of vibration to the head and shoulder and further develops the optimal control model to predict effects of vibration on tracking performance. Rms control & error scores tended to increase with shoulder acceleration.	Data used to further develop application of optimal control model. Compares predicted vibration effects with two previous studies.

Table B.1. (continued)

	Authors and Date	Lewis & Griffin 1976	Lewis & Griffin 1977	Lewis & Griffin 1979
	Independent Variables	Vibration magnitude; Control stiffness	Control type; Control gain.	1. Vib. frequency at the control; control type 2. Vib. frequency; Vib. magnitude; control type;Vib. of control or whole-body.
	Dependent Variables	Mean-square tracking error; Information channel capacity.	rms tracking error & components. Closed-loop human operator transfer functions	rms tracking error and components. Closed-loop human-operator transfer functions.
	System Dynamics	Zero-order	Zero-order	Zero-order
	Task	Single-axis pursuit	Single-axis pursuit	Single-axis pursuit
	Forcing Function	0.1 to 0.9 Hz (sum of 4 sine waves)	0-0.9 Hz (filtered thermal noise)	-3 dB/octave above 0.9 Hz; -20 dB/octave above 1.5 Hz
	Task Duration	3 minutes	3.5 minutes	4 minutes
Control	Type	'Isotonic' and 'spring'	Isometric & Isotonic joysticks & rotary knobs	1. Isotonic, isometric or spring-centred. 2. Isotonic & isometric sticks
Control	Gain	0, 0.08 and 0.16 Kg cm^{-1}	Varied	Isotonic - 375mm rad^{-1}, Isometric - 50mm kg^{-1}, spring combination of above (display/control ratios)
Control	Location	Side (no arm support)	Side (no arm support)	Side (no arm support)
Vibration	Axis	z	z	z, 1. Control only; 2. control only & whole-body & control.
Vibration	Waveform	Multi-frequency	Sinusoidal	Sinusoidal
Vibration	Frequency (Hz)	Equal amplitude components at 3, 5, and 8 Hz	4 Hz	1. 0, 4, 8, 16, 32 and 64 Hz, 2. 4 and 16 Hz
Vibration	Magnitude	0, 0.43, 0.87, and 1.73 ms^{-2} rms	0 and 0.75 ms^{-2} rms	1. 0, 1.2, 1.2, 2.4, 4.8 & 9.6 ms-2 rms. 2. Dependent on condition: whole-body 0-4.0 ms-2 rms. Control only 0 to 7.0 ms-2 rms.
	Seat	Hard, flat seat No back or restraints	Hard, flat seat. No backrest or restraint	Hard, flat seat. No arm rest. No restraint.
	Number of Subjects	12	4	4
	Main Effects	Error increased with increasing vibration magnitude. Effect of vibration reduced as control stiffness increased. Information channel capacity reduced by all vibration conditions.	Optimum gain for minimising rms error was lower with vibration than without. Increasing control gain increased both vibration breakthrough and remnant. Much larger phase lags with isotonic controls than with isometric controls.	1. Main effect of vibration was to increase operator generated noise (remnant). Effects at 64 Hz attributed to neuromuscular interference. Effects at lower frequencies attributed either to neuromuscular effects or perceptual confusion due to vibration breakthrough. 2. Vibration principally increased remant, with isotonic stick. 4 Hz whole-body vibration produced greatest disruption. Similar effects occurred with apparent 4 Hz 'breakthrough' added to controlled element, (while subjects were stationary).
	Other Information	The authors describe a taxonomic model of human operator performance during vibration exposure. They suggest results are evidence of interference with kinasthetic feedback mechanism. Vibration increased tracking error at frequencies below 1 Hz.	Effects of vibration mainly attributed to operator-induced noise, (remnant). No effects of vibration on closed-loop human-operator transfer functions. Similar effects occurred with rotary knobs to those with joysticks.	Authors conclude that the increase in remnant can be completely accounted for by increased perceptual noise due to breakthrough appearing at the controlled element. A third experiment investigated effects of exposure duration up to 1 hour.

Table B.1. (continued)

	Authors and Date	Lewis & Griffin 1978	Lewis 1980	Lewis 1981
	Independent Variables	Vibration frequency; Vibration magnitude; Vibration waveform Prediction procedure	Vibration frequency; System dynamics; Display type	Vibration frequency; Vibration waveform.
	Dependent Variables	rms tracking error & components. Predicted rms error.	rms tracking error & components	rms tracking error & components. Predicted rms error
	System Dynamics	Zero-order	Zero- and first-order	Zero-order
	Task	2-axis pursuit	2-axis pursuit & compensatory	2-axis pursuit
	Forcing Function	-3 dB/octave above 0.9 Hz. -20 dB/ octave above 1.5 Hz	Flat to 0.1 Hz, -20 dB at 1.0 Hz, -3 dB/ octave thereafter	Flat to 0.2 Hz, -20 dB at 1.0 Hz, -30 dB/octave thereafter
	Task Duration	3 minutes	2 minutes	2 minutes
Control	Type	Isotonic	Isotonic	Isometric
Control	Gain	375mm rad^{-1} (display/ control ratio)	Not given	Not given
Control	Location	Side (no arm support)	Side (no arm support)	Side (no arm support)
Vibration	Axis	z	z	z
Vibration	Waveform	Sinusoidal and Dual frequency	Sinusoidal	Sinusoidal; 1/3rd octave random; Broad-band random
Vibration	Frequency (Hz)	3.15 and 5.00 Hz	2.5, 3.15, 4.0, 5.0, 6.3, 8.0, 10.0 and 12.5 Hz	Sine and 1/3rd random centred at 2.5, 3.15, 4.0, 5.0, 6.3, 8.0, 10.0, 12.5 Hz. Broad-band random; 1-octave centred on 4 or 8 Hz. 2-octave centred on 5.6 Hz.
Vibration	Magnitude	0, 0.4, 0.8, 1.2, 1.6 & 2.0 ms-2 rms. Ten dual-frequency combinations	1.5 ms-2 rms from 4 to 8 Hz, increased to 1.9 & 2.4 ms-2 rms at 2.5 & 12.5 Hz respectively	Sine and 1/3rd random at 1.5 ms^{-2} rms. Broad-band random at 2.0 ms-2 rms
	Seat	Hard, flat seat with backrest & restraints	Hard, flat seat with backrest & restraints	Hard flat seat with backrest and restraint
	Number of Subjects	8	4 groups of 8. (1 group for each control order and display type)	8
	Main Effects	Best predictions of overall rms tracking error were obtained from the rms sum of the weighted frequency components.	With both system dynamics & display types greatest sensitivity occurred at 5 Hz. The more difficult 1st order task was most sensitive to non-breakthrough related disruption.	Good predictions of total rms error during broad-band random motion were obtained from a frequency weighting procedure using sine or 1/3rd octave random motion. Greatest sensitivity at 5 Hz.
	Other Information	Prediction procedure over estimated input-correlated error and under estimated remnant.	Mean increases in total rms error could be predicted from one average sensitivity function with accuracy not less than 50%.	Sensitivity functions for individual subjects broadly similar to overall data.

Table B.1. (continued)

	Authors and Date	Lovesey 1971a	Lovesey 1971b	Shoenberger 1970
	Independent Variables	Vibration frequency; Vibration axis.	Vibration frequency; Vibration axis; Restraining harness; Visual feedback.	Vibration frequency; Vibration axis; Vibration magnitude
	Dependent Variables	Mean square tracking error	Control position	Integrated absolute error
	System Dynamics	Zero-order	Zero-order	First-order
	Task	2-axis compensatory tracking	hold controlled element stationary in 2 axes ~~in centre of display~~	2-axis compensatory
	Forcing Function	Sine waves at 0.05 & 0.18 Hz	None	Sum of 9 sinewaves, 0.01 to 0.21 Hz
	Task Duration	2 minutes	35 seconds	4 minutes
Control	Type	Miniature isotonic	'Ramshorn' type Isotonic	Moving
Control	Gain	1:1 cms (control/display ratio)	1:7 in pitch 1:4 in roll (deg) (control-to-display ~~ratios)~~	Not given
Control	Location	Side (with arm support)	Centre	Side
Vibration	Axis	z and y (single & dual axis)	z and y (single & dual axis)	x, y, z
Vibration	Waveform	Sinusoidal	Sinusoidal	Sinusoidal
Vibration	Frequency (Hz)	2, 5, 7 Hz	2, 2.7 Hz	1, 3, 5, 8, 11 Hz
Vibration	Magnitude	1.4 ms^{-2} rms in z-axis; 0.7 ms^{-2} rms in y-axis	1.77 ms^{-2} rms in z-axis; 1.0 ms^{-2} rms in y-axis	2 & 4 ms^{-2} rms
	Seat	Rigid seat with backrest	Rigid seat with backrest	Aluminium aircraft-type seat with no cushioning. Restraint used
	Number of Subjects	18	3	Independent groups of 5 subjects in each axis and magnitude condition.
	Main Effects	All frequencies in both single axes degraded performance. With 2 axis motion, disruption was greater than in either single axis alone.	All vibration conditions degraded performance. z-axis motion produced less disruption y-axis. 2-axis motion produced more disruption than in either single axis.	Both magnitudes of x- and y-axi motion degraded performance. Effects were greatest with y-axis motion, where most disruption occurred at 1 & 3 Hz. In the x-axis, effects tended to b greater at lower frequencies. All frequencies of z-axis motio degraded performance, although there was no frequency dependence. There were strong interactions between the vibration axis and the axis of greatest disruption on the display.
	Other Information	Providing a restraining harness improved tracking in the horizontal axis of the display, but degraded tracking in the vertical axis.	Adding a bias to the control position appreciably increased errors. A restraining harness also increased disruption.	Subjects performed a reaction-time task concurrently with the tracking task. Results showed some effect which depended on the vibration frequency.

Table B.1. (continued)

	Authors and Date	Shoenberger & Wilburn 1973	Shurmer 1969	Torie 1965
	Independent Variables	Vibration frequency; Control location	Vibration frequency; Vibration magnitude; Vibration axis; Control type	Vibration magnitude; Control parameter; Backlash, friction; arm support.
	Dependent Variables	Highest level of instability at which control could be maintained	Time-on-target	Integrated tracking error
	System Dynamics	First-order	Zero-order	First-order
	Task	Critical tracking (1-axis compensatory)	2-axis compensatory tracking	2-axis compensatory tracking
	Forcing Function	None	0.05 to 0.18 Hz	Sine wave at 0.09 and 0.11 Hz
	Task Duration	Dependent on performance 40-60 seconds	30 seconds	30 seconds
Control	Type	Isometric	Isotonic and isometric joysticks	Isotonic - varying amounts of backlash and friction
	Gain	0.85 cm/Newton; 51 mins arc/Newton (force/displacement of control)	Not given	4 mv/sec/degree (control/display ratio)
	Location	Centre or side (arm support with side)	Side (with arm support)	Side (with and without arm support)
Vibration	Axis	z	z, y, roll (single and combined axis)	z
	Waveform	Sinusoidal	Sinusoidal	Broad-band random
	Frequency (Hz)	2, 6, 10 Hz	2 and 4 Hz	Approximately 2-30 Hz
	Magnitude	2.8 ms^{-2} rms	y-axis; 0.7, 1.4 ms-2 rms: z-axis; 2.1, 3.5 ms-2 rms: roll; 2 Hz-1.01,2.01; 4 Hz-0.18, 0.36 deg s-1 rms	1.5, 2.0 and 3.0 ms^{-2} rms
	Seat	Rigid seat with back-rest and full harness	Ejection seat. 3 point harness	G-seat
	Number of Subjects	8	6	3
	Main Effects	With both controls, all vibration frequencies significantly degraded performance. Inter-action between vibration frequency and stick location: the side-stick was better at 2 Hz while the centre stick was better at 6 and 10 Hz.	Greater disruption occurred with vibration in y- or roll axes than in the z-axis. With y- and roll axis motion 4 Hz was more disruptive than 2 Hz, while 2 Hz was more disruptive in the z-axis. There was no difference between the controls without vibration, though the isometric stick was more sensitive to vibration effects	Providing an arm support produced a greater improvement in performance during vibration than by altering friction or backlash in the control. Disruption increased with increasing accelera-tion magnitude.
	Other Information	The author suggested that the superiority of the arm support at 10 Hz may be due to the arm support transmitting vibration to the hand with the side-stick.	Performance in multi-axis environments was poorer than in any single axis environ-ment, and could be predic-ted from the scaled response in each individual axis. The scale factor depended on the number of axes.	

Table B.1. (continued)

		Weisz, Goddard & Allen 1965	Wilson 1974
	Authors and Date	Weisz, Goddard & Allen 1965	Wilson 1974
	Independent Variables	Vibration waveform; Vibration magnitude; Task difficulty	Vibration frequency; Display collimation
	Dependent Variables	Tracking error	Time-on-target
	System Dynamics	First-order	Zero order
	Task	2-axis compensatory tracking	2-axis compensatory tracking
	Forcing Function	0.075 to 0.75 Hz (depending on task difficulty)	0.1 Hz sine waves
	Task Duration	20 minutes	5 minutes
Control	Type	Isometric	Isotonic joystick
Control	Gain	Not given	Not given
Control	Location	Side (with arm support)	Side (with arm support)
Vibration	Axis	z	z
Vibration	Waveform	Sinusoidal random	Sinusoidal
Vibration	Frequency (Hz)	5 Hz sine and random amplitude. 4-12 Hz random	2, 4, 6, 8 and 10 Hz
Vibration	Magnitude	0.35, 1.06 & 1.77 ms-2 rms In experiment II, 2.1 ms-2 rms was used instead of 1.77.	2.3mm rms
	Seat	Wooden chairs with backrest and harnesses	Ejection seat with rigid back
	Number of Subjects	12	8
	Main Effects	There was no effect of vibration type, although disruption increased with increasing acceleration magnitudes. With the broad-band random motion,disruption only occurred at the highest magnitude. Adding a secondary task increased the disruption caused by vibration	Collimation significantly improved tracking performance at 4 and 6 Hz, although significant disruption occurred at all frequencies in both conditions.
	Other Information	Subjects also performed visual and auditory monitoring tasks. There were no affects on these tasks.	In both conditions, disruption increased with increasing frequency, probably due to the very high accelerations at higher frequencies. Results are discussed in terms of body resonance phenomena.

Table B.2. Summary of Literature investigating Time-dependent vibration effects

Section	Authors	Duration	Vibration	Relation to FDP (max) 1	VDV (max) 2	Tasks	Continuous Performance?	Continuous Vibration?	Control Condition	Effect of Duration: Static	Effect of Duration: Vibration	Effect of Vibration
4.1 Studies Showing Vibration Dependent Effects	Bastek et al (1977)	30 mins	z-axis sinusoidal 2Hz at 1.6 and 2.4 ms^{-2} rms	2x	11.1	visual and auditory target detection	Yes (5 mins per task)	Yes	20 mins pre-exposure (Also other vibration conditions).	No effect of time	Slower response times at higher magnitudes	No frequency dependence. Effect attributed to non-specific stress.
	Dudek et al (1973)	2 hours	z-axis sinusoidal 5Hz at 1.4 ms^{-2} rms	~1.8x	18.1	zero-order compensatory tracking.	No. 30/30, 40/40 60/60 minute work/rest cycles	Yes	Yes	Performance declined due to boredom.	Performance declined due to boredom.	As Khalil and Ayoub (below) At 60/60, performance better with vibration than static. Vibration increased arousal.
	Glukharev et al (1973)	2 or 4 hours	z-axis sinusoidal 3-8 Hz at 1.5-4ms^{-2} rms	(4 Hz, 7.5x	$4ms^{-2}$) 61.3	Compensatory tracking. Simple RT. Visual acuity.	Yes (2 mins tracking every 15 mins).	Yes	Yes	No effect of time.	Dependent on frequency and amplitude.	Increased tracking error extending into post-vibration period.
	Khalil & Ayoub (1970)	1 hour	z-axis sinusoidal 5Hz at 1.4ms^{-2} rms	1.19x	15.2	zero-order compensatory tracking	No. 5/5, 10/10, 15/15 or 30/30 minute work/rest periods.	Yes	Yes	Performance declined due to boredom	Performance declined due to boredom	Difference between performance with and without vibration reduced as length of work/rest cycle increased. Vibration increased arousal.

1. FDP = 'Fatigue-decreased-deficiency' boundary defined in ISO 2631 (1985)
2. VDV = 'Vibration-dose-Value' as defined in BSI (1986)

Table B.2. (continued)

Section	Authors	Duration	Vibration	Relation to FDP (max)	VDV (max)	Tasks	Continuous Performance?	Continuous Vibration?	Control Condition	Effect of Duration		Effect of Vibration
										Static	Vibration	
Studies Showing Vibration Dependent Effects	Seidel et al (1980)	3 hours	z-axis sinusoidal 4 & 8 Hz at 1 ms^{-2} rms (4 replications in each condition)	~1.8x	14.3	visual and auditory target detection	No 20 minutes, or 10 and 20, minute rests	No	Yes	No effect of time	Slower response times with increasing duration.	No frequency dependence: effect attributed to non-specific stress. Repeated exposures reduced effect of vibration.
	Wilkinson and Gray (1974)	3 hours	z-axis sinusoidal 5 Hz 1.2 ms^{-2} rms	~1.9x	17.1	compensatory tracking, visual seach, vigilance, Handwriting	Yes. But tasks performed at different times	Yes	Yes	Vigilance impaired, Tracking improved.	Vigilance impaired, Tracking improved.	Dependent upon feedback of earlier results. No feedback (conditions unmotivating), vibration reduced disruption, suggested to be due to arousal.

Table B.2. (continued)

Section	Authors	Duration	Vibration	Relation to FDP (max)	VDV (max)	Tasks	Continuous Performance?	Continuous Vibration?	Control Condition	Effects of Duration: Static	Effects of Duration: Vibration	Suggested Effect of Vibration
4.2 Studies Suggesting Vibration Dependent Effects	Guignard et al (1975)	16 mins to 8 hours	z-axis sinusoidal 2, 4 and 8 Hz on ISO boundaries	all 1x	16.5 (25 mins); 5.7 (8 hrs)	Foot tracking, visual detection, manual dexterity, visual acuity, auditory vigilance, grip strength.	No (rests provided with durations longer than 2.5 hours)	No	Yes	Performance on all tasks deteriorated with time. No difference in effect with vibration.		Subjects commented that the tasks were more difficult during vibration exposure.
	Hornick (1962)	30 mins	1.5-5.5 Hz, x,y and z-axes at 1.1, 1.8 and 2.5 ms^{-2} rms	(y-axis) ~2.1x	(y-axis) 22.8	Compensatory tracking, visual RT, foot pressure, peripheral vision, visual acuity	Yes	Yes	Pre- and post-vibration	--	Increase in tracking error carried over to post-exposure with y-axis vibration	Fatigue - but may not have been due to the vibration.
	Jackson (1956)	15 hours	Aircraft turbulence	Un-known	Un-known	Manual control of aircraft heading and altitude	No. 4 x 1hr periods within 2 hour watches	Var-ied	No	--	Deterior-ation over 4x2 hr periods within 15 hr flight	In first two 2 hour watches, turbulence enhanced per-formance. In last two watches turbulence impaired performance.

Table B.2. (continued)

Section	Authors	Duration	Vibration	Relation to FDP (max)	VDV (max)	Tasks	Continuous Performance?	Continuous Vibration?	Control Conditions	Effects of Duration		Suggested Effect of Vibration
										Static	Vibration	
Studies Suggesting Vibration Dependent Effects	Lewis and Griffin (1976)	60 mins	z-axis sinusoidal. 4 Hz at 1.2 ms^{-2} rms	1x	13	Zero-order pursuit tracking	Yes	Yes	Yes. also 15 mins post-exposure	Increasing mean square error (mainly remnant)	Increasing mean square error (mainly remnant)	Tendency for increasing error variance more prevalent for individual subjects data with vibration than without.

