Human response to vibration : some studies of perception and startle.

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ABSTRACT

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Human response to vibration : some studies of perception and startle.
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Experiments are described, the purpose of which were to investigate the perception and startle responses to whole body, vertical, sinusoidal vibration. An initial review showed that existing threshold of perception curves extend over a range of 40 dB. Some of the experiments attempted to explain the contributory sources of variance and some attempted to explain the nature of the way in which man perceives vibration. About 100 different subjects were used and some took part in several experiments so that there were some 200 subject/experiment exposures.

The traditionally held belief in a step-like psychometric function for the perception of vibration was shown to be misleading. Most of the following experimental variables were found to significantly influence perception: vibration frequency, background vibration, acoustic noise, subject versus experimenter presentation of stimulus, burst versus continuously varying stimulus presentation, analysis, methods for determining perception, subjects' vision, footwear, sex, posture, attention, response criterion and type of footrest. The extent of within and between subject variance was also determined.

In the startle investigation, psychophysiological and subjective responses to short duration stimuli were recorded in twelve males. Heart rate, the galvanic skin response and vasoreaction at the forehead were recorded continuously. The stimulus evoked response in each of these three autonomic functions was found to be distinguishable from normal fluctuations in the same function. A method of magnitude estimation of the feelings of startle was used. Both the objective and subjective indices were sensitive to stimulus magnitude but only the heart rate showed sign of change on repetition. The degree of correlation between the autonomic and subjective measurements was poor. The relevance of the results to psychophysiological theory is presented and discussed.

The more practical relevance of both the perception and startle investigations to the human response to building vibrations is discussed with particular reference to excitation by sonic boom.

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INTRODUCTION

Noise and vibration have been part of our lives for as long as we can remember and will, no doubt, continue to be. At the same time, man has assessed their effects and responded to them, according to their characteristics and his previous experience of them. More recently, man has developed instrumentation for measuring the physical attributes of a noise and vibration environment but he has made somewhat less progress in the measurement of his feelings evoked by such environments. This thesis examines two types of feeling induced by vibration: perception and startle.

More particularly, this investigation set out to determine some effects on man of short duration vibration with special reference to sonic boom induced building vibration. A close look at these vibration measurements made in buildings overflown supersonically, showed their range to extend from just perceptible to "unpleasant" according to some sources (Goldman, Ref. 8). Since research into the human response to vibration has continued for at least 70 years we would expect that, at first glance, the boundary of perception would be fairly well defined. Such an assumption, however, is erroneous and this is supported by existing thresholds of perception which, although purporting to represent an absolute, differ by as much as 40 dB (see Fig. 1).

Quite clearly, if the question of subjective responses to sonic boom induced vibration is to be answered then further investigation of perception and particularly the sources of variance is a pre requisite. This assumes that perception is one of the more important categories of response. Some would argue that this is not so and that it hardly matters whether man can only just or clearly feel a particular vibration. Others would disagree. For example, the English courts (Ref.27) have recently ruled out the operation, at night, of factory machinery which resulted in complaints of building vibration from residents living nearby. The basis for this decision was that the residents could feel the vibration from this source and that, at night, this was a nuisance not to be permitted.

The approach to perception is comprised, firstly, of an understanding of the nature of perception, followed by an attempt to tackle the sources of the 40dB variance. A host of these sources are investigated on an experimental basis and perhaps the most important is linked with the nature of perception: namely, the confidence with which judgements of percpetion are made. Swets (Ref.26) writes : "There is now reason to believe that sensory excitation varies continuously and that an apparent threshold cut in the continuum results simply from restricting the observer to two categories of response". These being yes or no.

Such a belief generates interest in the nature of the psychometric function for the perception of vibration. Section A3 examines the nature of this function and attempts to satisfy the psychologist's interest. Using only one point selected from this function, subsequent sections attempt to answer the design engineers' questions regarding stimulus and other experimental variables.

Having looked at one end (perception) of the sonic boom induced building vibration range, a further experiment examines the response to higher levels of vibration, which nonetheless are typical of buildings excited by sonic boom. Perhaps the most important stimulus characteristic, as far as man is concerned, is the short duration. As a result, it is the startle aspect which forms the predominant feature of the response. Psychophysiological and subjective methods of measurement are used: their characteristics are presented and discussed along with the results in Section B.

CONCLUSIONS

The existing information on the threshold of perception for whole body, vertical, sinusoidal vibration is presented and discussed along with the limitations of this information. Experiments are described, the aims of which were to make a more definitive study of the threshold, its variability and themost appropriate experimental techniques used to define the threshold.

It is suggested that this information is relevant to man's perception of vibration in buildings and may therefore be of use to building designers and where complaints of vibration intrusion are made by the occupants of buildings.

The traditionally held belief in a step-like psychometric function for the perception of vibration was shown to be misleading. A threshold of perception in a group comprising twenty-four male and twenty-four female subjects had a median of $\pm$ 0.003g and interquartile range of $\pm$ 0.002 to $\pm$ 0.004g. A considerable number of experimental variables affecting perception were investigated. These were the stimulus characteristics: vibration frequency and background vibration. The laboratory acoustic noise was studied, as was the experimental method : subject versus experimenter presentation of the stimulus, burst versus continuously varying stimulus presentation, analysis and methods for determining thresholds. Subject variables were : vision, footwear, sex, posture, attention, response criterion, vibrating and stationary footrests, within and between subject variance. Many of these sources of variance were statistically significant.

Using one particular level of accuracy in measurement it was shown that perception does not change from NO to YES at a discrete level of vibration. It was demonstrated that there is a range, of which this discrete level is a part, and over this range, the probability of detection varies between 0 and 1.0. The inference should not be that the threshold curve reported here is correct and other thresholds are wrong: obviously, they are all right. But one reason why these thresholds do differ is because the measurement is of different parts of the perception function. Other reasons why they do differ have been listed above and these are discussed in detail in section A6.1. It is regretable that the importance of the experimental circumstances has only just been confirmed especially in view of the gaps in existing reports so clearly shown in Table 1.

The two existing extremes are Chaney and Meister and the experimental differences are as follows: acoustic noise, vision, analysis, stimulus presentation and stimulus control. These two extremes, being about 40 dB apart at 2.5 Hz, would have been closer by 1.5, 2.5, 7, 1 and 1 dB respectively: a total of 13dB, according to the results of the author's own experiments. However, inadequacies in reporting or experimental technique by both authors could lead to the following experimental differences: background vibration, footwear, subject response criterion, variance within and between subjects. Their respective contributions have been shown to be of the order of 20, 1, 9.5, 6 and 14 dB.