Table B.2. (continued)

Section	Authors	Duration	Vibration	Relation to FDP (max)	VDV (max)	Tasks	Continuous Performance?	Continuous Vibration?	Control Condition	Effect of Duration
4.3 Studies Showing No Effect of Duration	Catterson et al (1962)	20 mins	Sinusoidal z-axis. 2-15 Hz, magnitude dependent on frequency	~2.9x	47	Compensatory tracking	No (2x5 mins)	Yes	Same as vibration	No duration effect.
	Hornick and Lefritz (1966)	4 hours	Random, z-axis 1-12 Hz at 3 magnitudes up to 1.4 ms^{-2} rms	2.6x (based on 4-8 Hz)	21 (based on 4-8 Hz)	Compensatory tracking (3 difficulty levels), visual RT, vigilance	Yes	Yes	Pre- and post-vibration	At highest tracking difficulty level error increased with time.
	McLeod et al (1977)	50 mins	Random, pitch and roll axes. ~0.17 Hz at 0.17 ms^{-2} rms	Frequency range not covered in standards.		Pursuit tracking	No 7 second runs every 20-30 secs.	No 2x22 mins with 25 secs rest	Pre- and post-vibration only	No duration effect.
	Schmitz (1979)	90 mins	Sinusoidal z-axis. 2.5 and 3.5 Hz at 1.0 to 2.1 ms^{-2} rms	~1.6x	23	Compensatory tracking, visual acuity, foot pressure, foot RT, body equilibrium, hand tremor.	Yes	Yes	Pre- and post-only	No duration effects.

Table B.2. (continued)

Section	Authors	Duration	Vibration	Relation to VDP (max)	VDV (max)	Tasks	Continuous Performance?	Continuous Vibration?	Control Condition	Effect of Duration
Studies Showing No Effect of Duration	Shoenberger (1973)	41 mins	Sinusoidal z-axis. 5Hz at $3.5 ms^{-2}$ rms	2.5x	35	Sternberg task (choice RT)	Yes	Yes	None	No duration effect.
	Stave (1977)	3-8 hours	12 Hz at 0.707 ms^{-2} rms 12 Hz at 0.707 and 2.1 ms^{-2} rms	~ 4x	21	Flying heli-copter simula-tor.	Yes (except for 8 hr run)	Yes (except for 8 hr run)	Yes (But not all con-ditions)	Improvement up to 3 hours followed by impairment. Subjects reported fatigue and lack of arousal.
	Stave (1979)	2 hours	Sinusoidal z-axis 6,8,10,12 Hz at 1-3 ms^{-2}rms on floor	~ 3x	32	Flying heli-copter simu-lator	No 5 mins rest after 1 hour	No 5 mins rest after 1 hour	Same as vibration	Some initial improvement followed by impairment.

Appendix C: System Dynamics

The system dynamics used in the experimental program described in this thesis were based on information supplied by the Flight Systems group at the Royal Aircraft Establishment (RAE), Farnborough. The dynamics were programmed on VIDAC 1224 and 336 analogue computers. The author wishes to acknowledge the assistance of Dr. C.H. Lewis of the ISVR in implementing these dynamics.

The dynamics were based on the MD20 fly-by-wire control system which was used in a Hunter aircraft at the RAE. In the small perturbation dynamics used in the thesis, the MD20 system was simplified by ignoring all lag terms with natural frequencies greater than 20 rads s^{-1} (which are mostly due to gyro noise filters). The rudder inputs and trim system were also omitted. No stick shaping or filtering was used.

The dynamics define angular rotations of the 'airframe' in roll, pitch and yaw axes in response to stick commands in 2 axes (fore-and-aft and lateral). The 'airframe' rotations were resolved with respect to a fixed ground reference. Rotations were limited to ± 10 degrees in pitch and yaw axes, and to ± 90 degrees in the roll axis.

The flight conditions represented by the model are listed in Table C.1, and the theoretical short period response of the aircraft is compared with the analogue computer model in Table C.2. The natural period of the short period mode (10.24 rads s^{-1}) was close to that of the theoretical aircraft (10.04 rads s^{-1}). Although the damping of the model (0.39) was lower than that of the aircraft (0.66), the system was subjectively easy to control.

The equations used to define the analogue computer model are shown in Table C.3. Symbols used are defined in Table C.4.

The moduli of the transfer function of these dynamics in the roll, pitch and yaw axes is shown as Figure 4.2 in Chapter 4. The analogue computer patch diagram is shown on Figure C.1.

TABLE C.1

HUNTER MODEL FLIGHT CONDITIONS

Forward speed	:	272 ms^{-1} = 0.8 Mach
Altitude	:	50 m
Gross weight	:	9072 kg
Trim condition	:	Straight and level flight

TABLE C.2

COMPARISON OF SHORT PERIOD PITCH RESPONSE CALCULATED FOR AIRCRAFT WITH THAT MEASURED FROM THE ANALOGUE COMPUTER MODEL

	NATURAL FREQUENCY	DAMPING
Theoretical Aircraft	10.04 rad s^{-1}	0.66
Analogue Computer Model	10.24 rad s^{-1}	0.39

TABLE C.3

EQUATIONS USED TO DEFINE THE SYSTEM DYNAMICS

(SEE TABLE C.4 FOR KEY TO VARIABLES)

$$sp = -4.21p + 0.345r - 48.6\xi + 35.1\beta$$

$$sq = -17.7\alpha - 11.4\eta - 2.86q$$

$$sr = -0.692r + 12.2\beta - 4.0\xi - 0.042p$$

$$s\alpha = 2.45\alpha + 0.022\eta - q$$

$$s\beta = -0.267\beta + 0.016p - r + 0.036\phi$$

$$s\phi = p + 0.016r$$

$$s\theta = p$$

$$s\psi = r$$

$$s\eta = -20\eta + 7.06C\theta - 2.66q$$

$$s\xi = -20\xi + 20C\phi + 1.51p$$

(N.B. $s = \frac{d}{dt}$)

TABLE C.4

AIRCRAFT MODEL VARIABLES

SYMBOL	VARIABLE	UNITS	POSITIVE SIGN CONVENTION
p	airframe roll rate	degrees/s	Starboard wing down
q	airframe pitch rate	degrees/s	Nose up
r	airframe yaw rate	degrees/s	Turn to starboard
α	angle of attack	degrees	Nose up
β	sideslip angle	degrees	To starboard
ϕ	roll attitude	degrees	Starboard wing down
θ	pitch attitude	degrees	Nose up
ψ	yaw attitude or heading	degrees	Turn to starboard
η	elevator angle	degrees	Downwards
ξ	aileron angle	degrees	Starboard aileron down
n_z	normal acceleration	G	Gravitation
$C\theta$	Longitudinal stick command	volts	Forwards
$C\phi$	Lateral stick command	volts	To starboard

Note: Positive deflection of the control surface produces a negative moment about the appropriate axes.

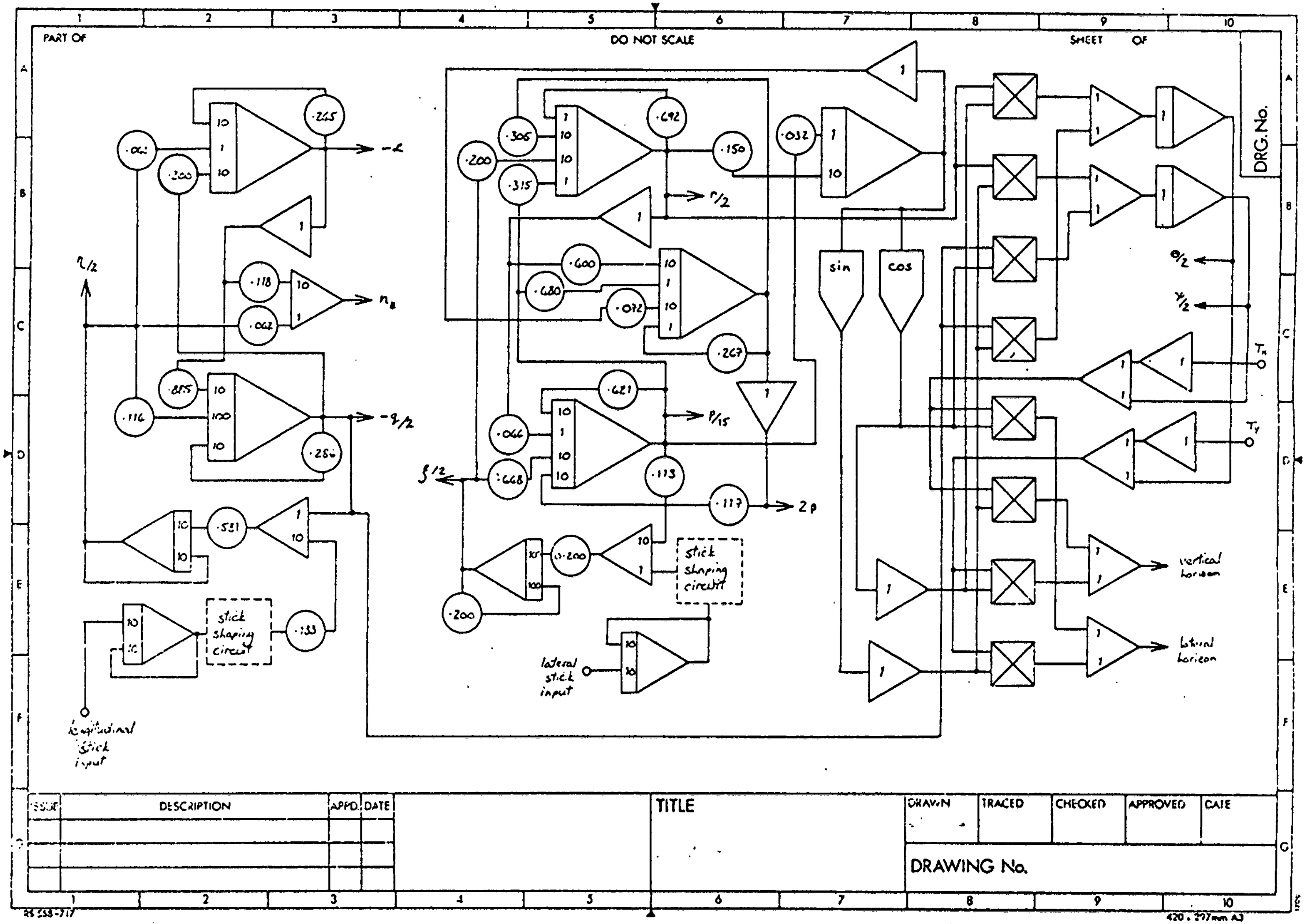


Figure C.1. Analogue computer patch diagram for implementing the system dynamics. (Drawn by C.H.Lewis)

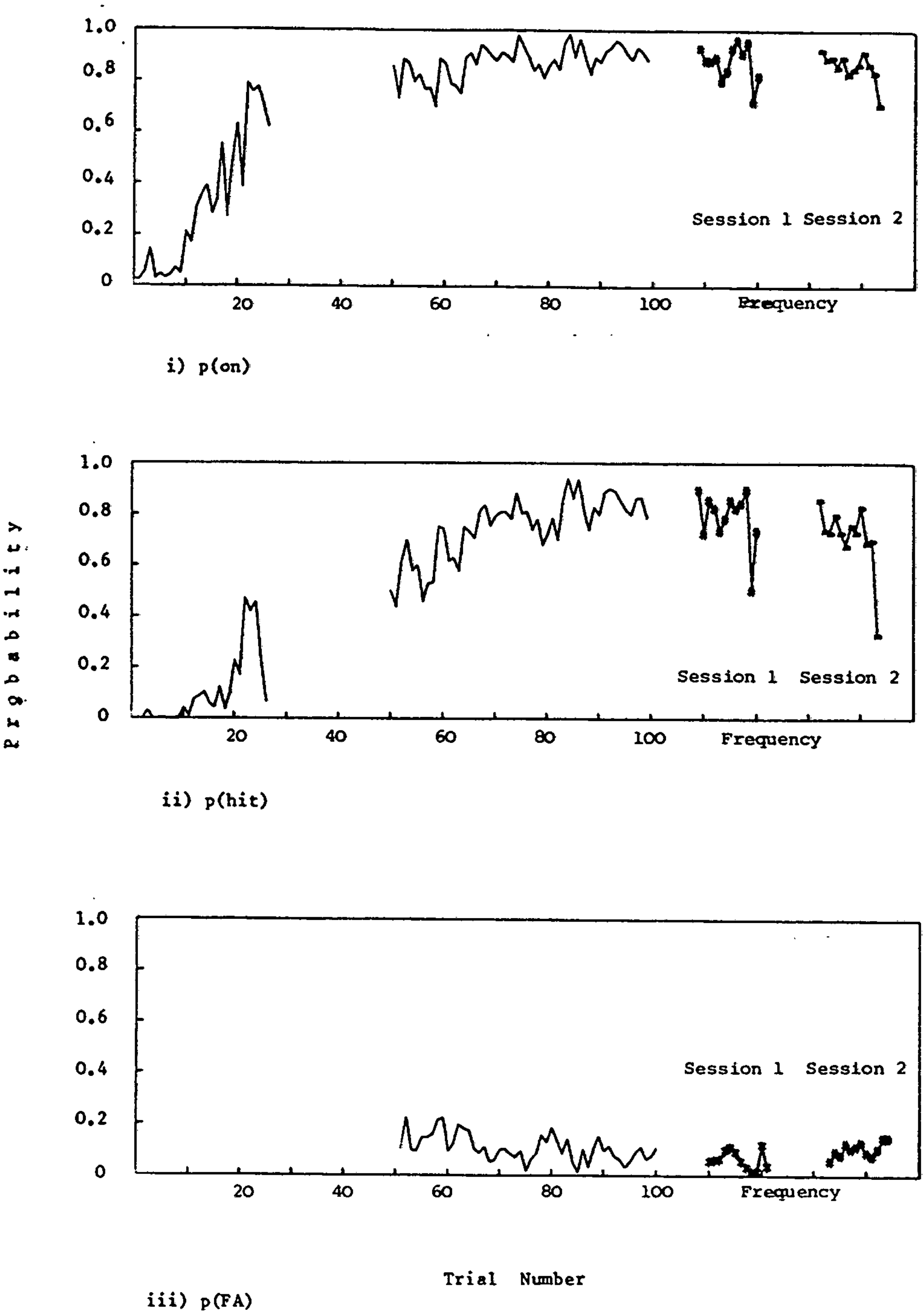
APPENDIX D

TRAINING DATA

This appendix provides training data for the subjects used in the experimental program reported in Chapters 5 to 10. Two groups of subjects were used. Group A comprised 8 subjects. They all took part in Experiment 2 (Chapter 6), and 6 of them took part in Experiment 3 (Chapter 7). Details of the training provided for these subjects are described in the 'Method' section of Experiment 2. Figure D.1. shows the probability of being 'on' target - p(on) -, of 'hitting' the target - p(hit) - and of making a 'False Alarm' - p(FA) - for the 100 training runs, and on the final 2 experimental sessions (referred to as Sessions II and III in Chapter 6). The first 2 experimental sessions were presented after training trial 26; these data are not included on Figure D.1. For 6 of these subjects, the training data for runs 1 to 50 lost. Data for the two experimental sessions are shown as a function of increasing vibration frequency, not the trial number. Subjects 7 and 8 were recruited after the first 2 experimental sessions.

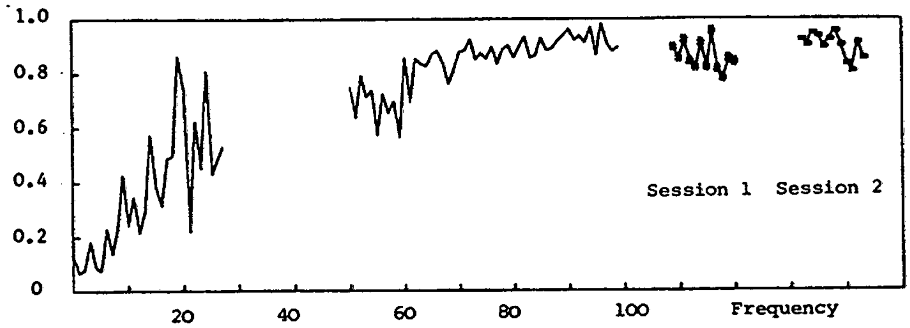
There were 16 subjects in the second group (Group B). All 16 subjects took part in Experiment 4 (Chapter 8), 14 took part in Experiment 6 (Chapter 10), and 8 took part in Experiments 1 (Chapter 5) and 5 (Chapter 9). Details of the training provided for these subjects are described in the 'Method' section of Experiment 4. Figure D.2. shows p(on), p(hit), and p(FA) as a function of trial number for the 16 subjects in Group B.

Details of the subjects used in each experiment are given in Table 4.4 in Chapter 4. (On this table, the subjects in Group B are numbered 9 to 24).

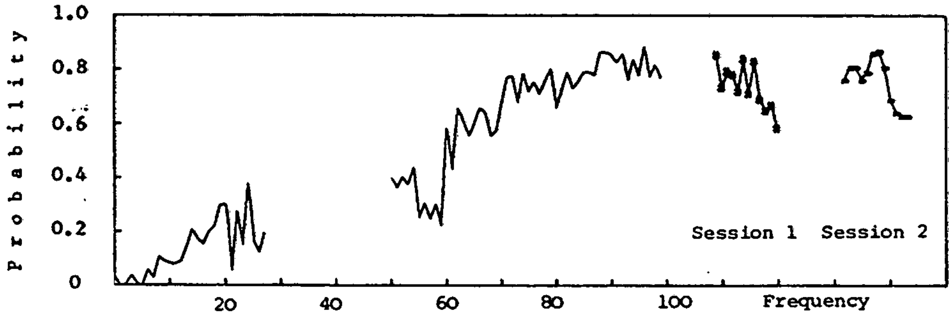


Group A, Subject 1

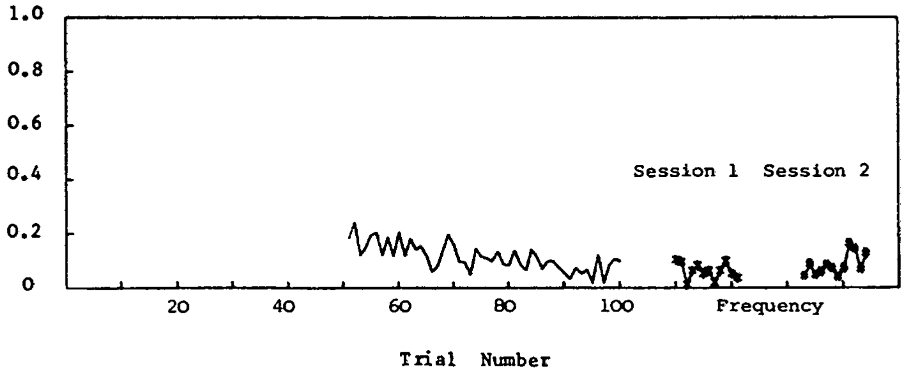
Figure D.1. Training data for the 8 subjects in Group A.



i) p(on)



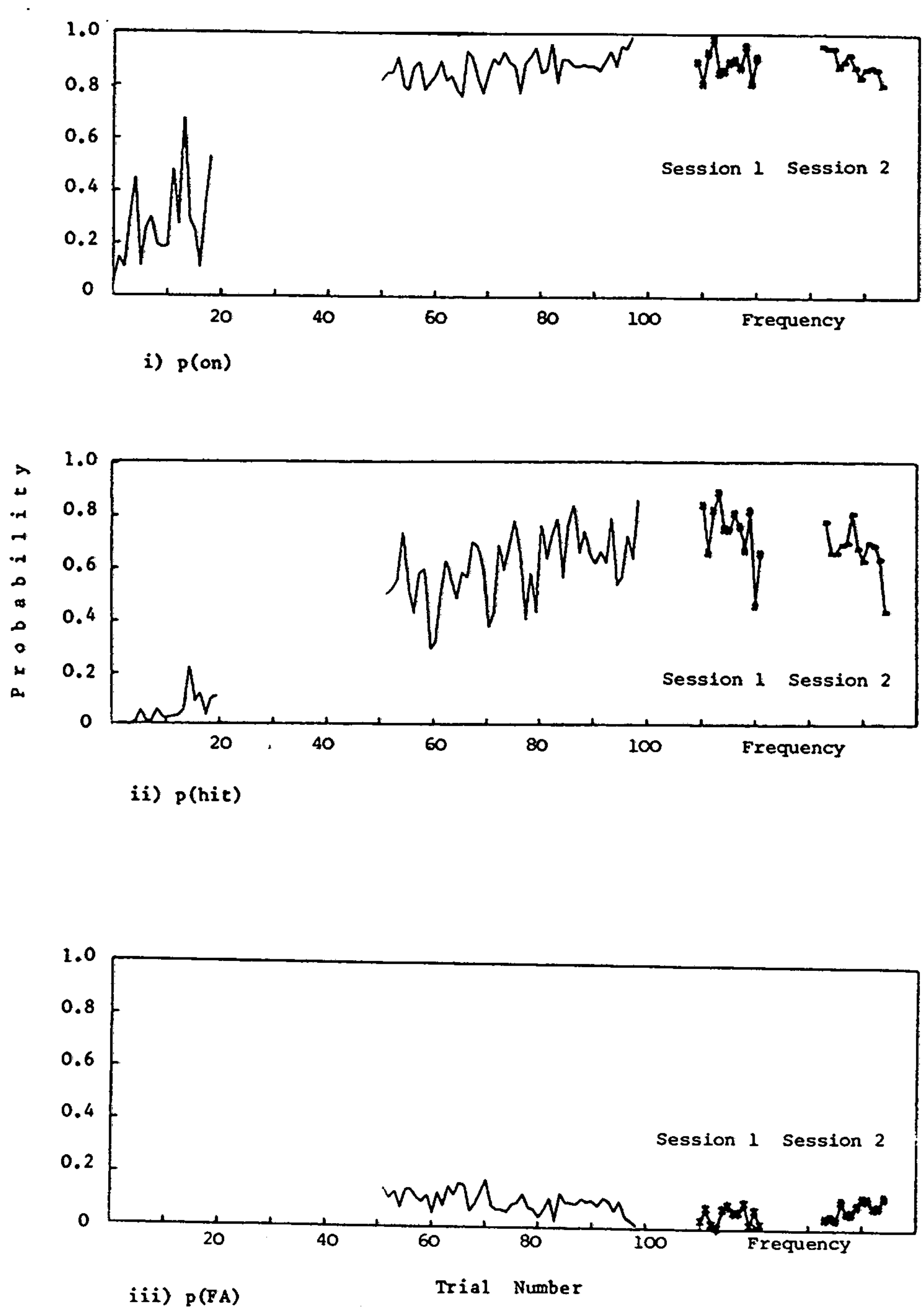
ii) p(hit)



iii) p(FA)

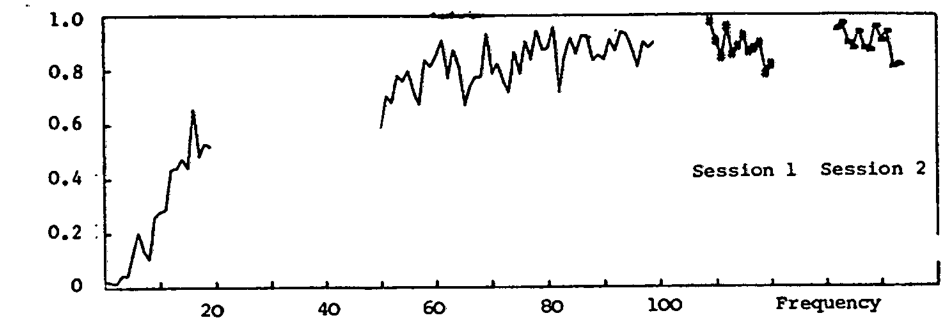
Group A, Subject 2

Figure D.1. (continued)

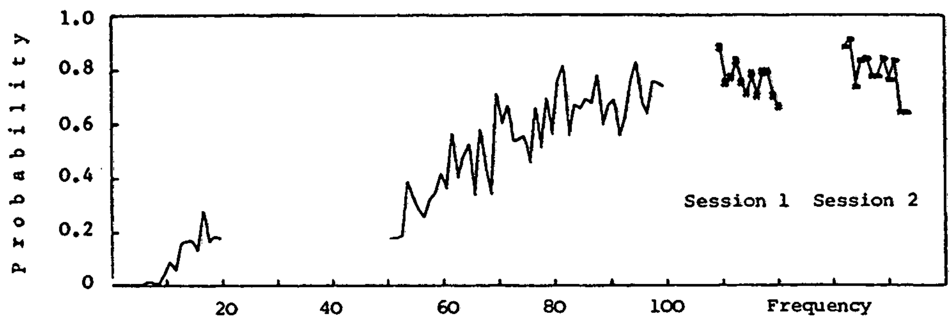


Group A, Subject 3

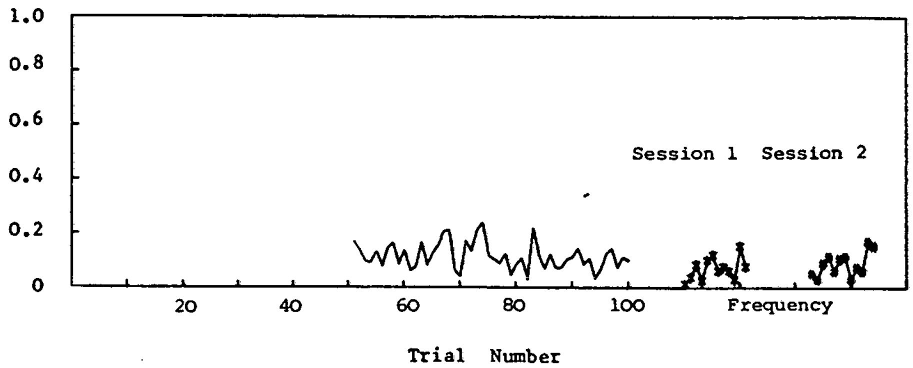
Figure D.1. (continued)



i) p(on)



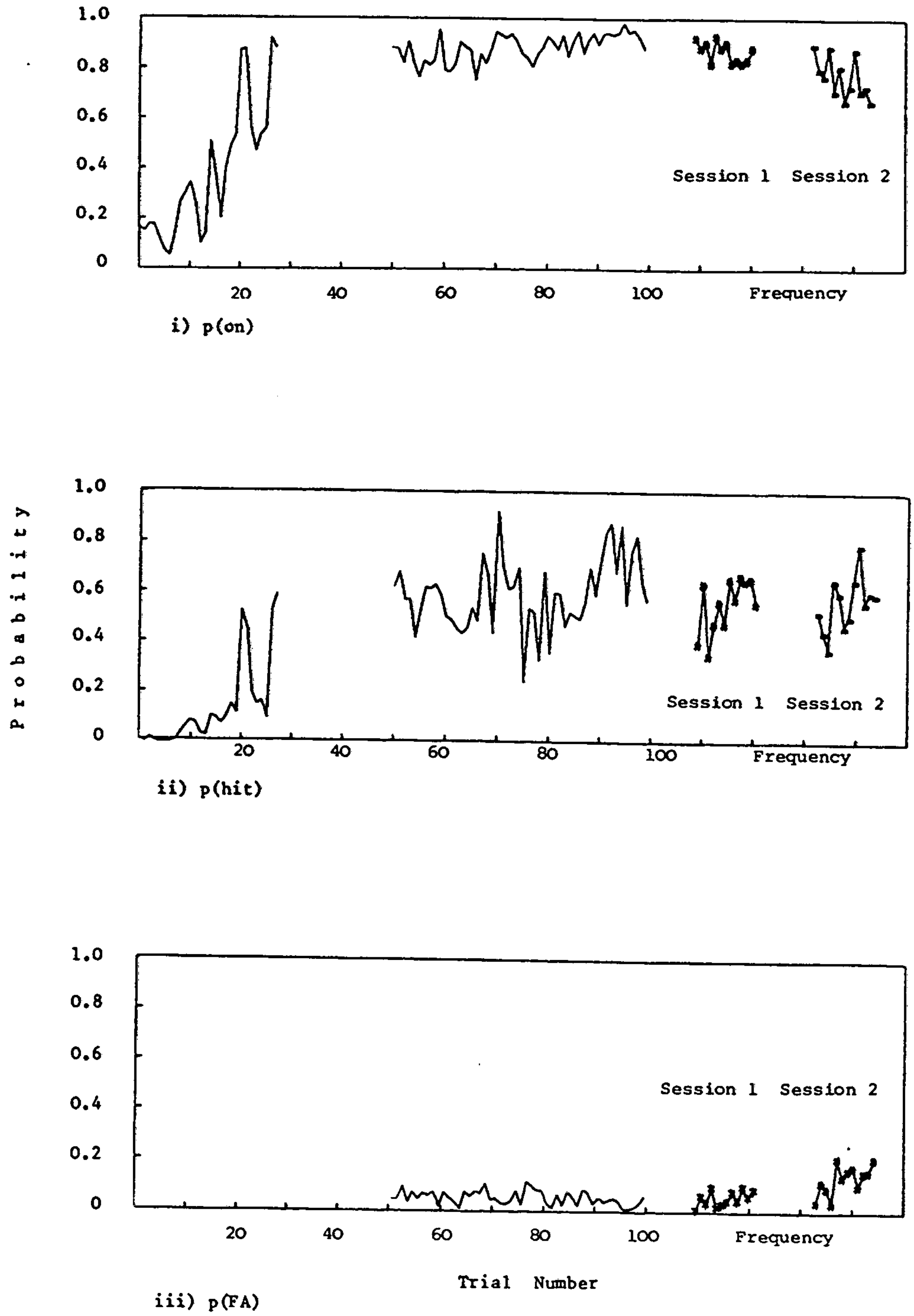
ii) p(hit)



iii) p(FA)

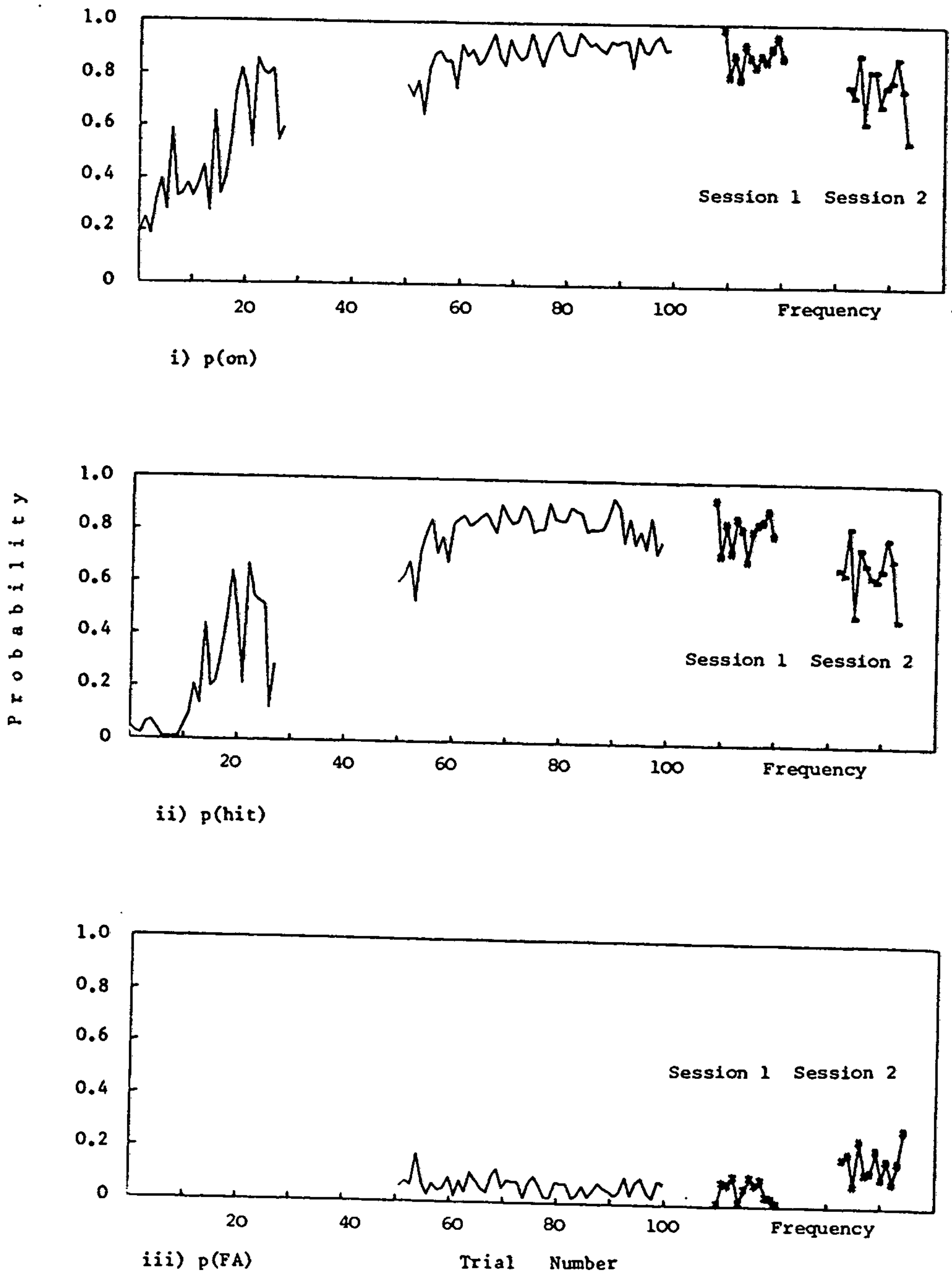
Group A, Subject 4

Figure D.1. (continued)



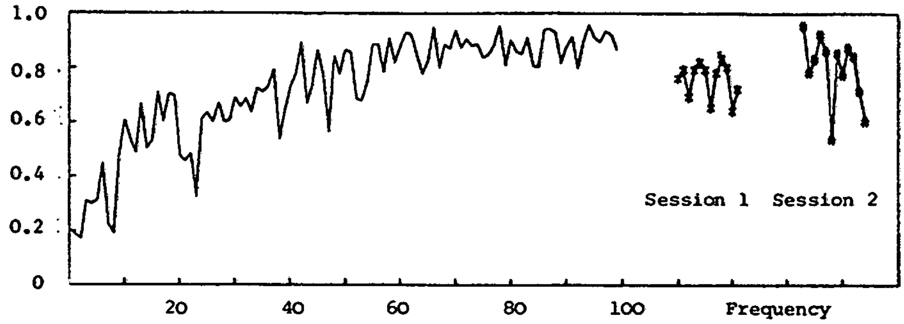
Group A, Subject 5

Figure D.1. (continued)

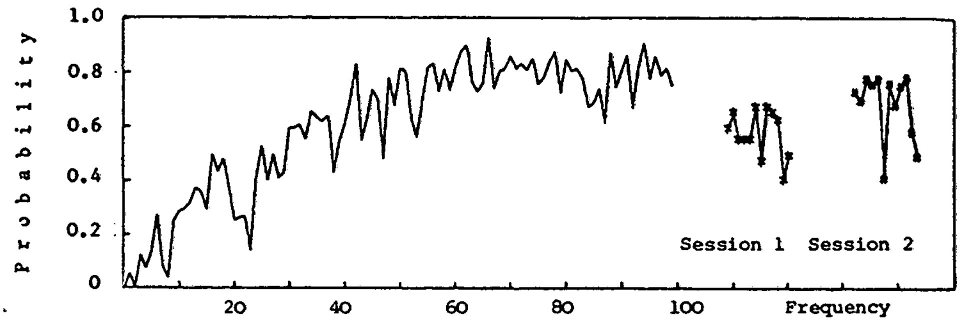


Group A, Subject 6

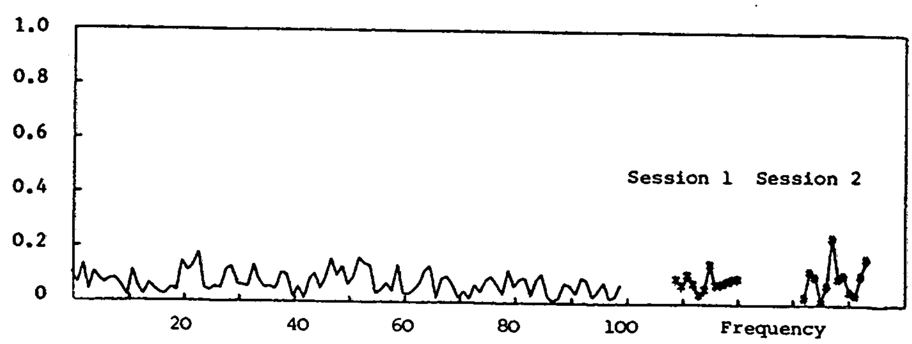
Figure D.1. (continued)



i) p(on)



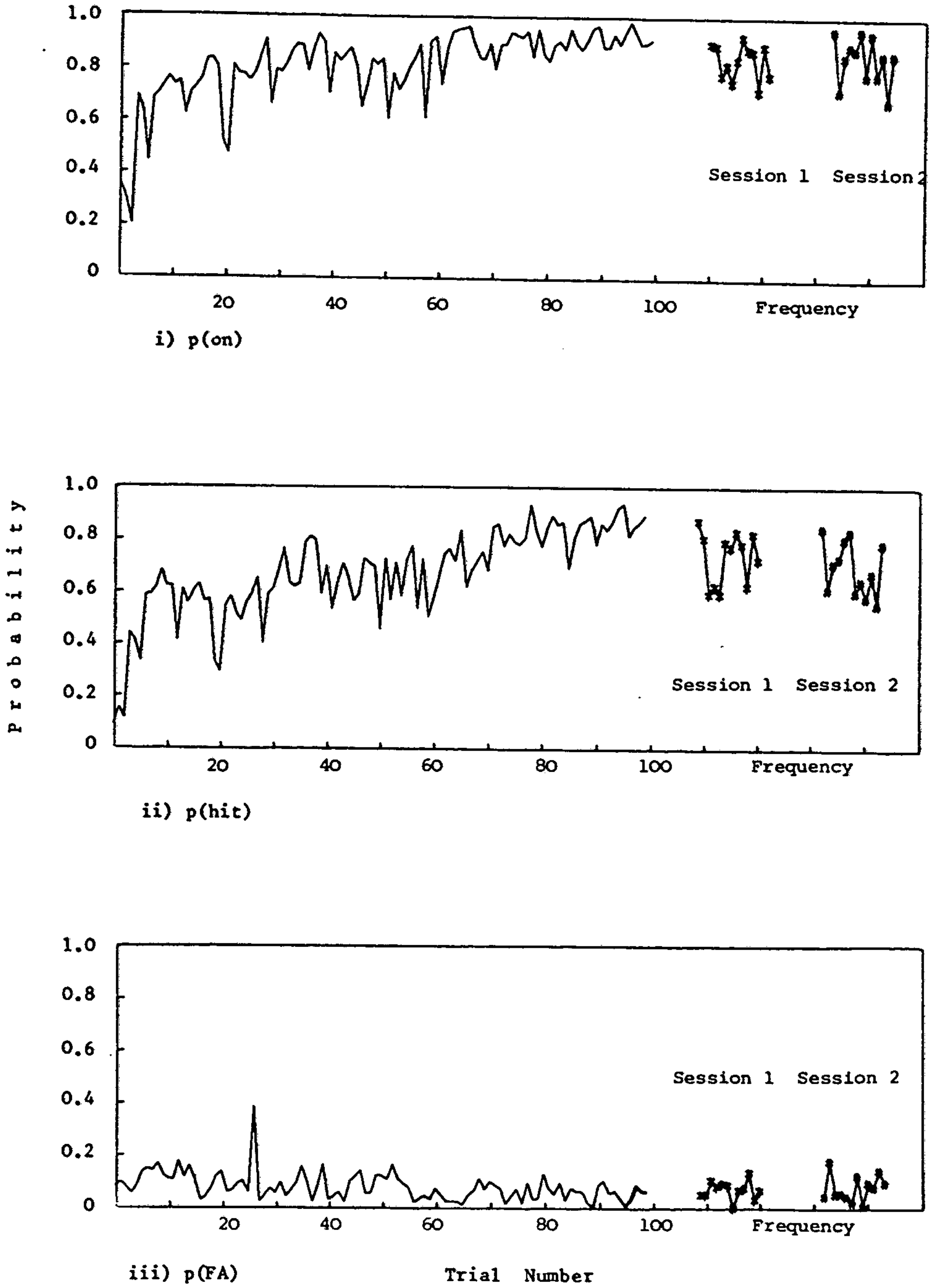
ii) p(hit)