The conclusions of the study of vibration induced startle are a function of the two types of response which were measured: psychophysiological and subjective. The fundamental autonomic problem was to define the normal fluctuations in the response and subsequently compare these with the stimulated response. At a stimulus level typical of buildings the heart rate response was distinct from normal fluctuations and was dependent on both stimulus magnitude and number of repetitions. Beat by beat, there is a tendency for increased rate for six post stimulus beats and thereafter, a tendency for reduced rate.

The other cardiovascular measures were of the forehead vasoreaction. More limited differences were observed between the stimulus and control responses: blood volume showing greater reactivity than pulse amplitude. Stimulus magnitude was a dependent variable.

The galvanic skin response was seen to agree with the cardiac response in as much as it was sensitive to stimulus magnitude and showed differences between stimulus evoked responses and spontaneous fluctuations.

With regard to habituation the heart rate was the only response whose nature hanged on repeated stimulation. This change was towards reduced magnitude of response and to a less distinct biphasic cardiac pattern. The implications of these results are discussed. Psychophysiological theory and particularly Sokolov's (Ref.37) theory of the orienting and startle responses are considered.

In order to give these autonomic changes some practical significance, a method for subjective assessment of startle was developed and used, despite its limitations which were discussed. On the one hand, there are the results of objective or unconsciously controlled physiological measurements and on the other hand, the measurements of subjective sensations. The two types of response agreed in respect of their sensitivity to stimulus magnitude but not repeated stimulation: heart rate alone showed significant change with repetition. With regard to the degree of correlation between the subjective and so-called objective measurements, the results were extremely disappointing. Possible reasons for this are discussed.

There is one common theme in the results for both perception and startle and this concerns the nature of the response. Traditionally, we have looked for a simple categorisation of the response, for example, startle or orienting; perceived or not. The results reported here indicate a wide variety of responses, be it orienting or perception. Whether or not there exists a threshold for perception or startle will depend on whether we are prepared to select a particular response criterion and this is, in turn modulated by the experimental circumstances.

It could be argued that there is no threshold; only different kinds of response.

Section A PERCEPTION

SECTION A PERCEPTION

A1. INTRODUCTION

The threshold of perception for whole body, vertical, sinusoidal vibration has been determined in a number of previous investigations: why does the need arise to repeat this type of study? Why has one reviewer (Ref. 7) stated that: "there have not yet been many satisfactory studies of the threshold..."?

A cursory glance at the results of this earlier work reveals much confusion and some contradiction in the threshold, according to the investigator and at certain vibration frequencies, lying over a range of at least 100 to 1 on the acceleration scale.

Why has this spread in the data occurred? A threshold is an elusive phenomenon being dependent on many factors. However, the discriminative behaviour of an individual is commonly expressed as a function of two items: his sensitivity and his response criterion.

His sensitivity is determined not only by the sensory apparatus of the individual but also by parameters of the stimulus and other aspects of the physical circumstances of the experiment. His response criterion may depend on his mental and physical activity including motivation, learning and expectancy. Perhaps even more important is the individual's own definition of "perceived" which may vary from sure to unsure and may lead to varying probabilities of detection. Moreover, the experimenter may also have a definition of "perceived" which is in turn a function of the method he adopts to determine sensitivity.

As a result, a threshold should be considered as a range of (un)-certainty. The threshold may then be defined by a particular value, chosen from the range, according to some predetermined method. Section A2 evaluates previous investigations in the light of relevant experimental variables revealing a diversity of techniques, where these have been reported.

To date, there is evidence of a wide range which the mean of specific populations have described, by various methods, as perceptible. Building designers and the courts evaluating complaint of building vibration, already make use of this data. However, its limitations are less well recognised including the relevance of the data to the circumstances of building vibration. Furthermore, there is very little data on variance due to population alone and there has been no adequate statistical treatment of results to determine the extent of differences due to parameters of the stimulus and subject variables. What is more there has been no validation of methods used to define the threshold.

Building structures may be set in motion by a number of sources including industrial machinery, road, rail and air traffic and internal sources such as footfall. There are two basic response patterns of building floors, these being the structural element of interest here. First, in response to a single shock impulse, such as pile driving or sonic boom, the natural frequency of the structure forms the predominant feature. The second mode of response arises from more continuous excitation such as ground traffic and nearby industrial plant and in this case the response is usually a more complex harmonic motion the predominant frequency being characteristic of the exciting force. A comparison of human sensitivity to vibration with that of a building structure or fabric shows that damage to the latter occurs at vibration levels considerably higher than those first perceived by man.

With respect to the vibration of buildings, there are two fundamental questions. First and where the experimental circumstances closely approach normal human activity in buildings, the factors governing perception should be more clearly defined. This perception study should make a clear statement of human variability and other relevant variables. Second and where a vibration level is perceptible, research should evaluate the importance of stimulus duration, interval, intensity and frequency in the special context of buildings. The variation in the threshold of perception or disturbance arising from variations in human activity is a subject also needing research, in particular whether the building has an industrial, hospital or residential purpose. However, this last topic falls outside the scope of this thesis: section A attempts to answer question one above.