iii) p(FA) Trial Number

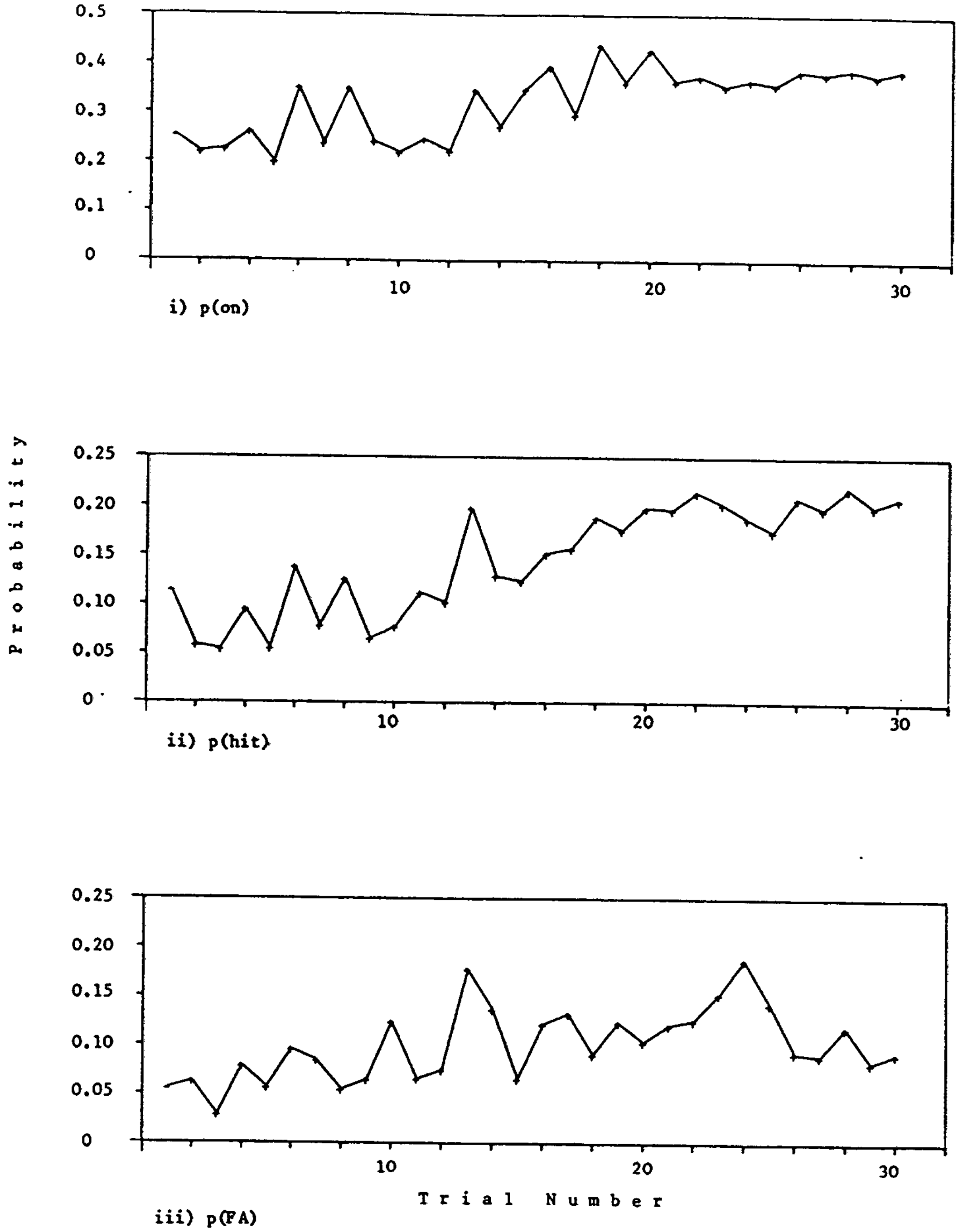
Group A, Subject 7

Figure D.1. (continued)



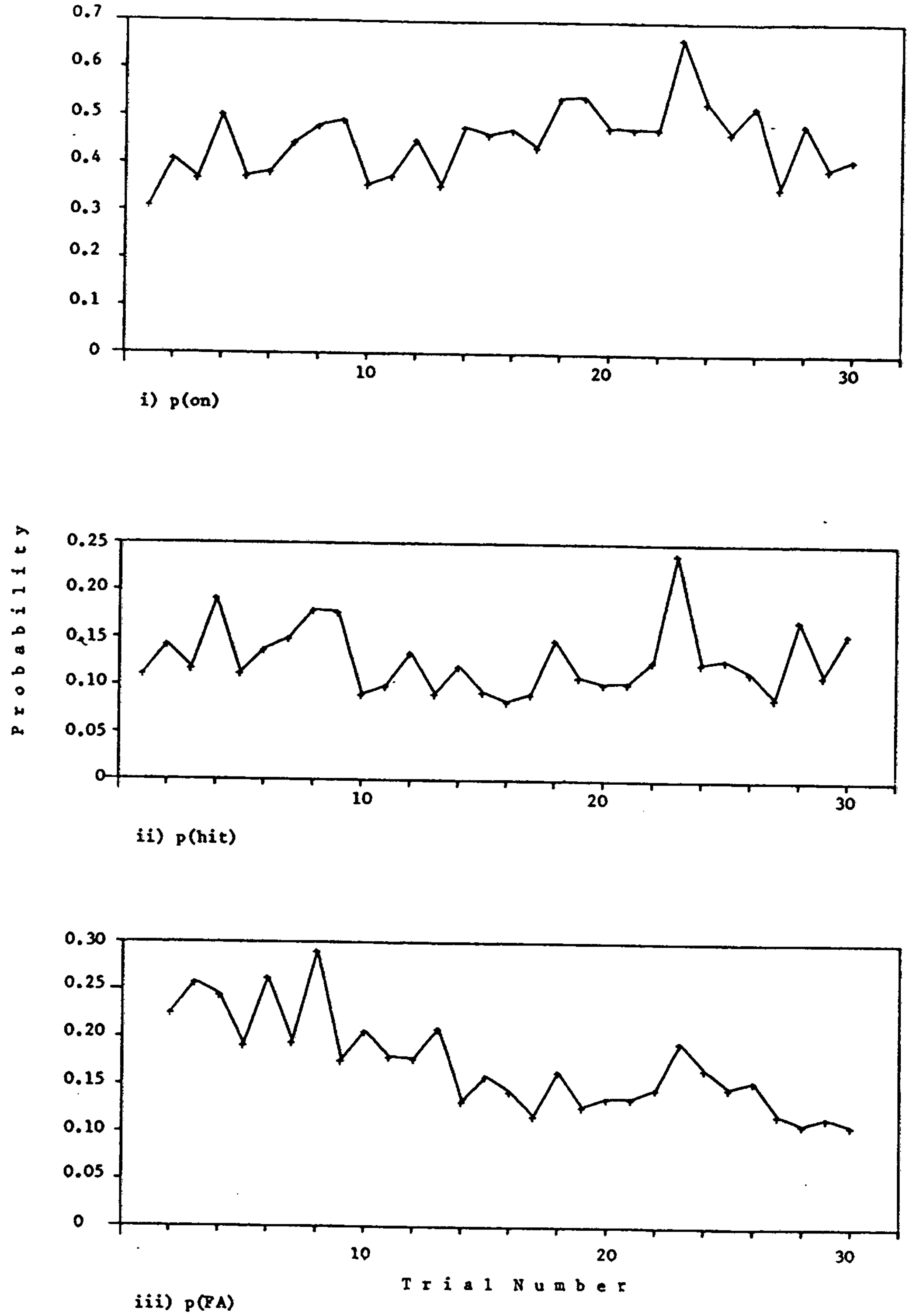
Group A, Subject 8

Figure D.1. (continued)



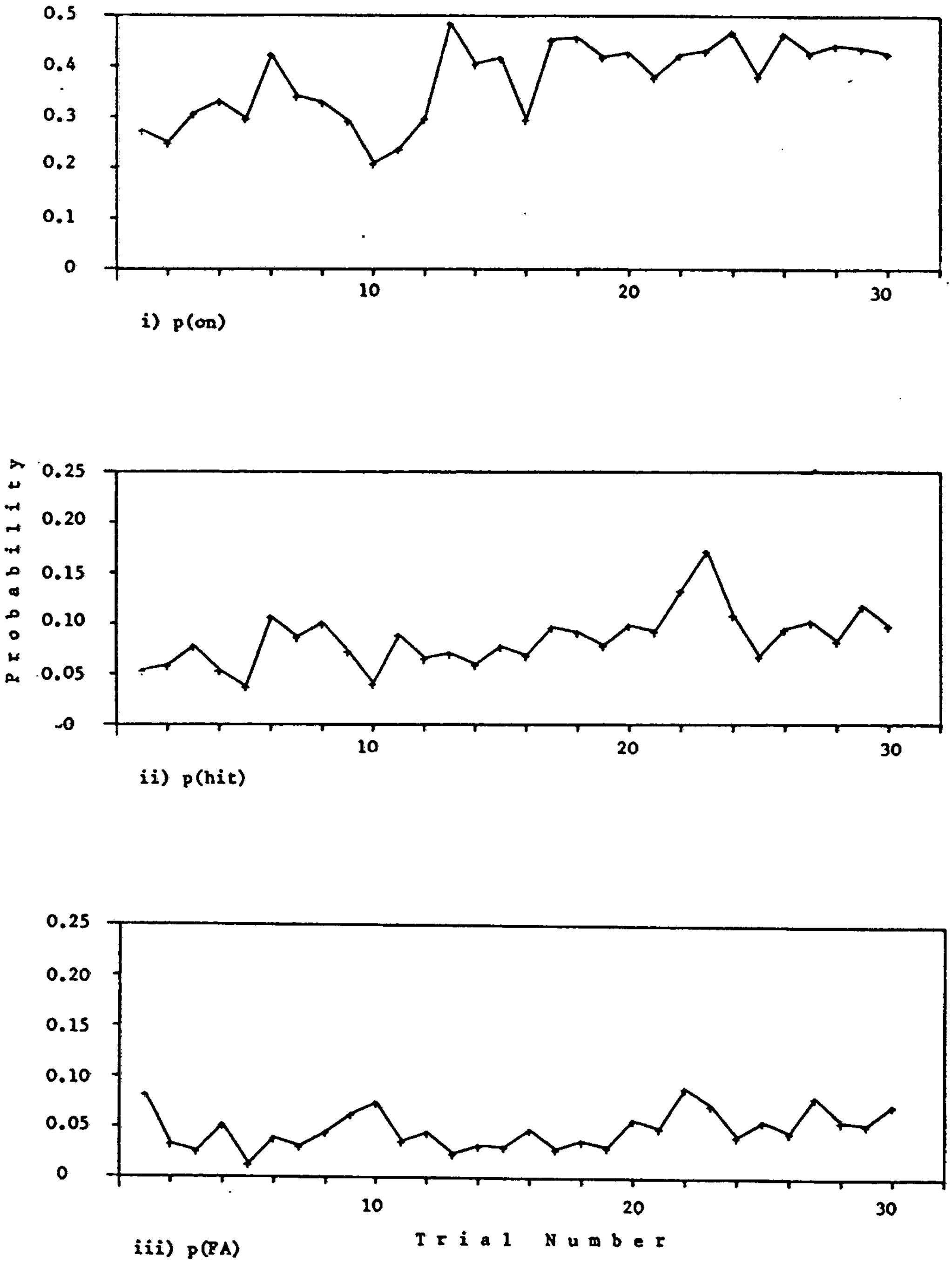
Group B, Subject 1

Figure D.2. Training data for the 16 subjects in Group B.



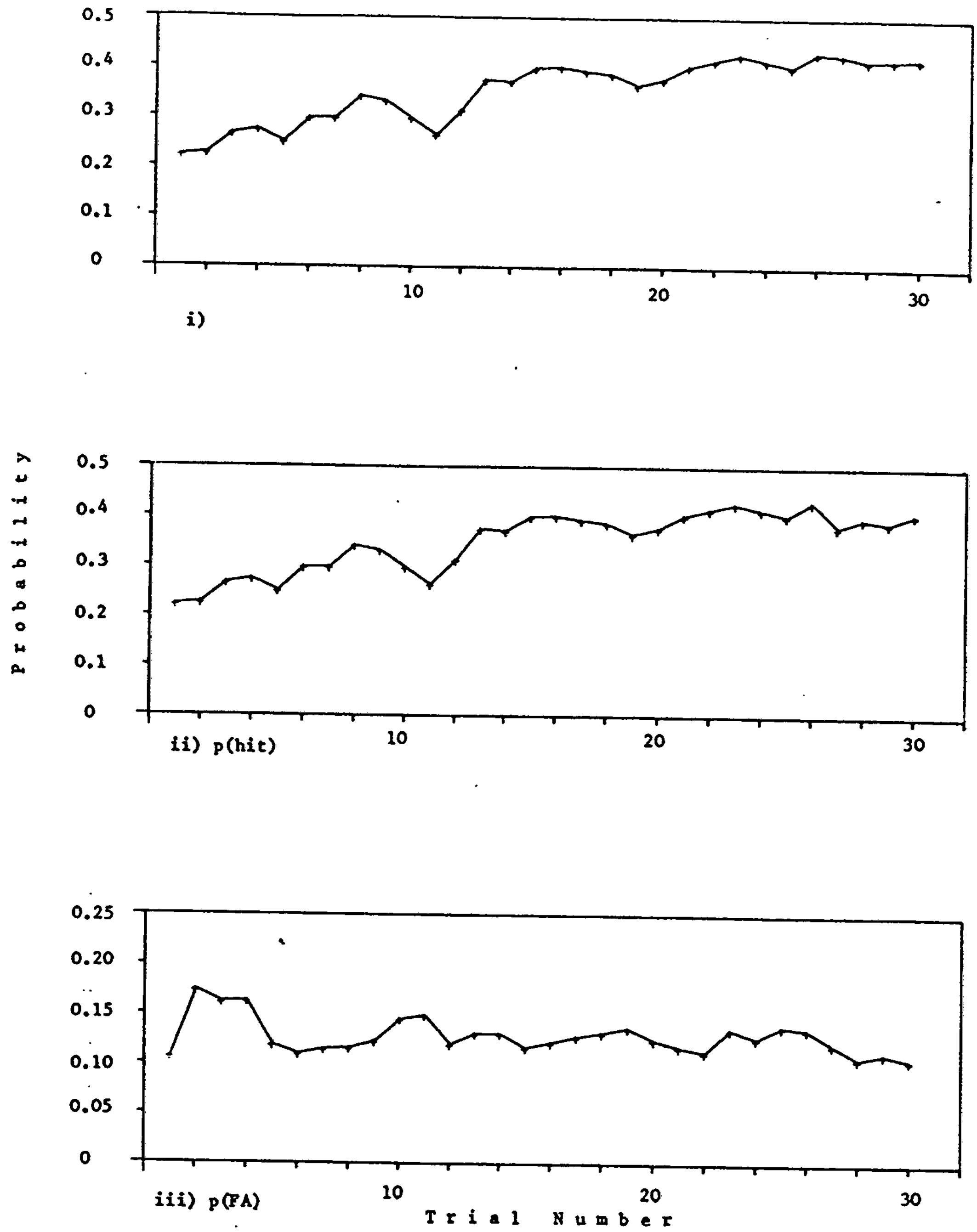
Group B, Subject 2

Figure D.2. (continued)



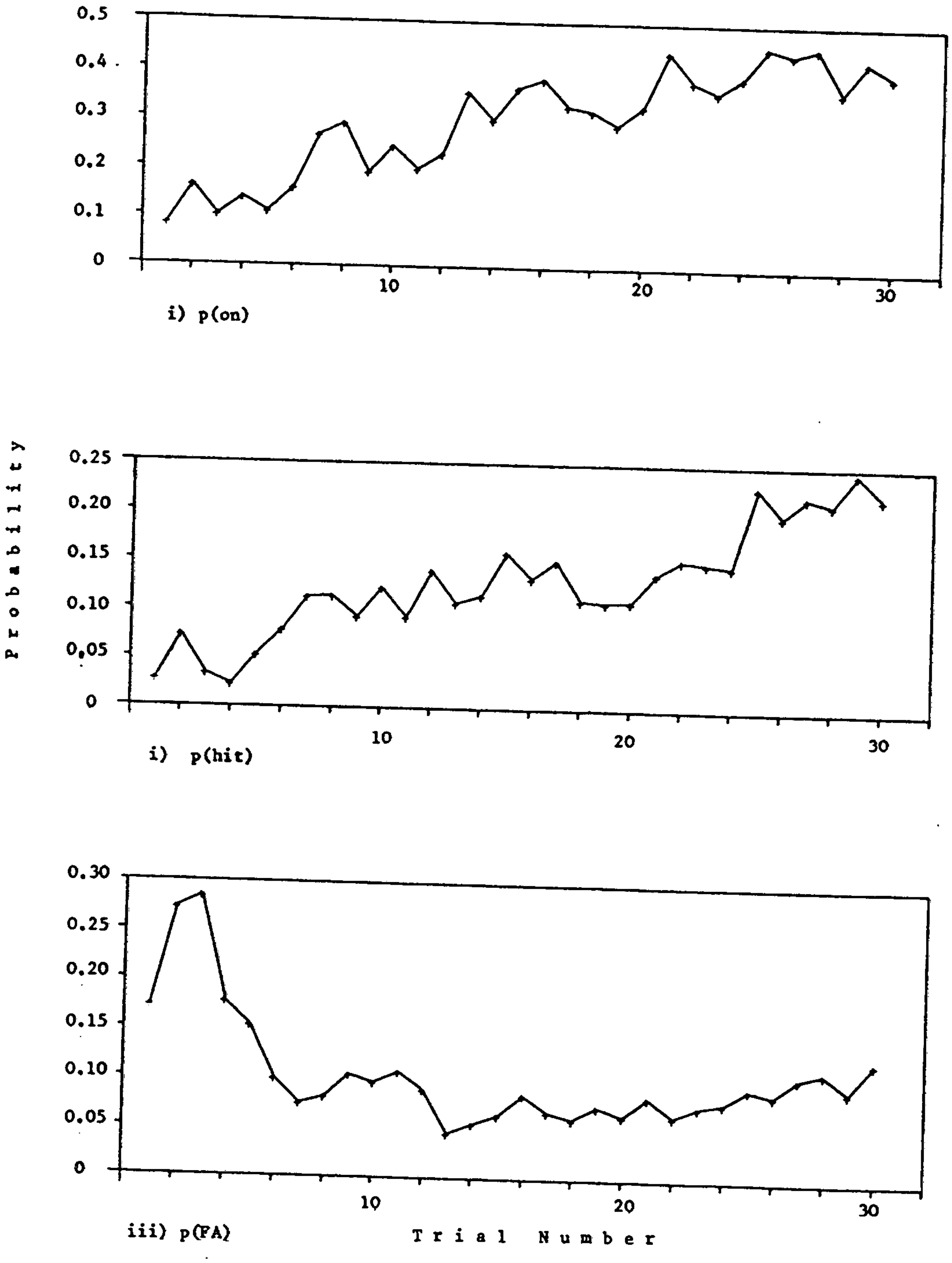
Group B, Subject 3

Figure D.2. (continued)



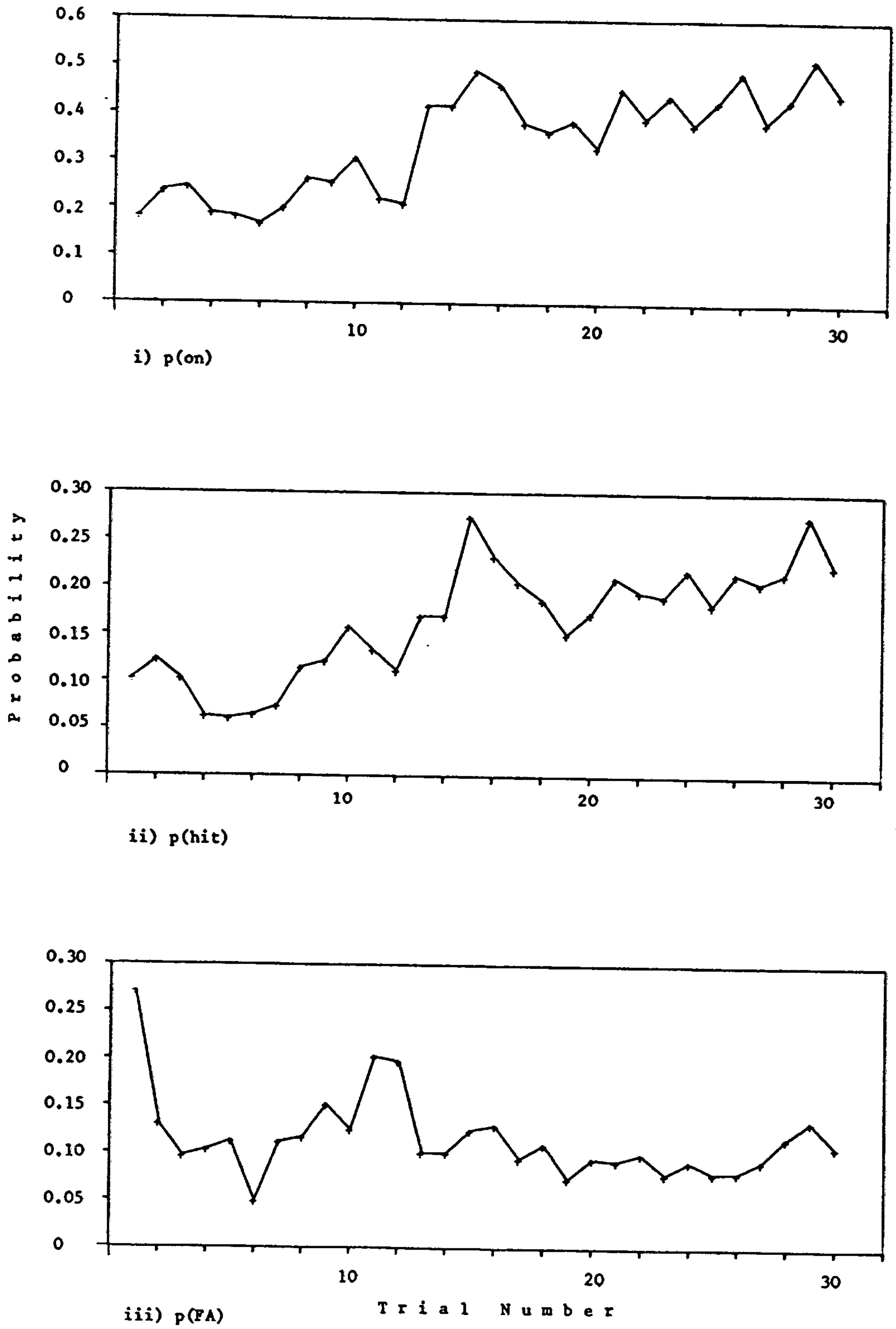
Group B, Subject 4

Figure D.2. (continued)



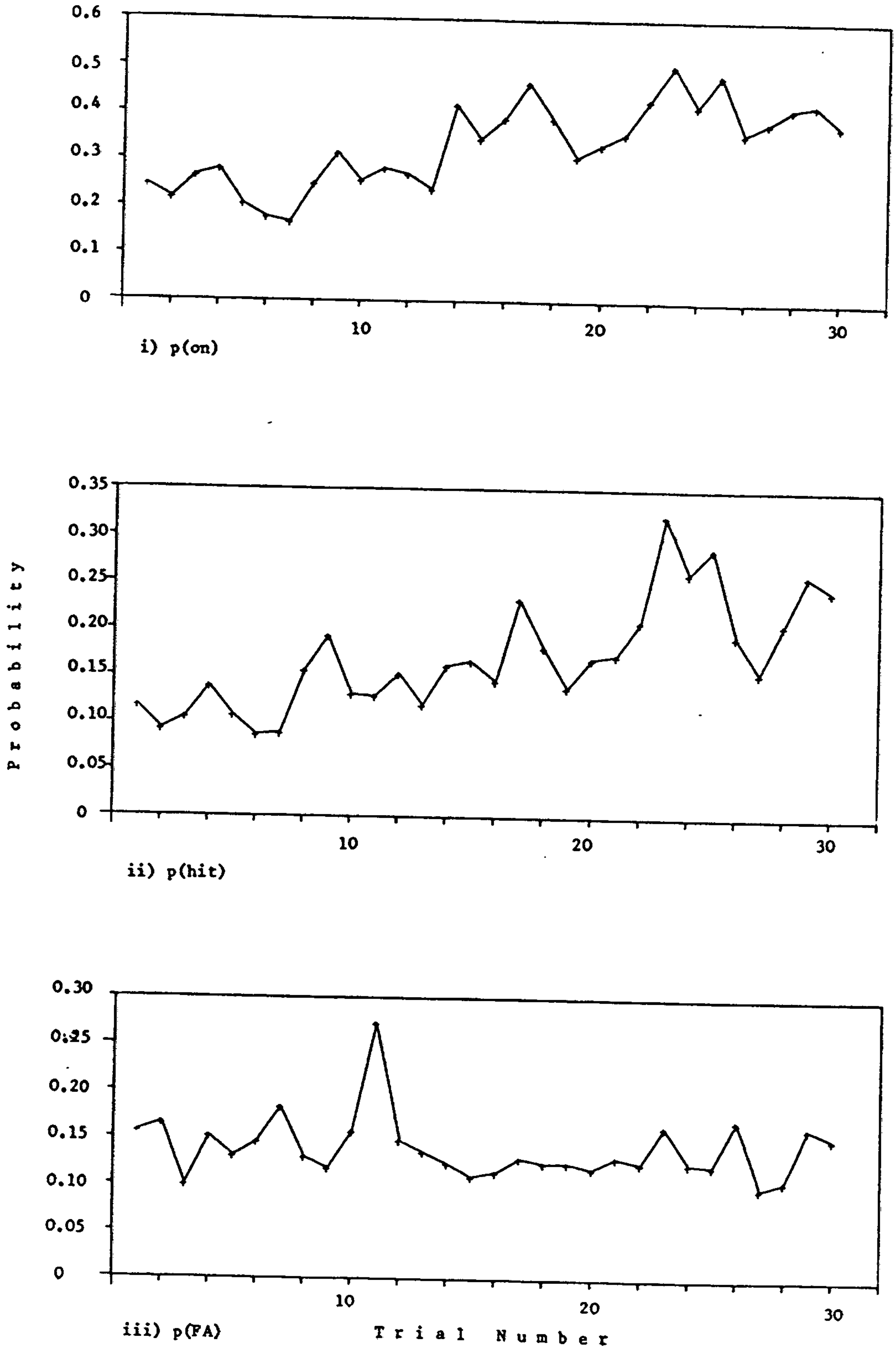
Group B, Subject 5

Figure D.2. (continued)



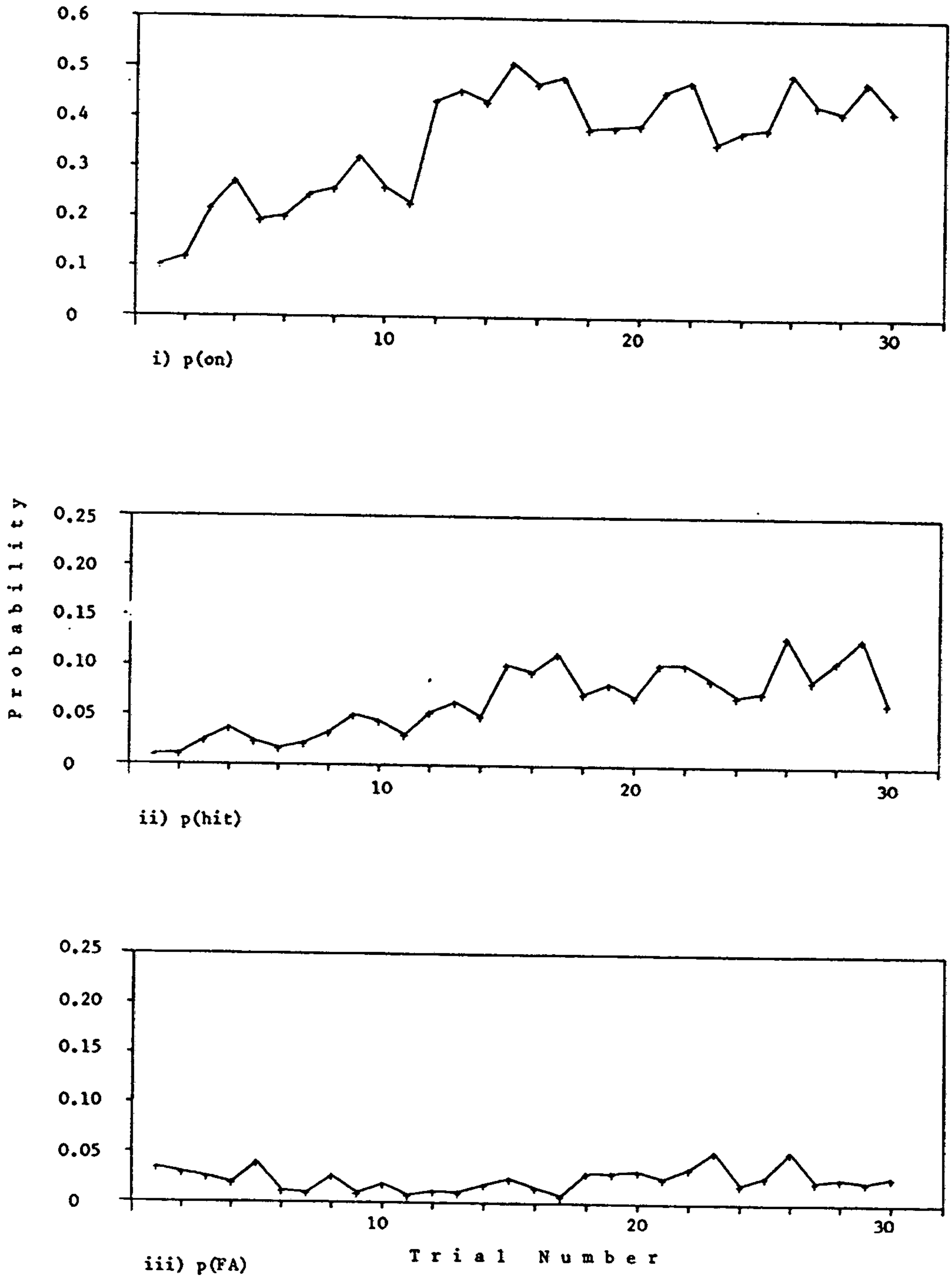
Group B, Subject 6

Figure D.2. (continued)



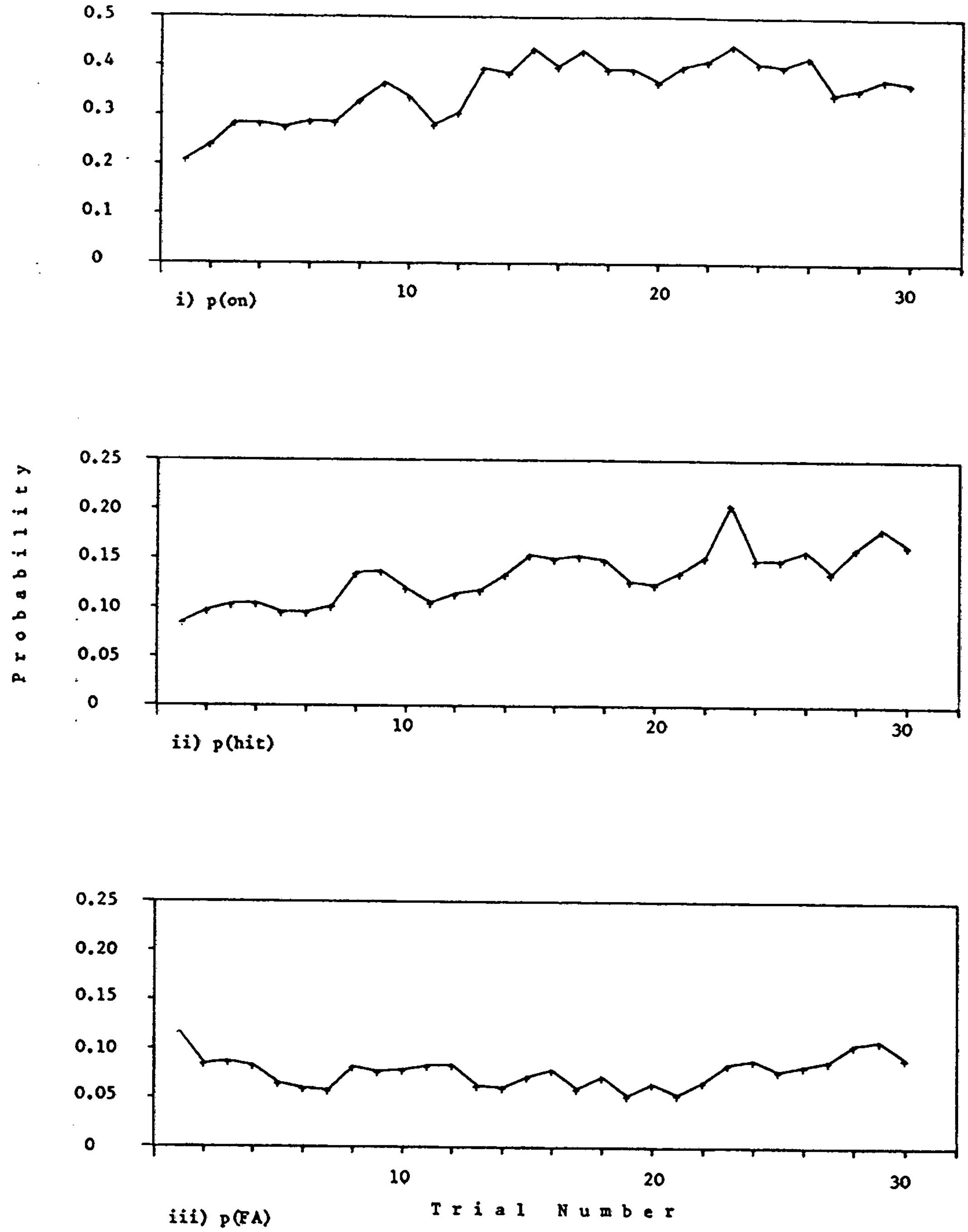
Group B, Subject 7

Figure D.2. (continued)



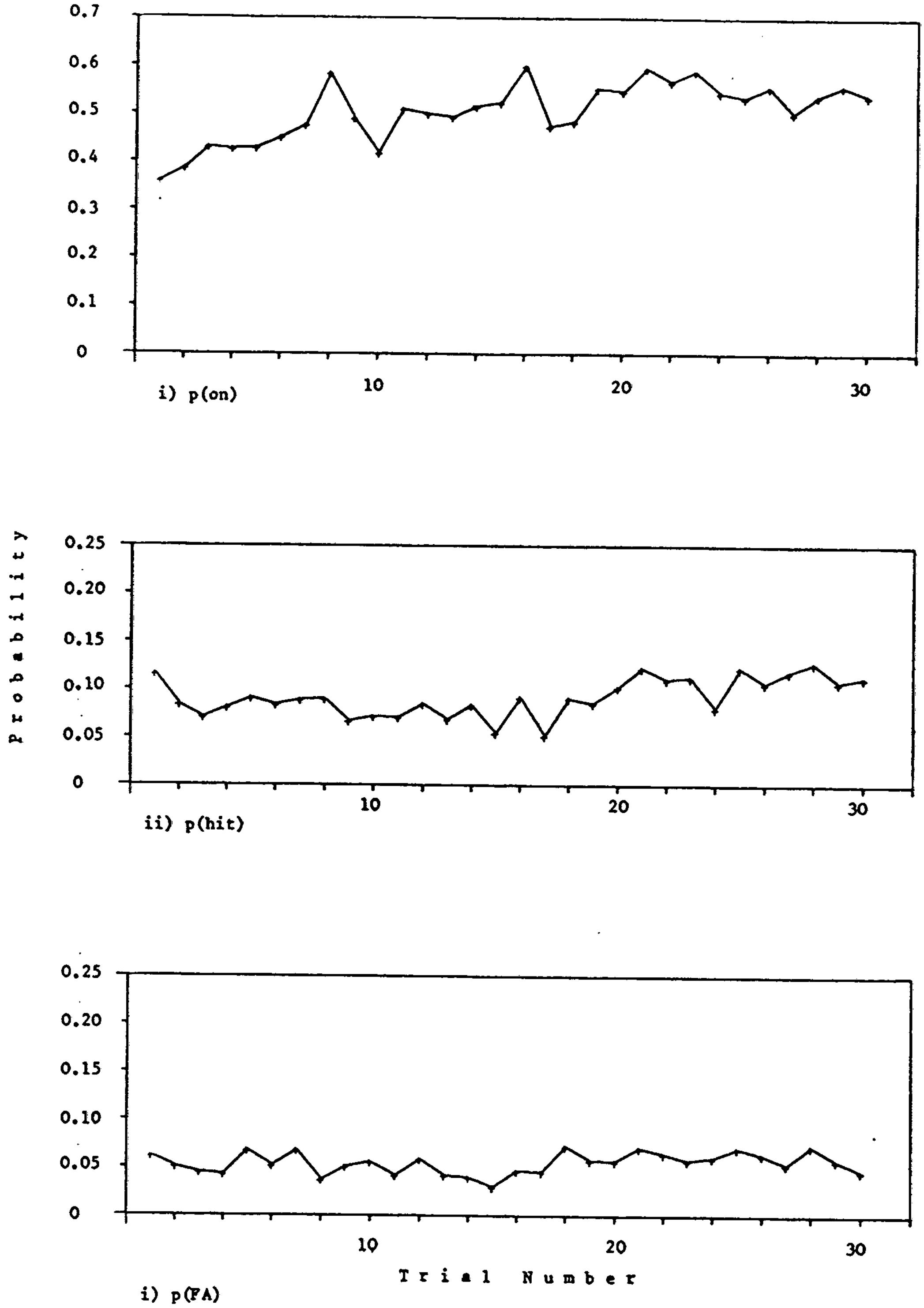
Group B, Subject 8

Figure D.2. (continued)



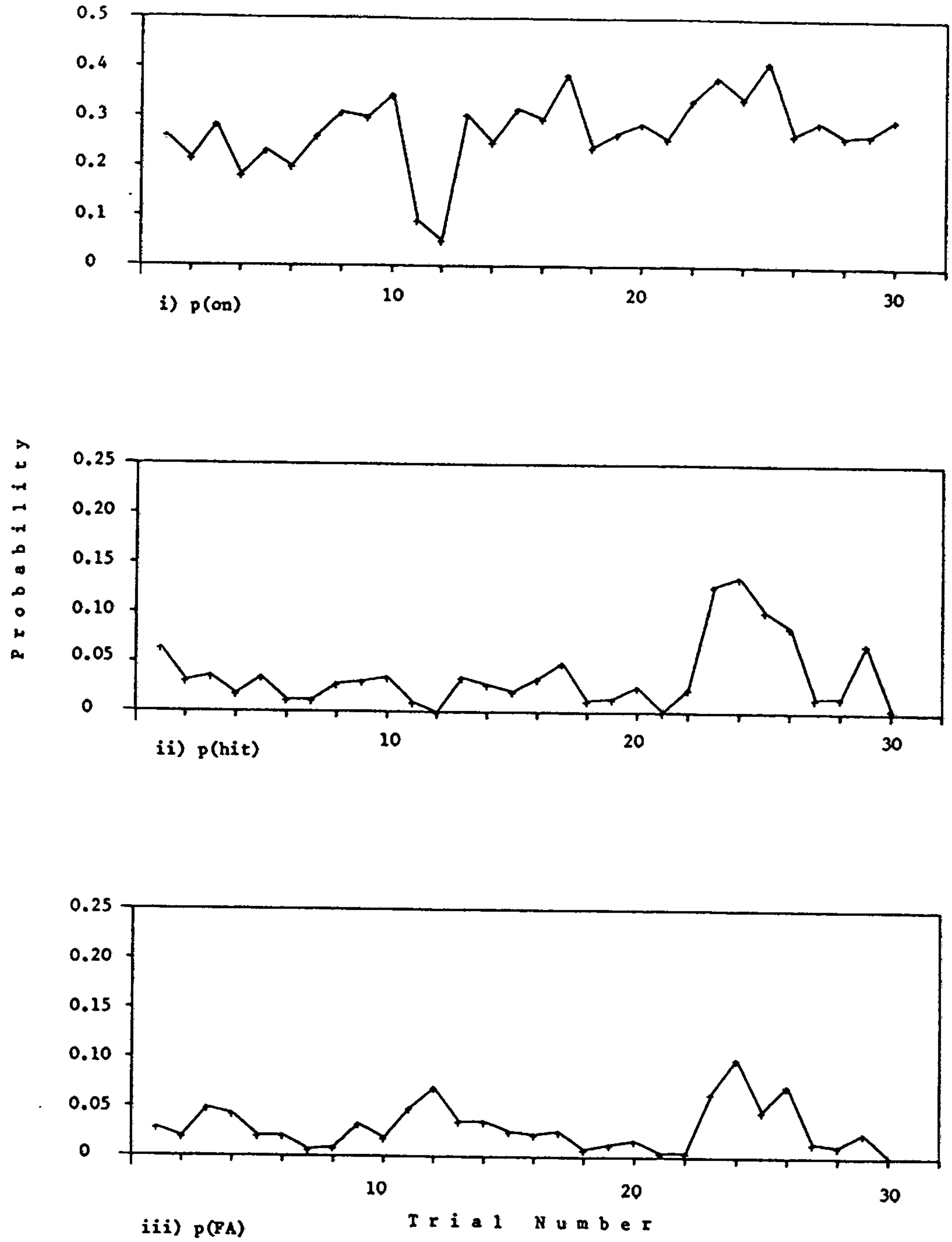
Group B, Subject 9

Figure D.2. (continued)