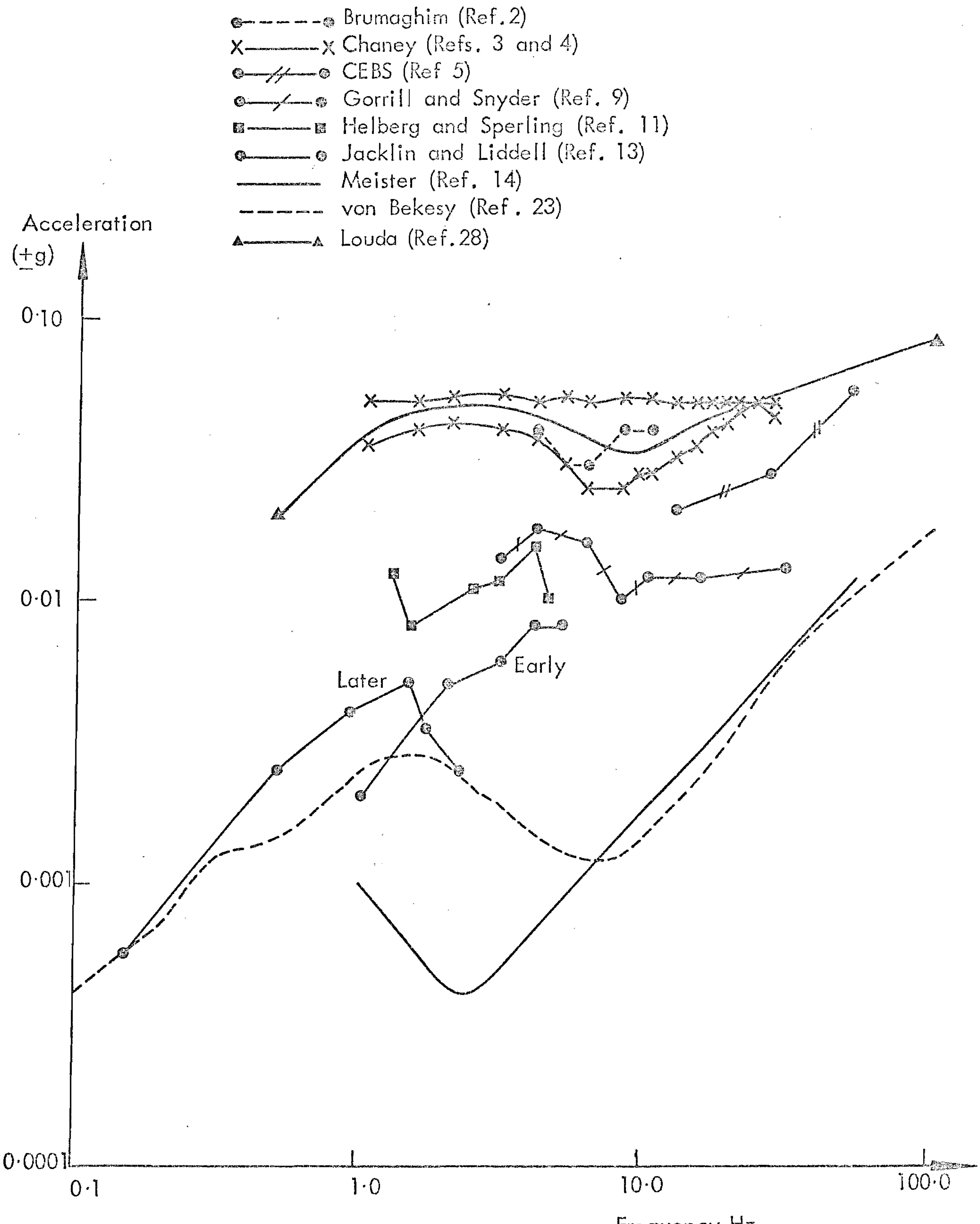
A2. LITERATURE SURVEY

Figure I presents the results of previous investigations of the threshold of perception for whole body, vertical, sinusoidal vibration. An attempt at comparison of the more important experimental details of these studies is made in Table I.

The major differences between previous studies can be grouped under three main headings: experimental method, analysis and equipment. The criterion of sensitivity is common, namely perception, but the limit of perception and the method used in its determination vary widely. These aspects are occasionally well reported, for example, Chaney (Ref.3) asked his subjects to make two judgements of the "lowest intensity of vibration which can be felt". More often, these reported details are less explicit, for example, in some cases neither method nor instructions are reported, other than to say that results formed the "threshold" (Ref.23) and "definitely perceptible" (Ref.11).

As regards the analysis of data, each investigator has used his preferred method. There seems to be some confusion in the early work, concerning the statistical definition of the mean, mode and median as measures of central tendency. The Reiher and Meister reports(Refs.14,17,18) avoid this distinction by drawing the threshold curve below (by different amounts at different frequencies) all the subjects' points for "just noticeable".

In recent years the analysis methods have improved and Chaney plotted median curves, probably the most appropriate measure of central tendency (Ref. 15). Moreover, Chaney is the only investigator to have reported



Standing and sitting subjects exposed to whole body, sinusoidal vibration. For derivation of these curves see Appendix C.

FIG. 1 THRESHOLD OF PERCEPTION FOR VIBRATION : PREVIOUS RESULTS COMPARED.

Table 1 Threshold of perception for whole body, vertical and sinusoidal vibration: a comparison of some experimental details of previous studies.

Author	Criterion of perceptibility (Subject instructions)	Experimental method	Analysis	Equipment				Subjects				
				Vibration frequency used	Distortion	Minimum vibration level	Background S.P.L.	Number	"Naivity"	Posture	Restraint	Detailed instructions
2. Brumaghim (1967)	PERCEPTIBLE "...point at which you first begin to feel effects of vibration."	Each subject made 3 judge -ments as displacement changed (frequency const.) in presence of 0, 0.38 and 0.68 ±g at 17 Hz.	Mean of subjects was reported. Their consist-ency was also analysed.	4-10 Hz Five freq. points.	Acceleration waveform compared with sine wave: "slightly more peaked".	NO REPORT	White noise masked vibration generator. S.P.L. unspecified	8 Male	Previous experience of vibn. expts.	Sitting. Adjustment to standard -ise posture was provid -ed.	Lap belt tension of 30 lbs.	Reported in detail. Reduced visual cues. Subject controlled amplitude.
3. Chaney (1964)	PERCEPTIBLE "Lowest intensity of vibration which can be felt."	Each subject made 2 judgements as displacement changed (frequency const.)	Median, 20 and 80th. percentiles reported.	1-27 Hz Sixteen freq. points.	" Vibn. harmonics at 1-2 Hz prob. had an effect.	NO REPORT	"	10 Male	9 were new, tenth had prev. experience	"	"	"
4. Chaney (1965)	"	"	"	"	"	NO REPORT	"	5 Male	1 only naive.	Standing	Boot tops at 30 lbs tension	"
5. Commonwealth Experimental Bldg. Station (1966)	IMPERCEPTIBLE "...where a vibration has not been remarked upon, it is imperceptible"	Building caused to vibrate unknown to subjects, whose judgements were: "voluntary and casual".	NOT REPORTED	12-50 Hz Unstated number of freq. pts.	N O T R E P O R T E D							
9. Garrill and Snyder (1957)	PERCEPTION "By intense concentration ...you first detect the presence of vibration."	Each subject made one judgement as displacement increased (constant freq.)	Mean of all subjects was plotted.	3-30 Hz Seven frequency points.	NOT REPORTED			5 Male	No prev. experience of vibn. expts.	Sitting. B-47 pilot seat.	Standard military seat belt + harness	Reported. "...attempt to imagine you are in flight in a high speed aircraft".
11. Heiberg and Sperling (1941)	"clearly perceptible"	Each subject made one judgement as frequency increased (displacement constant).	Modal score for all subjects was plotted.	1-5 Hz Six frequency points.	"Nearly sinusoidal".	NOT REPORTED		25	"experience with riding props. of rail travel"	Sitting.	None	Subject judgement after 2-10 mins. of exposure. No other details.