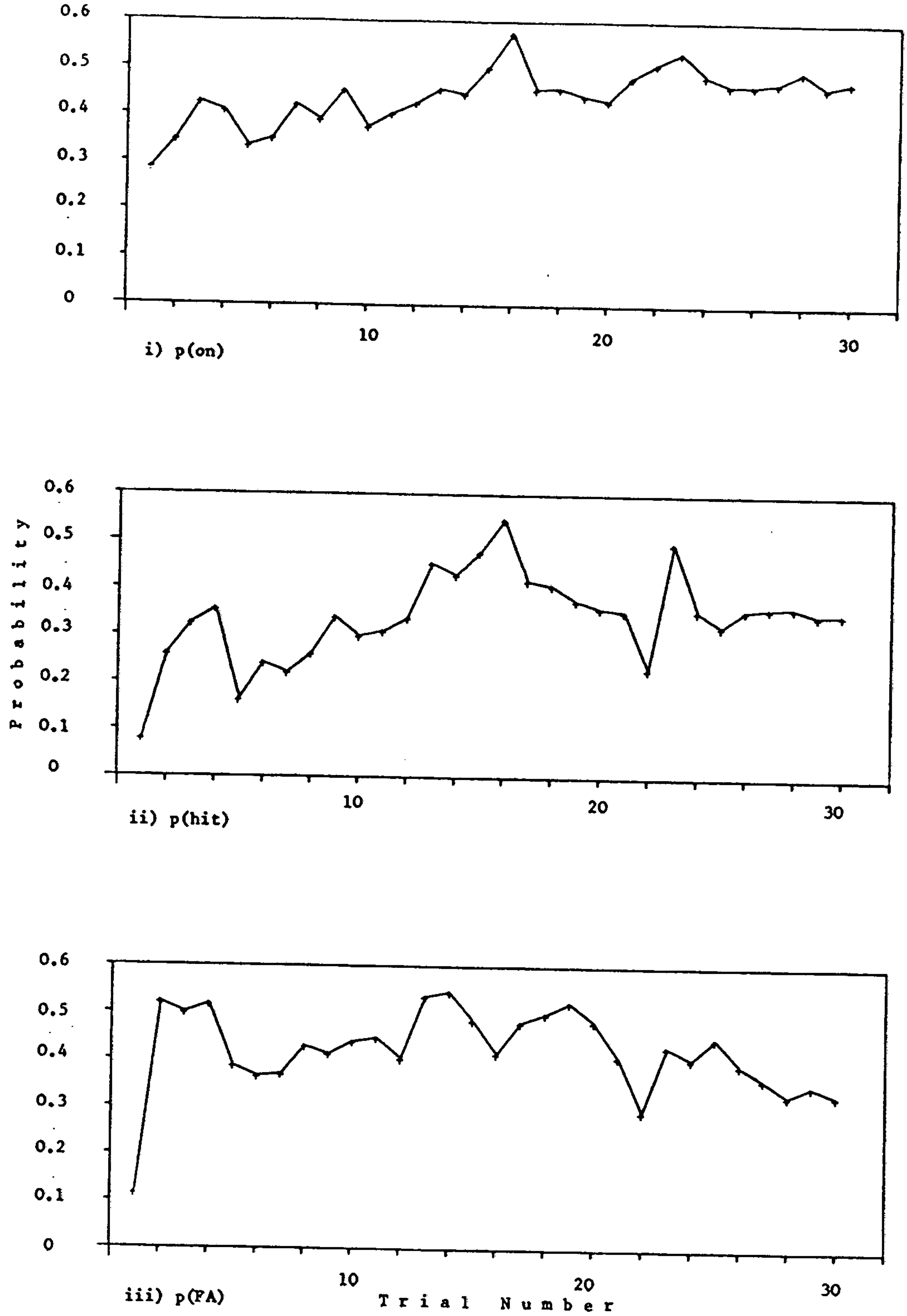
Group B, Subject 10

Figure D.2. (continued)



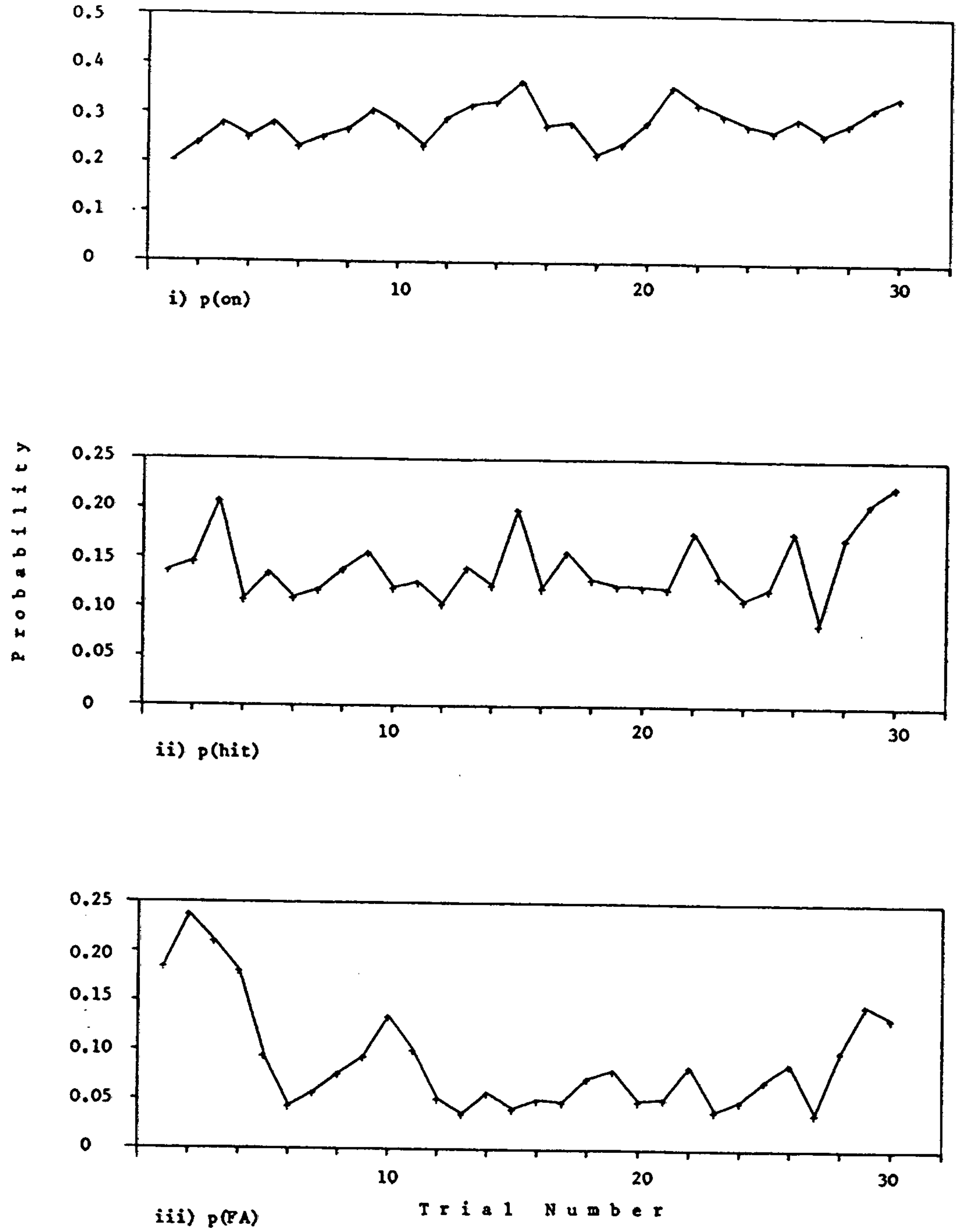
Group B, Subject 11

Figure D.2. (continued)



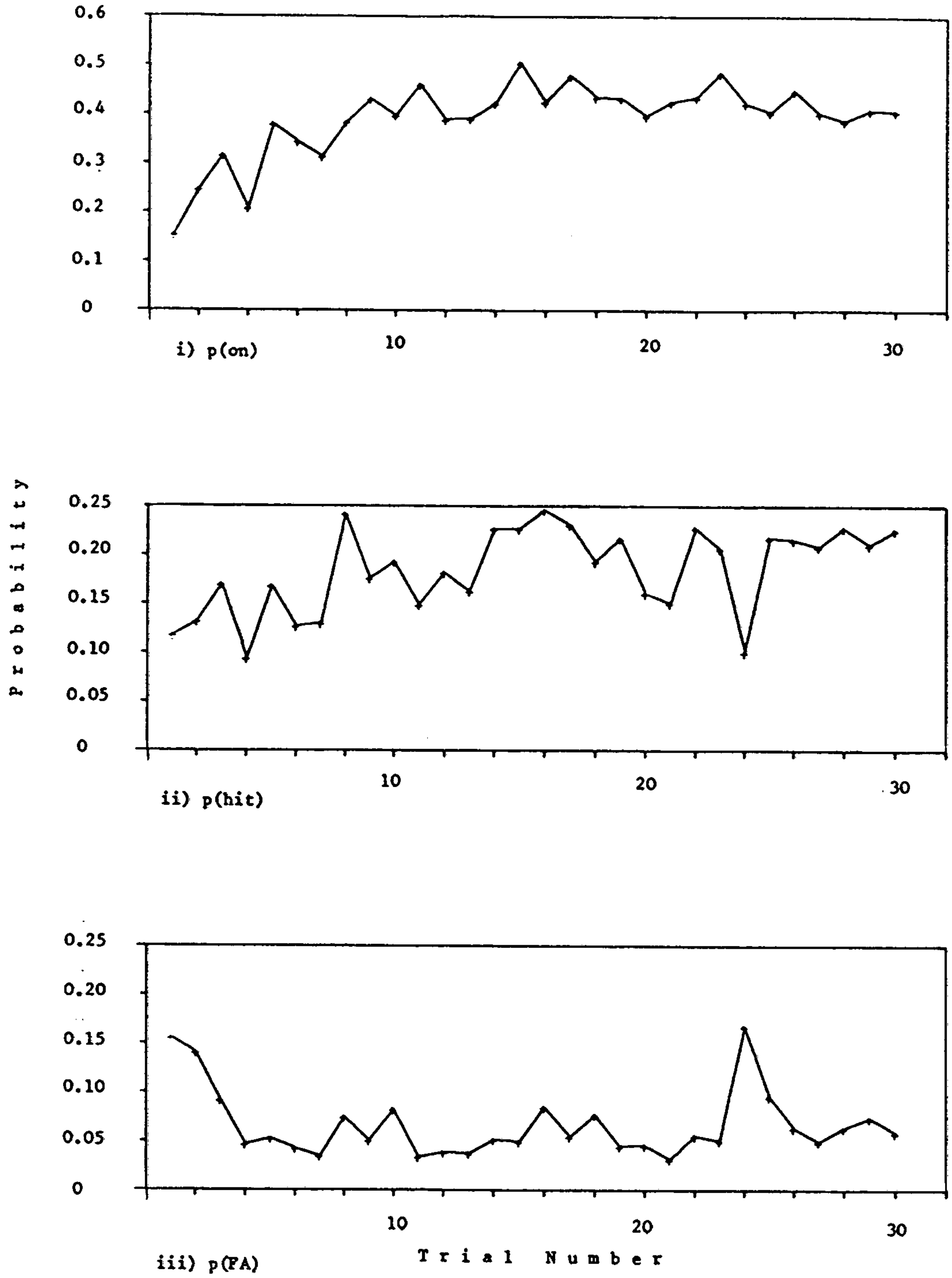
Group B, Subject 12

Figure D.2. (continued)



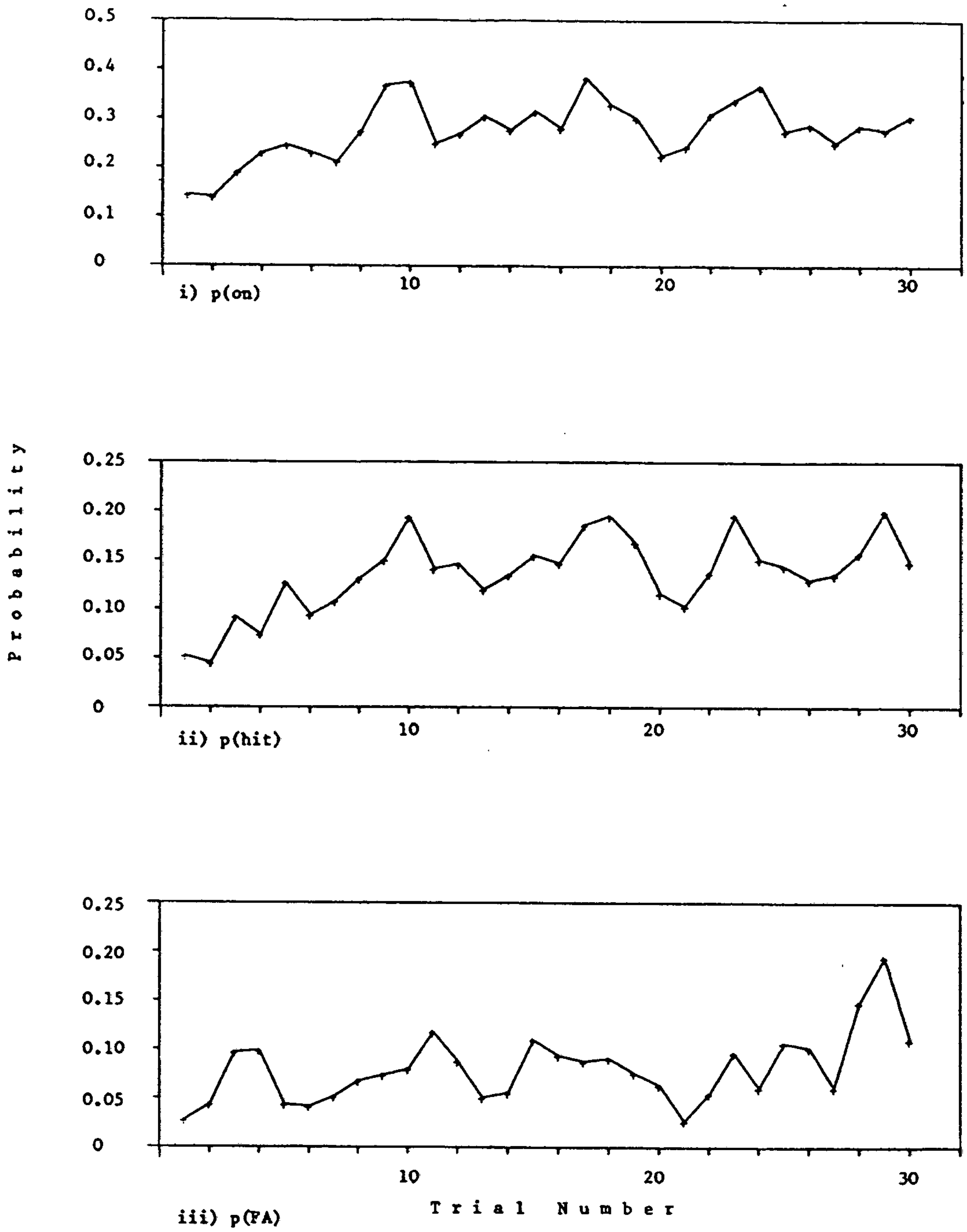
Group B, Subject 13

Figure D.2. (continued)



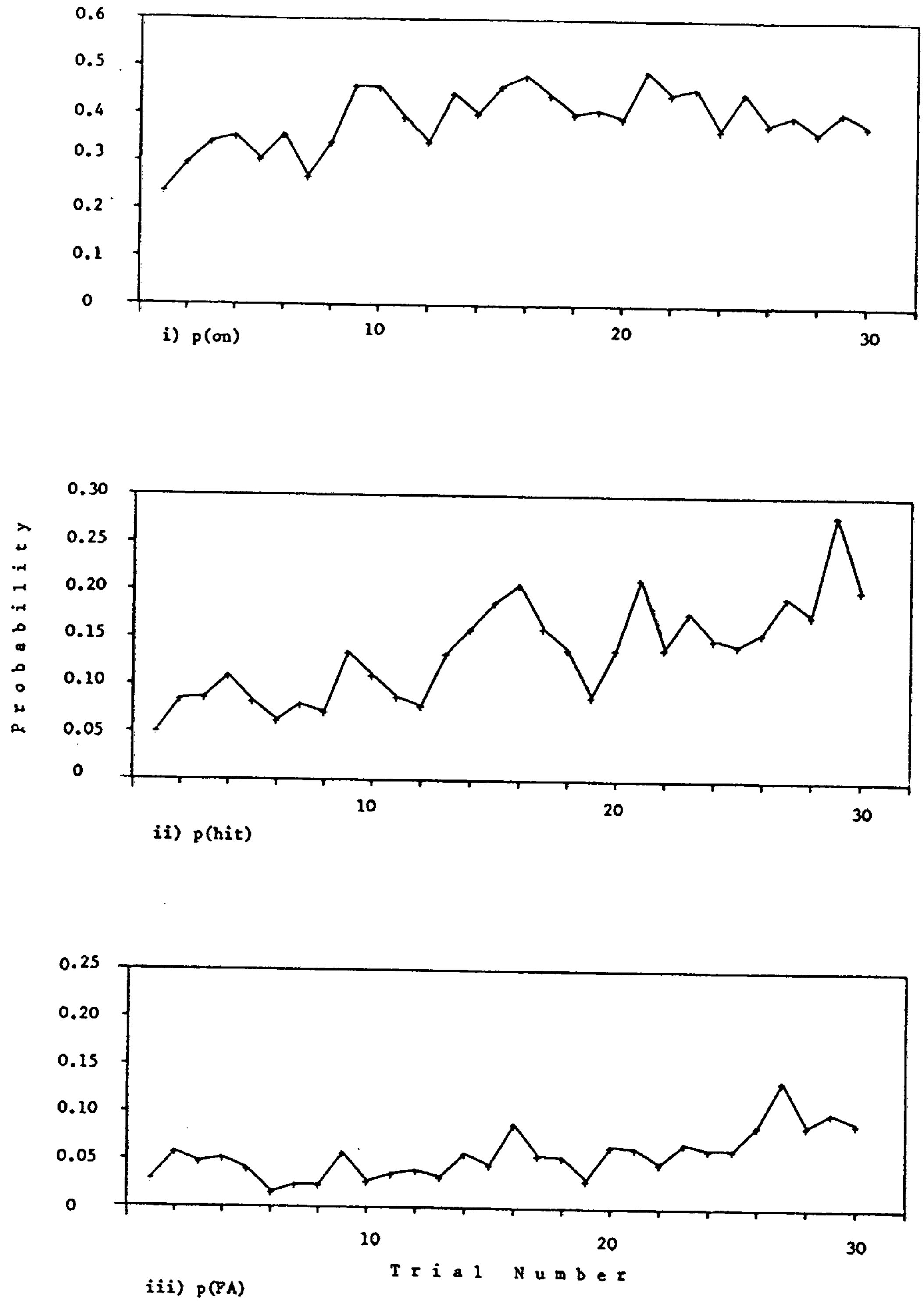
Group B, Subject 14

Figure D.2. (continued)



Group B, Subject 15

Figure D.2. (continued)



Group B, Subject 16

Figure D.2. (continued)

Appendix E: Computer Programs

This Appendix provides listings of 3 computer programs used in analysing the results of the experiments described in Chapters 5 to 10. The programs are written in Fortran - IV plus, and run on a DEC PDP 11/34 digital computer under the RSX-11M operating system.

Three programs are listed:

E.1. XPROB.FTP: Used in analysing performance of the combined continuous and discrete tracking task. Calculates simple probabilities of being 'on' target - p(on) - 'hitting' the target - p(hit) - and making a 'false alarm' - p(FA).

E.2. MEDIQ.FTP: Calculates the median and inter-quartile range across files. One file per subject, N values (= conditions) per file.

E.3. FRIED.FTP: Performs a Friedman 2-way analysis of variance by ranks. One file per subject, N values (= conditions) per file.