13. Jacklin and Liddell (1933 early)	PERCEPTIBLE	Each subject made one judgement as displacement increased (constant frequency).	Averaged over all subjects.	1-5 Hz Five frequency points.	"a very close approximation of SHM with superimposed vibrations.	NOT REPORTED	31 Both sexes.	NOT REPORTED	Sitting	None	NOT REPORTED
13. Jacklin and Liddell (1933 later)	PERCEPTIBLE "You now feel that you are moving or that distant objects are moving or becoming hazy."	Each subject made one judgement as frequency increased (displacement constant).	Arbitrary statistical procedure applied with plot of "mean" values.	0.15-2.2 Hz. Six frequency points.	"	NOT REPORTED	Approx 100 males.	NOT REPORTED	"	"	NOT REPORTED
14. Meister (1935) (incl. data from Ref.17)	PERCEPTION "just noticeable....la"	After exposure subject made one judgement. Displacement increased/frequency const.	Curve drawn BELOW all plotted points	1-52 Hz	NOT REPORTED		15	"Some used in previous experim'ts"	Standing and prone	"	NOT REPORTED
16. Oshima * (1953)	"Lowest limits of the sense of vibration."	Subject judgement not specified. Displacement const./frequency incresaed.	NOT REPORTED	1.5-1.9 Hz. Five freq.pts.	"generalised harmonic motion"	NOT REPORTED	20	NOT REPORTED	Sitting	"	NOT REPORTED
18. Reiher and ** Meister (1935)	"threshold of perception"	Using impact pulse, repetit^{n}. rate was varied at fixed displacements. Subject judgement unspecified.	Curve drawn BELOW all plotted points	1 and 6 impacts/ sec. Rise time: 3-10 msec.	NOT REPORTED				Standing and prone	"	NOT REPORTED
23. von Bekesy (1939)	"threshold"	Displacement increased/ frequency constant. Subject judgement unspecified.	NOT REPORTED	0.1-100 Hz. No. of freq.pts. unstated.	NOT REPORTED		Possibly 2 but not clear	NOT REPORTED	Standing and sitting.	"	Normal vision was prevented. No other details.
28. Louda L. (1970)	"just perceptible"	NOT REPORTED		0.5-70Hz No. of freq.pts. unstated.	NOT REPORTED		9	NOT REPORTED	Sitting	"	NOT REPORTED

Translation of the original was not available and data is taken from: ** Broch (Ref: 1)
* Hanes (Ref: 10)

measures of dispersion from his median values. There have been no attempts to determine the statistical significance of variables such as vibration frequency, posture, sex, acoustic noise, footwear, experimental methods and so on. Indeed the small number of subjects which have generally been used hardly warrant the use of further statistical treatment.

Perhaps the most serious criticism of previous efforts concerns the quality of the vibration stimulus, particularly at levels of perception, and the brief description (if any) of this stimulus. Whatever the method for generating vibration, there are limitations to the quality of the stimulus and these should always be reported. In only one previous investigation (Ref. 3) is any attempt made to quantify the distortion of the acceleration waveform; a few reports make do with a brief qualitative description but the majority avoid any statement of stimulus purity. Not one report specifies the background or minimum vibration level of the generating or measuring system and not one report specifies concomitant environmental factors, perhaps the most important being the sound pressure level at the subject's position.

Whilst the frequency range 5-50 Hz usually covers the vibration of building floors, in a more general study of the human response to vibration, the frequency range of interest extends from below 1 Hz to above 100 Hz. Because of the variation in experimental techniques described above, these previous investigations cannot be considered to complement one another. Consequently, a composite picture covering the whole frequency range and constructed from the results of different studies, is of dubious validity. The need for more definitive threshold information therefore arises, provided that a wider frequency range is covered in a single investigation.

With regard to threshold determinations the importance of the psychological circumstances cannot be overstressed. The mental and physical activity of the subject are likely to have a marked influence on his sensitivity. To some extent, these aspects have been considered in research carried out by the Commonwealth Experimental Building Station (Ref.5). Their report describes an experiment where a vibrator was: "attached clandestinely to floors on which a variety of unsuspecting subjects indulge in a variety of activities. The activities investigated have been those in which the subjects could be expected to be least affected by vibration, ranging from lunching.... to normal office activities which involve reading, writing.... telephoning". The assumption was made that: "where a vibration has not been remarked upon, it is imperceptible". The results show: "that provided human subjects are not informed of the existence of a vibration their threshold of perceptibility lies along a line of higher vibrational intensity than the Reiher and Meister scale would suggest". This is an interesting approach to the problem and worthy of continuing study but once a building occupant has identified a source of vibration nuisance resulting, for example from traffic or industrial plant, data using unsuspecting subjects is less relevant. Moreover, in such situations, building occupants are commonly subjected to both noise and vibration the presence of one being a cue to the other, and usually find difficulty in dissociating the two.

Subjects and their instructions form a major source of variance. At the lower frequencies where larger displacements are required, the Chaney perception curve (highest level of vibration) would undoubtedly have been closer to the Meister curve (lowest level of vibration) had the former's subjects had visual cues and the latter's curve been a 50th and not a strangely weighted 0th percentile. However, selection of particular items of variation is somewhat misleading and each result should only be viewed in the context of all experimental details.

A large number of reviews (Refs. 1, 6, 8, 10, 21, 22 and 24) of these experimental findings have previously been made. Some of the authors have proposed "averaged" limits based on some of the experimental evidence cited herein and some of their limits are only empirically based. In view of the experimental confusion and diversity of techniques, previous experiments cannot be regarded as complementary; reviews of this work are not therefore discussed in detail here. In general, they make little or no contribution and without knowledge of the limitations of the original work these reviews can be misleading.

A3. THE NATURE OF PERCEPTION

Mention has already been made of the dependence of discriminative behaviour on an individual's sensitivity and his response criterion. In the light of these two behavioural aspects the subject's task is to detect a vibration signal from varying periods of noise.

This noise may be physical, for example the surrounding acoustic field or the minimum or background vibration of the subject/support interface. The noise may be physiological, that is the subject has to recognise signal from noise in his sensory processes. It may be psychological noise arising from variations in attention or learning. Essentially, the nature of perception is detection of signal from noise.

Let us set aside for the moment, study of vibration sensitivity and factors affecting it. Consider first our subject's reponse criterion and in particular his definition of perception. Imagine that you are the subject and being asked to respond to very small and barely distinguishable movements. Quite clearly you will respond with various degrees of certainty; these being largely dependent on the strength of the stimulus. In response to some stimuli you will be certain, at other times highly uncertain. As a consequence your definition of perception or your response criterion will vary. This concept is central to the understanding of the nature of perception.

It follows from this argument that where a series of vibration stimuli are presented to the subject at about threshold level, each level being presented several times, then the response to higher levels will evoke 100% detection and to lower levels, zero detection. For stimulus levels between these two extremes there will be a probability of detection between 1.0 and zero. In other words, the response criterion or definition of perception will vary. Figure 2 shows the results of such an experiment.

This Figure demonstrates the erroneous assumption of a step like psychometric function for the perception of vibration, this having been presupposed by those who have previously studied perception. That is, there is no discrete level of vibration, below which perception never occurs and above which perception always occurs. Between these two extremes, Figure 2 shows that there are vibration levels which evoke probabilities of detection between zero and 1.0.