E.1. Listing of XPROB.FTP

```
      DIMENSION A(300),B(300),C(300),D(300),CB(128)
      DIMENSION AA(14,3),TON(10),THIT(10)
C     ****************************************************************
C     THIS PROGRAM IS IN THREE SECTIONS.  THE FIRST CALCULATES THE PROB.OF ;
C         1. BEING ON TARGET IN THE X-AND Y-AXES SIMULTANEOUSLY (TT),
C         2. BEING ON TARGET (X,Y) AND PRESSING BUTTON (THIT),
C         3. BEING OFF TARGET AND PRESSING BUTTON (TFA)
C     ****************************************************************
C
      NT=0
      CALL TYPE('&XPROB')
      CALL ASKN(A,'&X-AXIS ERROR FILE')
      CALL ASKN(B,'&Y-AXIS ERROR FILE')
      CALL ASKI(J,'&IS THERE A TRIGGER FILE ? 0 = NO 1 = YES')
      IF(J.EQ.0)GO TO 10
      CALL ASKN(C,'&TRIGGER FILE NAME')
      CALL ASKR(VBUT,'&TRIGGER THRESHOLD ')
10    CALL ASKR(TGT,'&TARGET SIZE (VOLTS) ')
      CALL ASKN(D,'&OUTPUT FILE NAME ')
      IF(J.EQ.0)GO TO 15
15    CALL INPUT(A,CB,M)
      ASSIGN 65 TO M
      NSAMP=CB(1)
      SRATE=CB(2)
      TTOT=NSAMP/SRATE
      TGT=TGT/2
      CALL TYPE('&LENGTH OF RUN (SECONDS) IS')
      CALL TYPER(TTOT)
      CALL INPUT(B,CB,M)
      IF(J.EQ.0)GO TO 20
      CALL INPUT(C,CB,M)
20    CALL OUTPUT(D)
      CALL INS(A,0,0)
      CALL INS(B,0,0)
      IF(J.EQ.0)GO TO 30
      CALL INS(C,0,0)
30    CALL IN(A,XE)
      CALL IN(B,YE)
      IF(J.EQ.0)GO TO 40
      CALL IN(C,T)
40    XE=ABS(XE)
      YE=ABS(YE)
C
C     ************************************************
C                           SECTION ONE
C     ************************************************
C
      IF(XE.LE.TGT.AND.YE.LE.TGT)TT=TT+1
      IF(J.EQ.0)GO TO 50
      IF(XE.LE.TGT.AND.YE.LE.TGT.AND.T.GT.VBUT)GO TO 41
      IF(XE.LE.TGT.AND.YE.LE.TGT.AND.T.LT.VBUT)GO TO 42
      IF(XE.GT.TGT.OR.YE.GT.TGT)GO TO 43
41    TH=TH+1
      GO TO 50
42    TM=TM+1
      GO TO 50
43    IF(T.GT.VBUT)GO TO 44
      CR=CR+1
      GO TO 60
44    FA=FA+1
      GO TO 60
C
```

XPROB.FTP (continued)

```
C       ****************************************************************
C                                SECTION TWO
C
C       THIS SECTION CALCULATES THE TIME CONSECUTIVELY ON TARGET
C       AND, WHERE APPROPRIATE, THE TIME-ON-TARGET FOR WHICH THE
C       BUTTON WAS PRESSED.
C
C       ****************************************************************
C
50      NT=NT+1
        IF(J.EQ.0)GO TO 55
        IF(T.GT.VBUT)NP=NP+1
55      GO TO 30
60      IF(NT.EQ.0)GO TO 30
65      IF(NT.EQ.0)GO TO 120
C
C       TIME-ON-TARGET
C
        TN=FLOAT(NT)
        TS=(TN/SRATE)+TS
        IF(J.EQ.0)GO TO 70
C
C       TIME PRESSING BUTTON WHILE ON TARGET
C
        PN=FLOAT(NP)
        PT=(PN/SRATE)+PT
70      CONTINUE
90      NT=0
        NP=0
81      GO TO 30
C
C       ******************************************************
C                          SECTION THREE
C
C       THIS SECTION CALCULATES THE ABSOLUTE PROBABILITIES
C       AND STORES THE DATA.
C
C       ******************************************************
C
120     CALL TYPE('&TOTAL TIME ON TARGET IS ')
        CALL TYPER(TS)
        PTOT=TS/TTOT
        CALL TYPE('&% TIME-ON-TARGET IS ')
        CALL TYPER(PTOT)
        IF(J.EQ.0)GO TO 125
        THON=(PT/TS)*100
        TOFF=TTOT-TS
        TTFA=FA/SRATE
        TFOFF=(TTFA/TOFF)*100
        CALL TYPE('&% TIME HITTING / ON TARGET IS ')
        CALL TYPER(THON)
        CALL TYPE('&% TIME PRESSING / OFF TARGET IS ')
        CALL TYPER(TFOFF)
125     CALL OUT(D,TS)
        CALL OUT(D,PTOT)
        IF(J.EQ.0)GO TO 130
        CALL OUT(D,THON)
        CALL OUT(D,TFOFF)
130     CONTINUE
        CALL INEND(A)
        CALL INEND(B)
        IF(J.EQ.0)GO TO 175
        CALL INEND(C)
175     CALL OUTEND(D,CB)
        CALL RETNR(PTOT)
        CALL RETNR(THON)
        CALL RETNR(TFOFF)
        END
```

E.2. Listing of MEDIQ.FTP

```
      DIMENSION A(300),B(300),C(300),D(300)
      DIMENSION AX(10,450),BX(10,450),CB(128)
C
C     THIS PROGRAM CALCULATES THE MEDIAN AND INTER-QUARTILE RANGE OF A
C     SET OF INPUT FILES.  THE MEDIAN IS CALCULATED ACROSS FILES ;
C     E.G. 1 FILE PER SUBJECT, 10 CONDITIONS PER SUBJECT. 5 SUBJECTS.
C     RESULTS ARE COMPUTED FOR CONDITON 1, SS 1 - 5, CONDITION 2, ETC.
C
      CALL TYPE('&NON-PARAMETRIC FILE AVERAGING')
      CALL ASKI(MODE,'&1 = MEDIAN ONLY&2 = MEDIAN +/- I.Q.RANGE :')
      CALL ASKN(A,'&MEDIAN OUTPUT FILE NAME = ')
      IF(MODE.EQ.1)GO TO 5
      CALL ASKN(B,'&LOWER QUARTILE OUTPUT FILE = ')
      CALL ASKN(C,'&UPPER QUARTILE OUTPUT FILE = ')
5     CALL ASKI(NSUB,'&HOW MANY INPUT FILES ')
      IF(NSUB.GT.10)GO TO 200
      CALL OUTPUT(A)
      IF(MODE.LT.2)GO TO 6
      CALL OUTPUT(B)
      CALL OUTPUT(C)
C
C     THIS SECTION READS INPUT FILES INTO A 2-DIMENSIONAL ARRAY
C     X-AXIS = SUBJECTS,    Y-AXIS = CONDITIONS PER SUBJECT.
C
6     DO 10 I=1,NSUB
      CALL ASKN(D,'&INPUT FILE ')
      CALL INPUT(D,CB,M)
      NSAMP=CB(1)
      IF(NSAMP.GT.450)GO TO 210
      ASSIGN 100 TO M
      CALL INS(D,0,0)
C
C     DETERMINES WHETHER NUMBER OF SUBJECTS IS ODD OR EVEN.
C
      SUB=ABS(NSUB)
      DX=2.0
      XNUMB=AMOD(SUB,DX)
      IF(XNUMB.GT.0)GO TO 18
      NUMB=2
      GO TO 19
18    NUMB=1
19    IF(NUMB.EQ.1)MIDDLE=(NSUB/2)+1
      IF(NUMB.EQ.2)MIDDLE=NSUB/2
      S=ABS(MIDDLE)
      XS=AMOD(S,DX)
      IF(XS.GT.0)GO TO 21
      LOWER1=MIDDLE/2
      LOWER2=LOWER1+1
      UPPER1=MIDDLE+LOWER1
      UPPER2=UPPER1+1
      GO TO 25
21    LOWER1=(MIDDLE/2)+1
      LOWER2=0
      IF(NUMB.EQ.2)UPPER1=(MIDDLE+LOWER1)
      IF(NUMB.EQ.1)UPPER1=(MIDDLE+LOWER1)-1
25    CONTINUE
      DO 30 I1=1,NSAMP
      CALL IN(D,X)
      AX(I,I1)=X
30    CONTINUE
```

```
100     CALL INEND(D)
10      CONTINUE
C
C       CALCULATES MEDIAN AND I.Q.RANGE FOR CONDITIONS 1 TO NSAMP
C
        DO 110 IRUN=1,NSAMP
        RU=0.0
        RL=10000.0
C
C       NUMBER OF VALUES GREATER THAN REFERENCE
C
        DO 120 ISUB=1,NSUB
        X=AX(ISUB,IRUN)
        IF(X.GT.RU)RU=X
        IF(X.LT.RL)RL=X
        DO 130 IG=1,NSUB
        IF(IG.EQ.ISUB)GO TO 130
        Y=AX(IG,IRUN)
        IF(Y.GT.X)N=N+1
130     CONTINUE
        N=N+1
        BX(ISUB,1)=N
        N=0
120     CONTINUE
C
C       SORTS OUT TIED RANKS
C
        DO 140 J1=1,NSUB
        DO 150 J2=1,NSUB
        IF(J1.EQ.J2)GO TO 150
        IF(BX(J1,1).EQ.BX(J2,1))BX(J2,1)=BX(J2,1)+1
150     CONTINUE
140     CONTINUE
C
C       RANKS DATA IN SECOND ARRAY
C
        DO 160 J3=1,NSUB
        DO 165 J4=1,NSUB
        IF(BX(J4,1).EQ.J3)BX(J3,2)=AX(J4,IRUN)
165     CONTINUE
160     CONTINUE
C
C       CALCULATES MEDIANS
C
        XMED=BX(MIDDLE,2)
        IF(NUMB.EQ.1)GO TO 161
        MID=MIDDLE+1
        XM=BX(MID,2)
        XMED=(XM+XMED)/2
161     XL=BX(LOWER1,2)
        XU=BX(UPPER1,2)
        IF(LOWER2.EQ.0)GO TO 170
        XL1=BX(LOWER2,2)
        XL=(XL+XL1)/2
        XU1=BX(UPPER2,2)
        XU=(XU+XU1)/2
C
C       STORE RESULTS
C
170     CALL OUT(A,XMED)
        IF(MODE.LT.2)GO TO 110
        CALL OUT(B,XL)
        CALL OUT(C,XU)
110     CONTINUE
        CALL OUTEND(A,CB)
        IF(MODE.LT.2)GO TO 115
        CALL OUTEND(B,CB)
        CALL OUTEND(C,CB)
        GO TO 115
200     CALL TYPE('%USER ERROR : NUMBER OF FILES MUST NOT EXCEED 10 ')
210     CALL TYPE('%USER ERROR : SAMPLES PER FILE MUST NOT EXCEED 450 ')
115     END
.* WHICH FILE FROM DM1:[197,17] TO BE LISTED (NAME.EXT)  [S]:
```

E.3. Listing of FRIED.FTP

```
      DIMENSION A(300),B(300),CB(128)
      DIMENSION A1(100,20),A2(100,20)
      CALL TYPE('&FRIEDMAN ')
C
C     THIS PROGRAM PERFORMS A FRIEDMAN TWO-WAY ANOVA BY RANKS.
C     THE PROCEDURE IS DESCRIBED IN S. SIEGEL (1956),
C     NONPARAMETRIC STATISTICS FOR THE BEHAVIOURAL SCIENCES.
C     RESULTS ARE RETURNED TO THE SCREEN, AND MAY BE RETURNED TO
C     A JOB BY SPECIFYING A REAL VARIABLE AT RUN TIME.
C     SIGNIFICANCE OF RESULTS SHOULD BE DETERMINED FROM
C     SIEGEL,DEPENDENT UPON SAMPLE SIZE.
C
      CALL ASKI(NSUB,'&HOW MANY FILES (SUBJECTS OR GROUPS) ?')
      CALL ASKI(IOUT,'&DO YOU WISH TO STORE RANKED DATA 0 = NO ; 1 = YES ? ')
      CALL ASKI(IOPT,'&WRITE DATA TO SCREEN ? 0 = NO ; 1 = YES ')
      CALL ASKN(B,'&OUTPUT FILE = ')
5     IF(NSUB.GT.20)GO TO 200
      IF(NSUB.LT.2)GO TO 210
C
C     THIS SECTION READS ALL THE INPUT FILES INTO
C     A TWO-DIMENSIONAL ARRAY (CONDITONS * SUBJECTS )
C
      DO 10 I=1,NSUB
      CALL ASKN(A,'&INPUT FILE = ')
      CALL INPUT(A,CB,M)
      ASSIGN 40 TO M
      NSAMP=CB(1)
      IF(I.GT.1)GO TO 15
      NCHECK=NSAMP
      GO TO 20
15    IF(NSAMP.NE.NCHECK)GO TO 220
20    IF(NSAMP.GT.100)GO TO 230
      IF(NSAMP.LT.3)GO TO 240
      CALL INS(A,0,0)
      N=0
30    CALL IN(A,X)
      N=N+1
      A1(N,I)=X
      GO TO 30
40    CALL INEND(A)
      N=0
10    CONTINUE
C
C     SECTION 2    CALCULATE RANKS FOR EACH SUBJECT/GROUP.
C
      T=0
      TOT=0
      N1=0
      M=0
      DO 50 IS=1,NSUB
      DO 60 IR1=1,NSAMP
      X=A1(IR1,IS)
      DO 70 IR2=1,NSAMP
      IF(IR1.EQ.IR2)GO TO 70
      Y=A1(IR2,IS)
      IF(Y.LT.X)N=N+1
      IF(Y.EQ.X)T=T+1
70    CONTINUE
      M=N
```

```
      N=N+1
      IF(T.EQ.0)GO TO 75
      XM=FLOAT(M)
      DO 71 K=M,M+T
      TOT=TOT+K
71    CONTINUE
      T=T+1
      XN1=(TOT/T)+1
      GO TO 79
75    XN1=FLOAT(N)
79    A2(IR1,IS)=XN1
      N=0
      T=0
      TOT=0
      N1=0
60    CONTINUE
50    CONTINUE
C
C     CALCULATE SQUARE OF SUM OF RANKS PER COLUMN
C
      STOTAL=0
      TOTAL=0
      DO 80 IR=1,NSAMP
      DO 90 IS=1,NSUB
      TOTAL=TOTAL+A2(IR,IS)
90    CONTINUE
      STOTAL=(TOTAL*TOTAL)+STOTAL
      TOTAL=0
80    CONTINUE
C
C
C     THIS SECTION CALCULATES CHI-SQUARE, AND RETURNS RESULTS
C     TO JOB AND SCREEN
C
      NS=NSAMP+1
      S=FLOAT(NS)
      SUBS=FLOAT(NSUB)
      SAMP=FLOAT(NSAMP)
      X1=12.0/(SUBS*SAMP*S)
      X2=SUBS*S*3.0
      CHISQU=((STOTAL*X1))-X2
      IDF=NSAMP-1
      CALL RETNR(CHISQU)
      CALL RETNI(IDF)
      IF(IOPT.EQ.0)GO TO 150
      CALL PSCLR
      IF(NSAMP.GT.4)GO TO 100
      IF(NSAMP.EQ.3.AND.NSUB.GT.9)GO TO 100
      IF(NSAMP.EQ.4.AND.NSUB.GT.4)GO TO 100
      CALL TYPE('&THIS IS A SMALL SAMPLE AS DEFINED IN SIEGEL (1956)')
      CALL TYPE('&SIGNIFICANCE MAY BE TESTED USING TABLE N, P280/1')
      CALL TYPE('& ')
      CALL TYPE('&CHI-SQUARE IS ')
      CALL TYPER(CHISQU)
      CALL TYPE('&N IS          ')
      CALL TYPEI(NSUB)
      CALL TYPE('&K IS          ')
      CALL TYPEI(NSAMP)
      GO TO 150
```

FRIED.FTP (continued)

```
100   CALL TYPE('&THIS IS A LARGE SAMPLE AS DEFINED IN SIEGEL.')
      CALL TYPE('&SIGNIFICANCE MAY BE TESTED USING THE CHI-SQUARE')
      CALL TYPE('&DISTRIBUTION, TABLE C, P.249 ')
      CALL TYPE('&')
      CALL TYPE('&CHI-SQUARE          = ')
      CALL TYPER(CHISQU)
      CALL TYPE('&DEGREES OF FREEDOM = ')
      CALL TYPEI(IDF)
      GO TO 150
200   CALL TYPE('&USER ERROR : MAXIMUM NUMBER OF SUBJECTS IS 20')
      GO TO 180
210   CALL TYPE('&USER ERROR : INSUFFICENT SUBJECTS / GROUPS ')
      GO TO 180
220   CALL TYPE('&USER ERROR : UNEQUAL NUMBER OF CONDITIONS ')
      GO TO 180
230   CALL TYPE('&USER ERROR : MAXIMUM NUMBER OF CONDITIONS = 100 ')
      GO TO 180
240   CALL TYPE('&USER ERROR : INSUFFICENT CONDITIONS (MINIMUM IS 3) ')
      CALL TYPE('&TRY USING WILCOXON TEST ')
150   CONTINUE
      CALL OUTPUT(8)
      CALL OUT(8,CHISQU)
      CALL OUT(8,IDF)
      IF(IOUT.EQ.0)GO TO 180
      DO 160 I1=1,NSUB
      DO 170 I2=1,NSAMP
      CALL OUT(8,A2(I2,I1))
170   CONTINUE
160   CONTINUE
180   CALL OUTEND(8,CB)
      END
```

APPENDIX F

QUESTIONNAIRES

This Appendix provides examples of the questionnaires completed by subjects during the experiment reported in Chapter 10 (i.e. investigating the effect of exposure duration). There were 3 questionnaires:

Questionnaire A - asked subjects to rate their feelings of physical and mental well being before each exposure,

Questionnaire B - asked subjects to rate their physical and mental well being after each exposure. Also asked subjects to rate their motivation and performance during the session, and asked for any comments on the equipment, etc.

Questionnaire C - completed at 1 ast 3 days after the final session. Asked subjects to compare their performance and motivation across the 2 Sessions.

F.1. Questionnaire A. Completed before each exposure.

This questionnaire will ask you to rate how you feel. It is most important that you rate your feelings at the moment you reply to each question. Please try not to be influenced by replies given:

i) to earlier questions on this questionnaire;
ii) to any earlier questionnaire.

Thank you

1. Please rate how physically tired you feel overall. (Try to distinguish physical from mental tiredness).

0	1	2	3	4	5	6
Not at all tired						Extremely tired

2. Please rate how mentally tired you feel.

0	1	2	3	4	5	6
Not at all tired						Extremely tired

Over/...

3. How tired do your muscles feel in each of the following parts of your body?

	0	1	2	3	4	5	6
	Not at all tired						Extremely tired
Legs -							
thighs	0	1	2	3	4	5	6
calves	0	1	2	3	4	5	6
- buttocks	0	1	2	3	4	5	6
- back	0	1	2	3	4	5	6
- neck	0	1	2	3	4	5	6
- eyes	0	1	2	3	4	5	6
- head	0	1	2	3	4	5	6
Hand -							
right	0	1	2	3	4	5	6
left	0	1	2	3	4	5	6
Lower arm -							
right	0	1	2	3	4	5	6
left	0	1	2	3	4	5	6
Upper arm -							
right	0	1	2	3	4	5	6
left	0	1	2	3	4	5	6

Does any other part of you feel tired? If so, please state which part(s) and give a rating.

....

4. Are you suffering from any condition (e.g. headache, blisters, sore-thumbs etc.). If so, please state

....

5. Do you have any other comments concerning your well-being?

....

....

F.2. Questionnaire B. Completed after each exposure.

This questionnaire will ask you to rate how you feel. It is most important that you rate your feelings at the moment you reply to each question. Please try not to be influenced by replies given:

i) to earlier questions on this questionnaire;

ii) to any earlier questionnaire.

Thank you

1. Please rate how physically tired you feel overall. (Try to distinguish physical from mental tiredness).

0	1	2	3	4	5	6
Not at all tired						Extremely tired

2. Please rate how mentally tired you feel.

0	1	2	3	4	5	6
Not at all tired						Extremely tired

Over/...