A3.1. Probability of detection: methodology.

With regard to the experimental methodology leading to Figure 2, there are two comments necessary here. First, there were about ten levels of vibration between ± 0.0005 and ± 0.005g, each of these levels was presented ten times in a random order and at one frequency. The one subject attended the laboratory on four separate days for the four frequencies of vibration.

Second, as the criterion that a particular level was perceived, the duration of the subject's response had to match the stimulus duration. Interstimulus interval, and stimulus duration being varied within the limits shown in Table II.

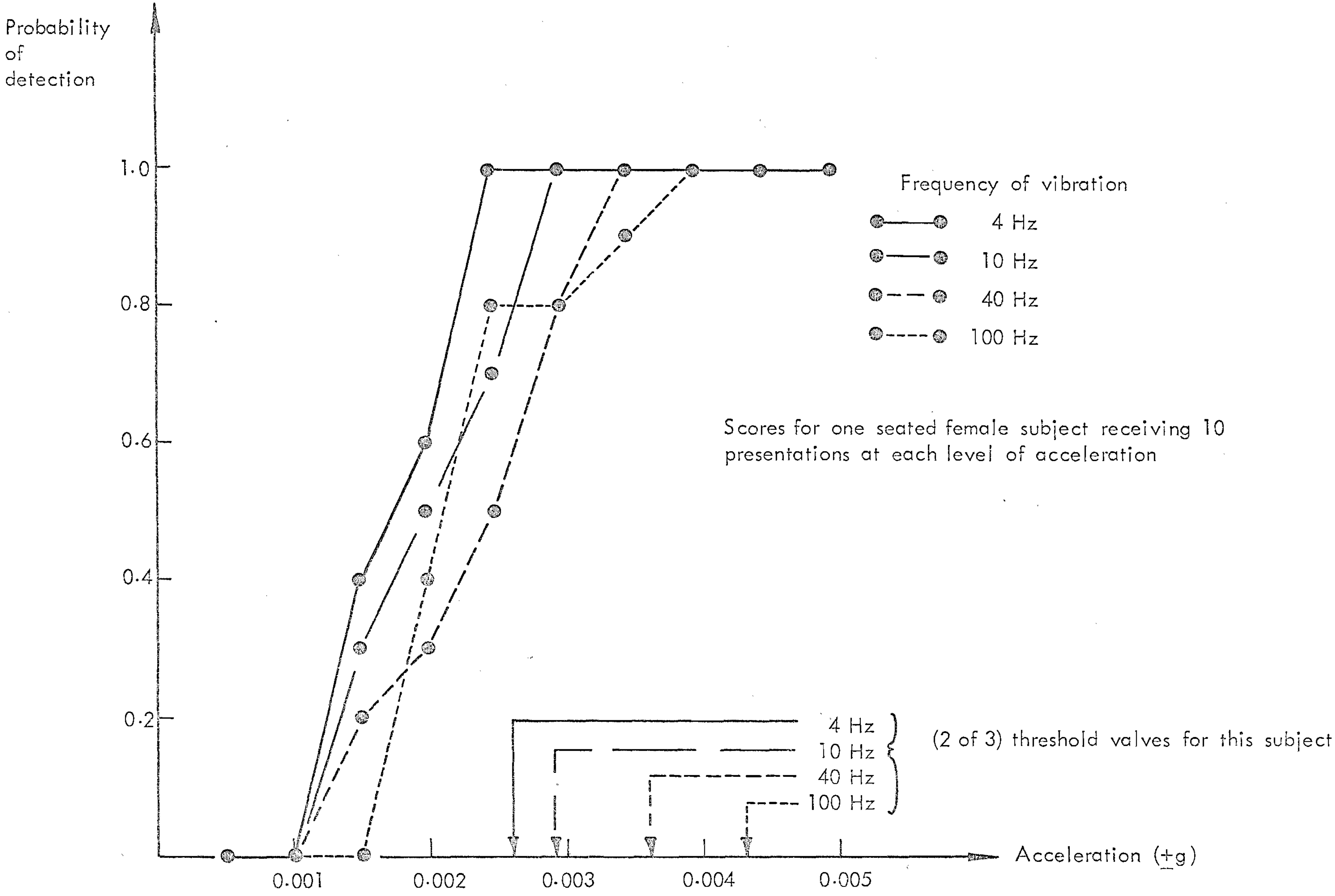


FIG 2 THRESHOLD OF PERCEPTION IN TERMS OF PROBABILITIES

A3.2. Implications of perception probabilities less than 1.0.

Consider now the need to investigate vibration sensitivity and factors affecting it. Figure 2 shows that the frequency of vibration essentially affects the position of the psychometric function for the perception of vibration. However, this frequency dependence is demonstrated in a way which is unnecessarily time consuming. To understand the effects of experimental variables it is necessary to select only one point from the curve shown and section A4 onwards describes several experiments based on this principle.

A4. EXPERIMENTAL METHOD

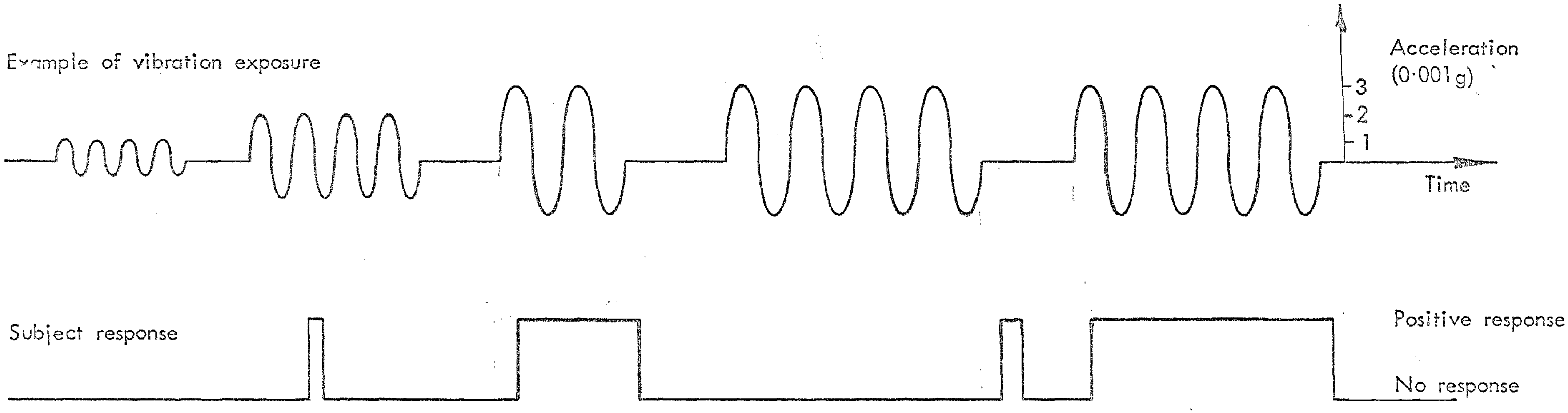
A4.1. To determine a threshold of perception in a large group of subjects.

A4.1.1. Procedure

A relatively fixed method for determining a threshold was used. The frequencies of vibration selected for this experiment were 1.5, 2.5, 4.0, 6.5, 10, 15, 25, 40, 65 and 100 Hz. At each frequency, a series of discrete sinusoidal vibration stimuli were presented to the subject beginning at $\pm$ 0.001g and increasing in steps of $\pm$ 0.001g until the subject correctly indicated the duration of the vibration (see section A4.1.4). When this level of vibration was repeated and the subject made the correct response and similarly when the subject missed the second repeat but responded to a third repeat, that acceleration value was recorded. If the subject missed both repeats two and three, the acceleration value was increased in steps of $\pm$ 0.001g until the correct response sequence was made (see Fig.3).

Beginning at $\pm$ 0.0005g and increasing in steps of $\pm$ 0.001g the above procedure was repeated and for the third presentation series the vibration began at $\pm$ 0.001g increasing by $\pm$ 0.001g increments. An example of data collection showing some fictitious but typical results is given in Fig. 4.

A method, such as the one described above, would fall into the fixed rather than adaptive category as defined by Taylor (Ref.25). However, it should be made clear that very often stimulus levels far below threshold were not presented. As a rule, subsequent presentation series commenced at levels two or three steps below the preceding threshold level which had elicited the



The acceleration value recorded was that value at which, for the duration of the vibration, the subject correctly responded to two out of three presentations. In the above case, $\pm$ 0 003g_z would be recorded. This procedure was repeated three times at each vibration frequency.

FIG.3 STIMULUS AND SUBJECT RESPONSE.

Name.......... Date...... Posture.... Sex.... Age....

Attenuator setting of 100 = ± 0.010 g.

Hz \ Attenuator setting		100	95	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	Value assigned	Notes
100												✓	✓	× ✓	×	× ×	×	× ×	×	× ×	0.0045	
65										✓		×		×	✓	✓ ×	×	× ×	×	× ×	0.0035	
40																✓ ✓	✓	× ×	×	× ×	0.0030	
25													✓	✓ ✓	×	× ×	×	× ×	×	× ×	0.0040	
15																						
10																						
6.5																						
4.0																						
2.5																						
1.5																						

Fig. 4 Data collection sheet.

correct subject response sequence. In other words, the method was adaptive inasmuch as large numbers of presentations at levels far removed from this threshold were not made. Having some flexibility this procedure yields information about the target level but not about the nature of the psychometric function at probabilities remote from the limit of perception defined in section A4.1.2 below. (The nature of the psychometric function has been discussed in section A3).

It should be noted also that prior to each stimulus presentation series, each subject, at each vibration frequency, received for the purpose of calibration, an exposur of about ten seconds. The level of this exposure was $\pm$ 0.010g and subjects therefore had some prior knowledge of the nature of the signal, they were required to detect.

A4.1.2. Limit of perception

The method adopted in this study for determining the limit of perception was as follows. Three stimulus presentation series were given to the subject, as described above, until the correct positive response sequence was made. The threshold was defined by the lowest acceleration value at which two positive judgements were made (2 of 3), frequency of vibration being constant. Why define the threshold in this way?

Previous vibration experiments have tended to define the limit of perception (where this limit is reported) on the basis of one judgement only by the subject. However, a threshold is selected from a range of certainty and to accept one judgement only by the subject is unrealistic, ignoring as it does, his inherent variability. In clinical or research audiometry, for example, it is usual for the stimulus to be presented four times (Ref.19). A more selective and accurc'' determination of the threshold can be made when, say, two or three judgements are chosen from four presentations (2 of 4 OR 3 of 4). By such methods, a single judgement, which may vary widely because of changes in attention or concentration, does not have a disproportionate effect on the threshold recorded.

In a small preliminary study using four subjects, a comparison was made between a threshold definition based on a number of judgements equal to or less than the number of presentations. Thresholds defined by 4 of 4, 3 of 3, 2 of 2, 1 of 1, 1 of 4, 1 of 3 or 1 of 2 presentations were all disregarded as the emphasis is still placed on the "outsider" or single judgement. The best choice lies between say, 3 of 4, 2 of 4 and 2 of 3 presentations. In 80% of these preliminary tests each of these three methods gave the same result, otherwise the tendency was for 3 of 4, to give a higher acceleration value ("pessimistic") and 2 of 4 to give a lower acceleration value than 2 of 3 presentations. Considering then, the accuracy, fairness and speed of execution of the test, a compromise was reached in the selection of the two lowest correct responses chosen from three stimulus presentations (2 of 3).

In the preliminary study, further consideration was given to presentation sequence. In particular, whether the vibration level should be decreased until the subject ceased to respond, then increased to an acceleration value eliciting positive response and so on, as is the custom in signal detection experiments. For a vibration stimulus, it was found that as acceleration decreased, the subject ceased to respond at a much lower level than if the acceleration was increasing. In general, there was also greater subject uncertainty. This variability was reduced for stimuli changing in the same direction (either increasing or decreasing). Consequently, it was decided to adopt the method of increasing acceleration, the reason being that in building situations, the occupants are more likely to become aware of vibration as it increases to a perceptible level, rather than the reverse.

One further point for comment on the methods used for determining perception, is their accuracy. This accuracy is a function of the method used and may be measured in terms of intraindividual variability or the consistency of the subjects' reponses. Section A5.3 reports temporal and intraindividual variability for the perception method described above. It should also be noted that there is a trade-off between the accuracy and the efficiency or work done to achieve a particular curve of perception.

A4.1.3. Subjects

Twenty four male and twenty four female subjects, in normal health and aged between 17 and 49 years gave verbal consent to take part in the experiment. They were recruited by personal invitation and selected from the students, academic, research, technical and clerical staff of the University. No payments were made to any subjects. The test duration was about 25 minutes. Only two subjects had previously taken part in experiments involving exposure to vibration but in neither case was the purpose for determining subjective reaction.

Adjacent to the laboratory, a trained first aider was available.

As the subject took his position, an emergency stop button located within easy reach, was pointed out.

A4.1.4. Subject Instructions

Twelve male and twelve female subjects stood on the vibration platform: they were instructed to distribute their body weight equally between each foot except during periods of relaxation whilst the changes in vibration frequency were made. The remaining subjects sat on the vibration platform: being instructed to sit erect on the two bony points of the pelvis with hands resting in their lap. The subjects' feet were placed on a stationary footrest, whose height was adjustable so that the underside of the thigh was not in contact with the platform. The angle between thigh and table was approximately 10° and from below the knee the leg was vertical. All subjects wore the clothing and footwear which they used in their normal occupations. They were instructed not to look downwards at the platform or its surround. Using a small hand held button, the subjects were asked to signal the duration of a vibration or movement of the platform which they felt sure was taking place. They were reminded that for most of the time there would be no vibration.