3. How tired do your muscles feel in each of the following parts of your body?

	0	1	2	3	4	5	6
	Not at all tired						Extremely tired
Legs -							
thighs	0	1	2	3	4	5	6
calves	0	1	2	3	4	5	6
- buttocks	0	1	2	3	4	5	6
- back	0	1	2	3	4	5	6
- neck	0	1	2	3	4	5	6
- eyes	0	1	2	3	4	5	6
- head	0	1	2	3	4	5	6
Hand -							
right	0	1	2	3	4	5	6
left	0	1	2	3	4	5	6
Lower arm -							
right	0	1	2	3	4	5	6
left	0	1	2	3	4	5	6
Upper arm -							
right	0	1	2	3	4	5	6
left	0	1	2	3	4	5	6

Does any other part of you feel tired? If so, please state which part(s) and give a rating.

....

4. Are you suffering from any condition (e.g. headache, blisters, sore-thumbs etc.). If so, please state

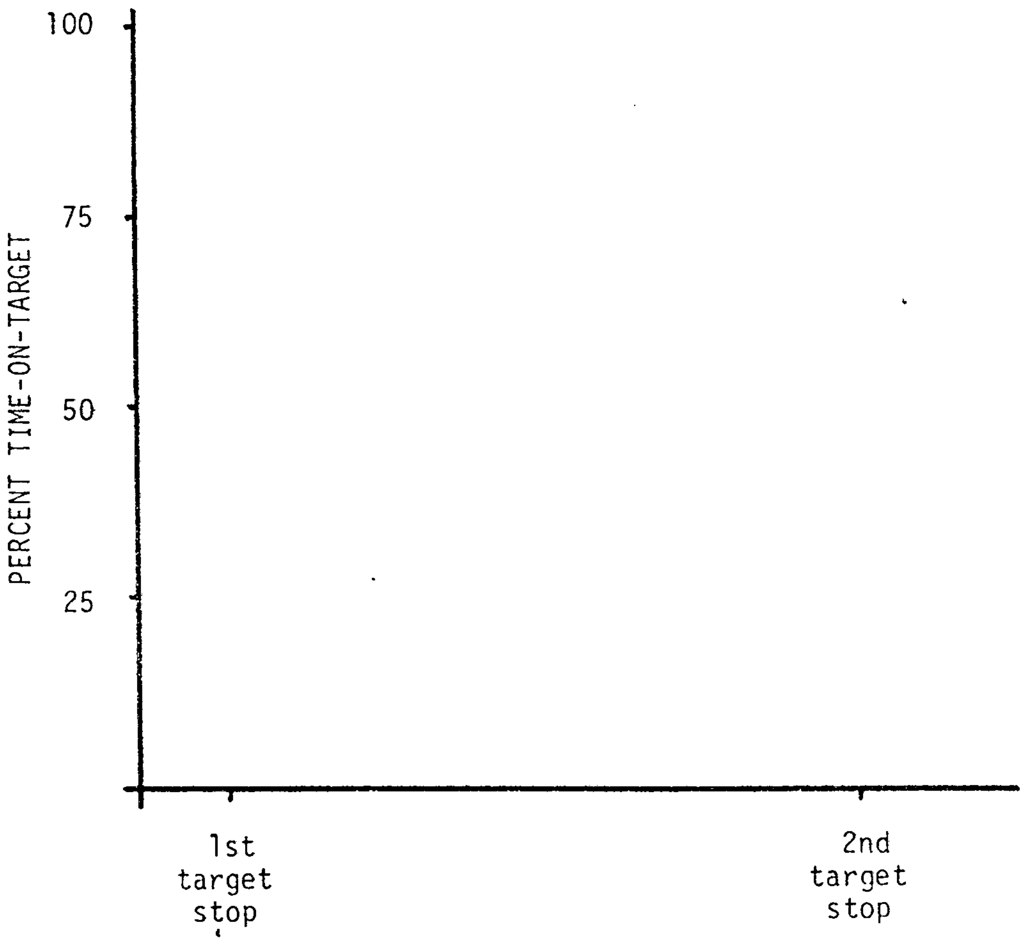
....

5. Do you have any other comments concerning your well-being?

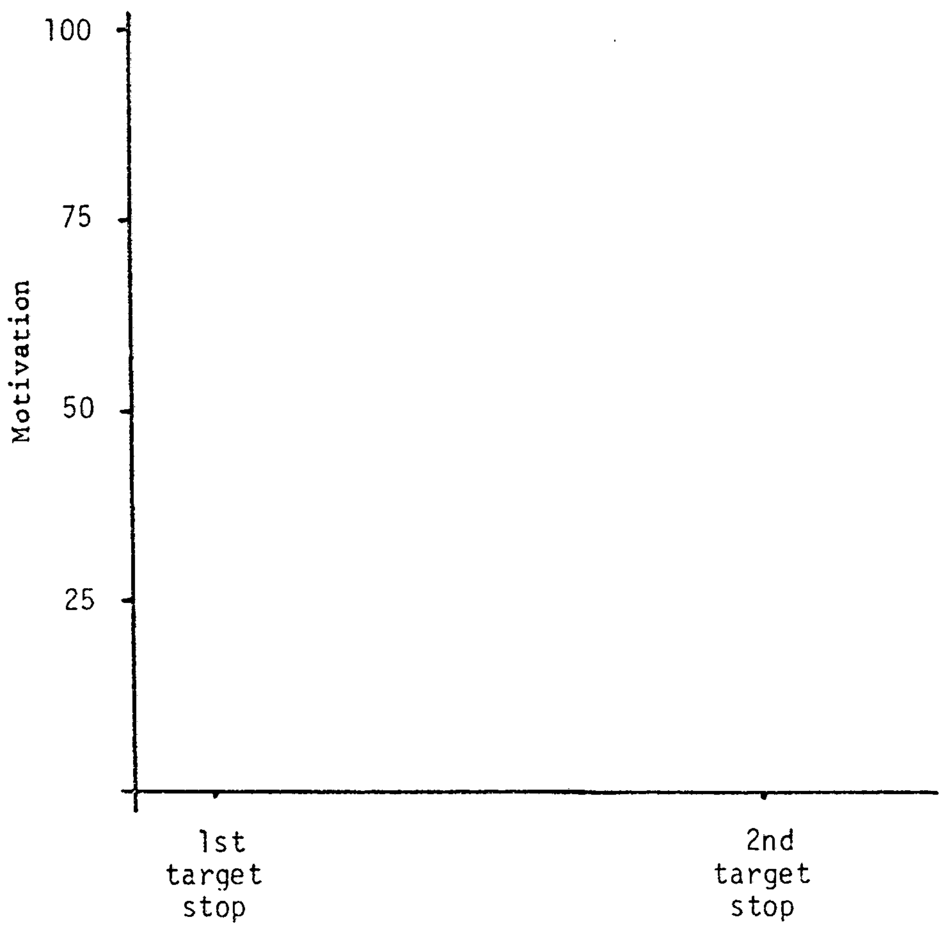
....

....

6. Please sketch below the proportion of time you think the aircraft symbol was inside the target during the course of the run.



7. Please sketch below how motivated you were during the course of the run.



8. (If performance changed in 6 or 7 above) Why do you think those changes occurred?

....

....

9. Do you have any comments about any of the following items of equipment? Yes/No

- Seat ....
- Control ....
- Display ....
- Noise ....
- Lighting ....
- Any other ....

10. How long do you estimate the run lasted?

.... Hours .... Minutes

11. Do you have any other comments which may help me to understand any changes in your performance during the run?

....

....

....

RWM/SBG
November 1984

F.3 Questionnaire C. Completed 3 days after the final session.

This questionnaire will ask you to make comparisons between the two sessions you have completed. Please try not to be influenced by replies given to earlier questionnaires.

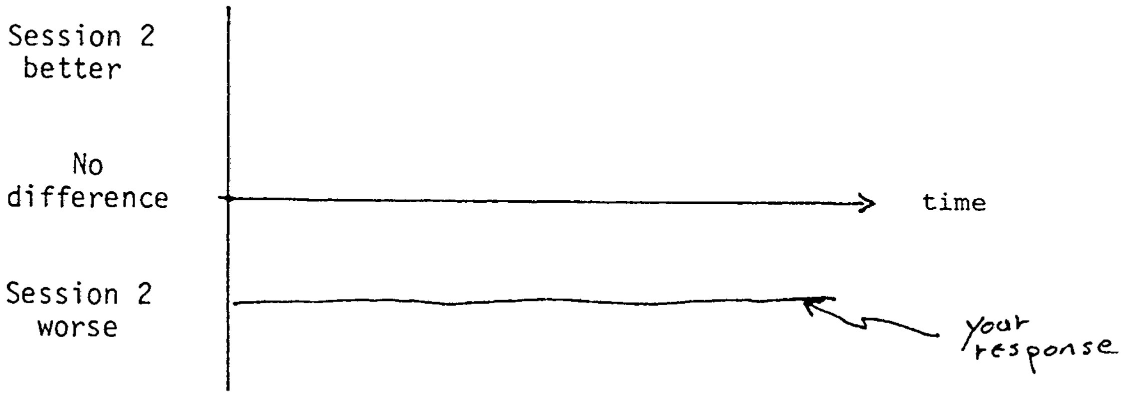
1. Although you may know how long each session lasted did the two sessions seem to be of the same duration? If not, please indicate which session seemed longer. (Tick appropriate answer).

   Yes
   No - Session 1 longer
   No - Session 2 longer

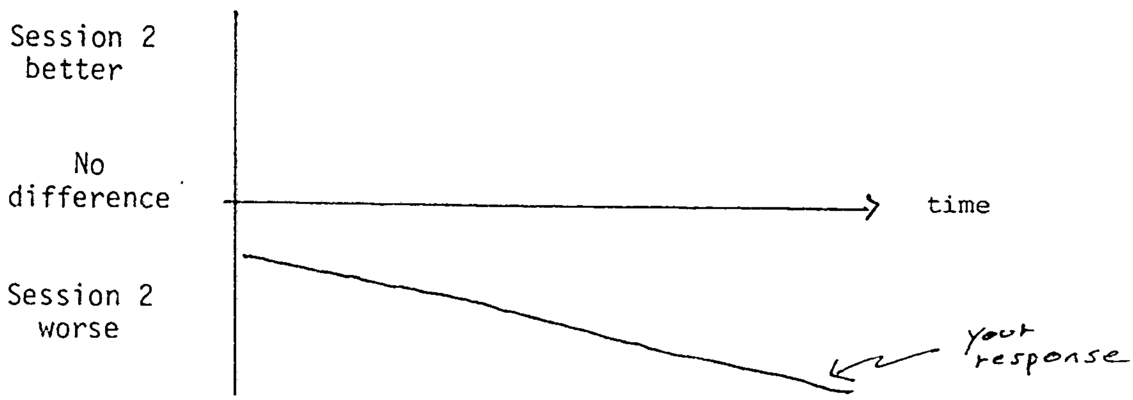
2. Do you think the difficulty of the task changed between the two sessions?

   No
   Yes - Session 1 easier
   Yes - Session 2 easier

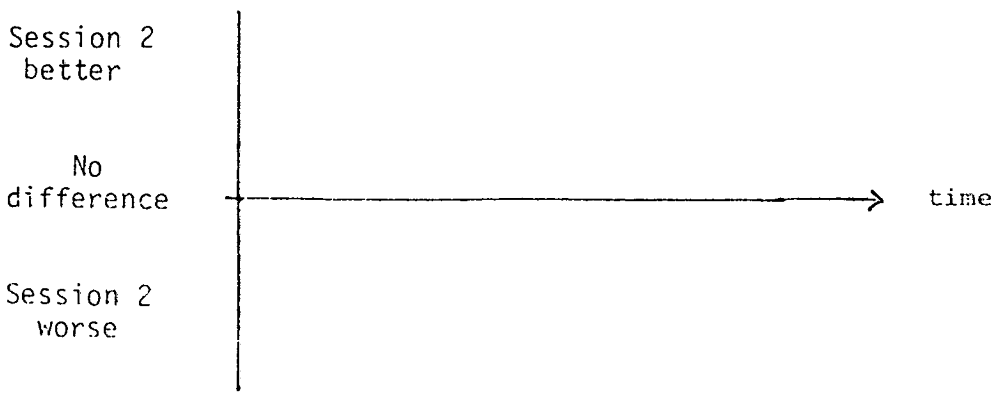
3. Please sketch how well you think you performed the task on Session 2 compared with Session 1 during the course of the run. For example, you may feel you performed better on Session 1 than on Session 2. In this case you would sketch the following if your performance was better by the same amount throughout the run:



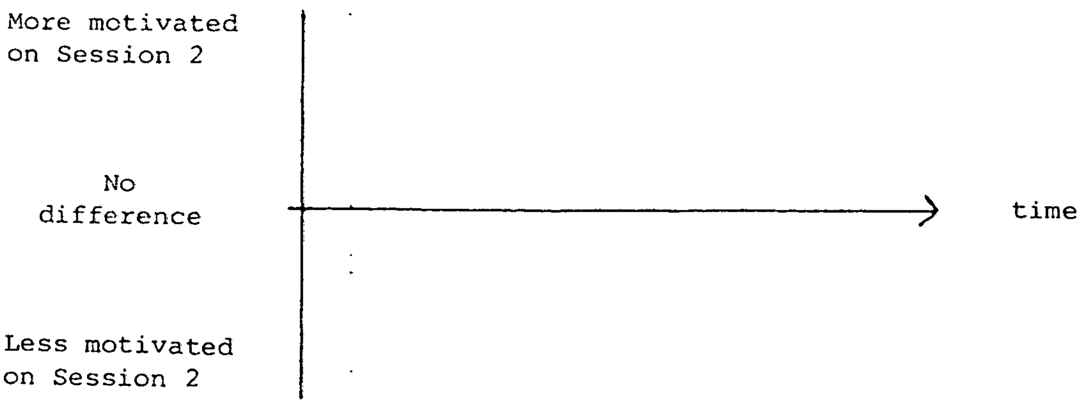
However, if you felt the difference between your performance on the two sessions increased as time went on, you would sketch:



Please complete the sketch below:



4. Please sketch how <u>motivated</u> you felt on Session 2 compared with Session 1 during the course of the run.



5. (If performance changed in 3 or 4 above) Why do you think the differences described above occurred?

6. Did you experience any after-effect of either session.
e.g. fatigue, pain: i) in the evening after each session?
ii) at any other time?

Please describe including which session.

7. Do you have any other comments about the experiment?

8. Would you be prepared to repeat the experiment in the future?

APPENDIX G

DATA FROM EXPERIMENT 6

This Appendix provides raw data for the individual subjects from the experiment reported in Chapter 10 (i.e. the effect of exposure duration on performance). The following tables give the probability of being 'on' target - p(on) - at each time period for each subject in both the static (i.e. no vibration) and vibration exposed groups on both sessions. The data are presented graphically as Figure 10.1 in Chapter 6.

Table G.1. No Vibration group; Session 1

Time Period	Subject Number						
	1	2	3	4	5	6	7
1	0.29	0.32	0.38	0.25	0.56	0.42	0.23
2	0.18	0.31	0.30	0.17	0.41	0.34	0.23
3	0.28	0.30	0.28	0.27	0.46	0.31	0.21
4	0.26	0.30	0.26	0.27	0.40	0.30	0.18
5	0.22	0.25	0.25	0.26	0.39	0.26	0.19
6	0.29	0.27	0.24	0.28	0.29	0.21	0.19
7	0.18	0.23	0.24	0.23	0.25	0.24	0.19
8	0.11	0.23	0.20	0.16	0.35	0.20	0.17
9	0.32	0.24	0.20	0.13	0.48	0.23	0.16
10	0.21	0.28	0.21	0.14	0.47	0.17	0.15
11	0.20	0.23	0.19	0.11	0.42	0.20	0.15
12	0.21	0.26	0.17	0.09	0.43	0.17	0.15
13	0.15	0.26	0.15	0.12	0.32	0.20	0.15
14	0.16	0.24	0.13	0.11	0.40	0.16	0.18
15	0.11	0.23	0.12	0.08	0.34	0.17	0.16
16	0.13	0.22	0.16	0.08	0.34	0.21	0.13
17	0.14	0.23	0.15	0.09	0.29	0.23	0.12
18	0.13	0.26	0.18	0.12	0.43	0.16	0.12

Table G.2. No Vibration group; Session 2

Time Period	Subject Number						
	1	2	3	4	5	6	7
1	0.34	0.28	0.35	0.31	0.45	0.38	0.24
2	0.27	0.29	0.33	0.33	0.52	0.30	0.23
3	0.26	0.27	0.41	0.32	0.49	0.28	0.21
4	0.27	0.27	0.44	0.27	0.36	0.28	0.18
5	0.31	0.28	0.28	0.30	0.28	0.25	0.23
6	0.25	0.30	0.25	0.28	0.57	0.24	0.18
7	0.28	0.28	0.24	0.26	0.49	0.26	0.19
8	0.23	0.25	0.21	0.24	0.51	0.25	0.23
9	0.24	0.27	0.23	0.29	0.60	0.24	0.19
10	0.20	0.25	0.41	0.26	0.50	0.23	0.19
11	0.25	0.26	0.25	0.27	0.49	0.20	0.20
12	0.24	0.26	0.25	0.27	0.49	0.22	0.14
13	0.22	0.30	0.31	0.25	0.48	0.21	0.17
14	0.21	0.28	0.15	0.28	0.48	0.19	0.19
15	0.24	0.28	0.14	0.20	0.37	0.07	0.15
16	0.23	0.28	0.13	0.17	0.37	0.14	0.19
17	0.25	0.25	0.16	0.19	0.29	0.08	0.20
18	0.28	0.24	0.21	0.25	0.55	0.26	0.21

Table G.3   Vibration group; Session 1

Time Period	Subject Number						
	8	9	10	11	12	13	14
1	0.23	0.24	0.24	0.22	0.21	0.25	0.27
2	0.24	0.28	0.21	0.20	0.18	0.20	0.27
3	0.23	0.21	0.18	0.12	0.16	0.18	0.26
4	0.22	0.16	0.15	0.09	0.13	0.14	0.23
5	0.19	0.18	0.15	0.09	0.09	0.18	0.24
6	0.18	0.19	0.13	0.06	0.10	0.16	0.22
7	0.15	0.14	0.13	0.07	0.09	0.16	0.21
8	0.16	0.18	0.13	0.04	0.11	0.13	0.22
9	0.14	0.15	0.14	0.08	0.10	0.16	0.20
10	0.15	0.12	0.12	0.08	0.08	0.13	0.19
11	0.15	0.12	0.11	0.06	0.05	0.13	0.19
12	0.15	0.15	0.12	0.06	0.07	0.15	0.21
13	0.09	0.18	0.09	0.04	0.03	0.13	0.18
14	0.07	0.15	0.11	0.05	0.04	0.14	0.20
15	0.07	0.20	0.11	0.07	0.04	0.13	0.20
16	0.06	0.21	0.09	0.05	0.03	0.11	0.17
17	0.08	0.24	0.09	0.05	0.04	0.11	0.17
18	0.08	0.24	0.12	0.08	0.07	0.13	0.22

Table G.4. Vibration group; Session 2

Time Period	Subject Number						
	8	9	10	11	12	13	14
1	0.26	0.24	0.30	0.22	0.19	0.27	0.30
2	0.25	0.23	0.45	0.20	0.17	0.29	0.29
3	0.23	0.15	0.39	0.18	0.18	0.25	0.45
4	0.22	0.16	0.34	0.16	0.15	0.21	0.46
5	0.15	0.17	0.30	0.13	0.15	0.25	0.29
6	0.18	0.26	0.32	0.12	0.12	0.23	0.28
7	0.18	0.24	0.23	0.13	0.12	0.22	0.27
8	0.20	0.23	0.14	0.10	0.11	0.21	0.27
9	0.21	0.22	0.22	0.12	0.10	0.20	0.30
10	0.22	0.19	0.17	0.09	0.12	0.16	0.41
11	0.24	0.19	0.11	0.09	0.13	0.22	0.30
12	0.24	0.21	0.12	0.06	0.10	0.18	0.29
13	0.24	0.29	0.14	0.05	0.09	0.17	0.40
14	0.24	0.28	0.18	0.06	0.07	0.19	0.28
15	0.22	0.28	0.09	0.04	0.07	0.19	0.25
16	0.22	0.27	0.11	0.06	0.06	0.18	0.23
17	0.22	0.27	0.10	0.07	0.09	0.17	0.20
18	0.20	0.31	0.22	0.09	0.12	0.21	0.25