Responding to the duration of the stimulus gives the experimenter better guidance when the stimulus is being perceived; stimulus duration and inter-stimulus interval were varied within the limits of Table II.

TABLE II. Stimulus duration and inter-stimulus interval

	Minimum	Maximum
Stimulus duration	3 secs.	20 secs.
Inter-stimulus interval		

On completion of the experiment, subjects were asked, in an informal way, the following questions. Their answers are presented here for convenience.

1. Did you find difficulty in isolating the vibration from the ambient noise in the laboratory?

   Answers: 25 subjects found the noise a difficulty including 4 who thought the noise masked the perception of vibration although the frequency at which this occurred was variously reported.

2. How did you become aware that the platform was vibrating?

   Answers: One subject said by hearing, 47 subjects said by feeling including 6 who qualified this by hearing the high vibration frequencies. Two subjects noticed visual cues at low frequencies.

   N.B. It was some of those subjects who believed they became aware of the vibration through the sense of hearing who also thought the acoustic noise of the laboratory masked their perception of the vibration stimulus.

3. Did you find the test duration too long and did you find your attention wandering?

<u>Answers:</u> Ten subjects replied yes including one who thought she became less sensitive. Two subjects thought they became less sensitive although concentration was unaffected and one subject thought the reverse. Two subjects thought standing made them tired.

4. Did you find you could predict when the vibration would begin and end? Were there any other cues as to the presence of vibration?

<u>Answers</u> : No subjects believed they could predict the presentation rhythm. One subject was cued by seeing a cable vibrating and a second by noticing resonance of the thumb.

5. Do you have any comments about the vibration itself?

<u>Answers:</u> Four disliked and one liked the low frequency vibration; four found the high frequencies unpleasant and one liked all the vibration. The remainder had no comment.

6. Other comments included 18 subjects who noticed the vibration start and/or stop rather than its continuing presence at a fixed level. The tendency was at or near threshold, for the subject to make a positive response at stimulus onset. As the vibration continued, at the same intensity, this response became uncertain but a short positive response was made just after stimulus offset. (See Appendix A for details of acceleration waveform at stimulus onset and offset and see Section A6.1 for further discussion of this result).

One subject thought his sensitivity was reduced during deep respiration and another subject noticed greater sensitivity when all his body weight was supported by just one (either) foot.

In addition to these comments six subjects were questioned more closely concerning how or where they perceived the vibration, this questioning took place after the main experiment. In helping subjects with this task of introspection, they were encouraged to sit or stand for some time on the platform which was vibrating at low levels. After some thought all these subjects decided that they became aware of the vibration by feeling it in various anatomical sites: for example the head, shoulders, stomach, limbs or the whole body. None of these subjects thought vision or hearing played a part. But further experimentation of the role of vision is described in section A4.7.

It was as a result of these informal comments that many of the following experiments were carried out and these are described in section A4.2 onwards.

A4.1.5. Test presentation

One third of the subjects completed the test with vibration frequency increasing from 1.5 to 100 Hz; one third of the subjects were tested in the reverse order and one third in a random order as follows: 6.5, 1.5, 100, 25, 4, 65, 15, 40, 2.5 and 10 Hz. Frequency was selected using a continuously variable control and the accuracy, with which a particular value was chosen, was + 9%, - 3%.

There were 12 test configurations (2 postures x 2 sexes x 3 frequency orders), so that four subjects completed identical test presentations. Their order was randomised.

A4.2. Methods for determining thresholds of perception.

The important characteristics of the (2 of 3) method for determining perception are as follows. The experimenter presents a stimulus burst in response to which the subject has to indicate stimulus duration. From this method, two thresholds are derived (1 of 1) and (2 of 3) for further consideration (see Fig.10).

For comparison purposes, three other methods for determining perception were used in an experiment using six seated male subjects. In the first of these the subjects were asked to adjust stimulus level. The attenuator, which controlled stimulus level, was placed adjacent to the subject and he was asked to adjust the setting so that the vibration level was the lowest he was sure he could feel. The manner of adjustment which the subject chose to use was left entirely to him.

Another method used continuously increasing levels of stimulus, presented by the experimenter, as distinct from the stimulus bursts used in the main experiment. Other aspects of the experiment, i.e. three presentation series at each frequency, remaining the same.

Finally, a two alternative, forced choice (2AFC) procedure was used. Using one of two push buttons, the subjects were required to indicate in which of two consecutive five second periods, the vibration stimulus had occurred. Two different coloured lights immediately in front of the subject indicated the two periods in which a stimulus was possible: only/in one but always in one of these periods was a stimulus presented. The subject was asked always to give an answer: sometimes therefore he would respond with certainty and at other times by guessing.

In other words his response criterion would vary. Usually, 10-15 presentations at each frequency were required to define the boundaries of perception.

For this method, perception or the target level was set at 75% detection. Stimulus intensity was alternatively increased and decreased the step sizes being determined by previous responses. The method was similar to that described by Taylor (Ref.25).

The four methods for determining perception, described in this section, were investigated at only four vibration frequencies: 4, 10, 40 and 100 Hz.

A4.3. Temporal variability of a threshold of perception.

In a small subsidiary experiment, one female subject performed the threshold tests on a dozen occasions spread over ten weeks. This subject was seated for all tests, her instructions being the same as those described in section A4.1.4. Two frequency orders were used: increasing from and decreasing to 1.5 Hz. The fixed method for determining threshold, (2 of 3) as described in section A4.1.2, was used.

A4.4. Whole body vibration including feet and lower limbs

Six of the seated male subjects who performed the main experiment also carried out the experiment with their feet and lower limbs supported by a footrest which was attached to the seat and vibrated in an identical way to it. All other circumstances of the experiment remaining the same.

A4.5. Foot wear

Six of the standing male subjects who performed the main experiment also carried out the same procedure with bare feet. All other aspects of the experiment remaining the same.

A4.6. Activity of the subject

Six of the seated female subjects who performed the main experiment also carried out the experiment whilst reading material of their own choice. In this experiment the subjects were told to remain seated for about twenty five minutes during which time they would be presented with about ten stimuli. In fact, each of the ten vibration frequencies (1.5–100 Hz) was presented only once, at random intervals, with increasing stimulus intensity until the response and stimulus duration matched one another. In the analysis, these results were compared with the (1 of 1) threshold derived from the main experiment otherwise the experimental circumstances remained constant.

The purpose of this investigation was to determine what part the mental activity of the subject might play in the perception of vibration. This mental activity was divided somewhat crudely into two categories: where the subject's attention was devoted primarily towards the detection of vibration and secondly towards reading, whilst vibration exposure was short, intermittent and random.

A4.7. Vision

In an attempt to delineate the role of vision in perception, six of the standing male subjects who performed the main experiment also carried out the same procedure with eyes closed and blindfold. Only the five lower frequencies (1.5 – 10 Hz) were used: all other aspects of the experiment remaining the same.

A4.8. Consideration of the noise environment

The problem does exist, for this type of experiment, of subjects being cued by slight changes in the noise from the vibrator as the level of acceleration is changed. Undoubtedly, the subjects of this and previous experiments can be cued in this way; it therefore becomes necessary to report the acceleration level at which this occurs in subjects with normal hearing (see Table III).

TABLE III. Changes in acceleration detected by hearing: mean for two subjects sat adjacent to platform.

Acceleration $\pm g_z$	0.05	0.05	0.1	0.2	2	2	2	2	0.4	0.2
Frequency Hz	1.5	2.5	4.0	6.5	10	15	25	40	65	100

No previous investigators have reported similar data for their own experiments although one introduced white noise of unspecified sound pressure level for masking purposes.

Adding to these difficulties, there is also the problem of more general acoustic noise in the experimental situation. Acoustic noise from both the amplifier and vibrator air cooling systems was reduced as far as practicable. Notwithstanding these precautions, half the subjects of the main experiment found the noise distracting and/or thought the noise masked the vibration stimulus. Using a B & K microphone type 4131 and sound level meter type 2203, the noise, at the subject's position, measured 56 dBA, which is typical of many office and residential buildings: the noise having intensity and frequency characteristics similar to air conditioning units.

In order to confirm whether acoustic noise could mask or distract from vibration perception, six seated males who completed the main experiment also carried out the same procedure in the presence of acoustic noise increased to 85 dBA. All other aspects of the experiment remained the same. Frequency characteristics of the two noise spectrums are shown in Table IV.

TABLE IV Frequency characteristics of acoustic noise

Octave Centre Frequency (Hz)	dB	
	85dBA	56dBA - normal vibration tests
31.5	59	55
63	67	60
125	73	60
250	78	59
500	76	54
1000	79	49
2000	78	47
4000	80	42
8000	73	34
16000	61	24
31500	40	24
Linear	86	70

A4.9. Minimum or background vibration level

The minimum acceleration level of which the vibration generator is capable when running at its minimum output level is of great importance. A comparison between this minimum vibration level and the threshold curve is therefore essential to validate the results: not one previous investigator has reported this comparison. Similarly, the minimum acceleration, which the measuring system can resolve, should be reported. These omissions raise the suspicion that some reported threshold curves may have been distorted by an excessive minimum vibration level. These details for the main experiment are shown in Appendix B. Although no subjects could perceive the platform minimum vibration level of less than $\pm$ 0.001g, there is obviously room for improvement of the signal/background ratio, at threshold for some subjects.

Further study of background vibration, was made to determine its effects on thresholds of perception and in particular to show if the level of less than $\pm$ 0.001g, used in the main experiment, had caused distortion of the resulting perception curve.

The primary source of background vibration was found by a process of elimination, to be the 1500WT amplifier rather than the air cooling or DC field supply systems. By replacing the large amplifier with a similar 100 WT version it was possible to generate perceptible vibration in the range 15 - 100 Hz, with a background vibration of less than $\pm$ 0.0003g.

Accordingly, six seated female subjects performed the perception experiment with four levels of background vibration: ± 0.010, ± 0.005, ± 0.001 and less than ± 0.0003g. Only the five higher vibration frequencies were used (15–100Hz): all other aspects of the experiment remaining the same. Each subject carried out one of the background levels on each of four separate days: their order being randomised.

A4.10. Equipment

A Derritron VP 85 electromagnetic vibrator, the associated 1500 watt amplifier and its oscillator were used to generate the vibration. This particular model, using six link arms to support the vibrator armature, had sufficient suspension stiffness to support the weight of a man. Modification to the amplifier, made necessary by the need to reduce background vibration, included a resistor series connected to the vibrator coil. An attenuator was incorporated between the oscillator and the amplifier in order to provide finer manual control of stimulus duration, intensity and waveform at onset and offset. With prior calibration, this attenuator provided a stimulus range from ± 0.200g to below ± 0.001g but from ± 0.020g the increments could be ± 0.0001g.

However, differences in total body weight of the subjects and large variations in the posture of each subject could affect the acceleration value recorded on the vibration table. For these reasons, an attempt was made to control subject posture and a necessary precaution was the calibration of the attenuator at each vibration frequency for each subject.

In preliminary tests using a 200 lb. load the linearity in output from the attenuator was determined. Halving the attenuator setting caused a halving, within ± 5%, of the vibration output. During the experiments, with each subject in position the acceleration controls were adjusted, at each frequency of vibration, to give ± 0.010g table vibration for an attenuator setting of 100. This calibration was made using a Telequipment oscilloscope type D.3 and Dawe voltmeter type 614C. Subjects, therefore, had some prior knowledge of the characteristics of the stimulus. This exposure last approximately ten seconds, thereafter the procedure followed that described in Section A4.1.1.

The vibration platform was a $\frac{1}{2}$ in. thick, 14 in. square aluminium plate, in which the accelerometer was attached by screws. This platform was covered by plywood $\frac{3}{8}$ in. thick; on this surface the subject sat or stood.

The difference between the acceleration magnitude inside the aluminium plate and on the wooden surface was ± 5% at the two highest frequencies (65 and 100 Hz); at the eight remaining frequencies the measurement difference was less than ± 1%. At ± $0.200g_z$, lateral motion of the table was less than ± $0.001g_{x,y}$ only exceeding this limit at 100 Hz above ± $0.1g_z$.

Changes in the stability of the continuous vibration stimulus at ± 0.01g, through the range 1.5 - 100 Hz, was less than ± 2% and repeatability changed within the same limits. For details of the stability and repeatability for the rise/fall time of the vibration see Appendix A. Distortion of the acceleration waveform was not quantified but examples of the waveform are given in Appendix A.

As the stimulus was of a transient nature and as some subjects noticed change in stimulus, the acceleration waveform at onset and offset was examined closely. At all frequencies (except 1.5, 2.5, 4.0 and 100 Hz), there were no transients superimposed on the basic waveform as the vibration started and stopped (see Appendix A). For the 1.5, 2.5, 4.0 and 100 Hz frequencies, the start/stop switch of the attenuator could not be used because high frequency transients were introduced. For these frequencies, it was necessary to increase the acceleration using the continuously variable gain control thus imposing a slower rise and fall time (see Appendix A for typical examples).

A4.10.1. System for measurement of vibration.

Continuous monitoring of the vibration level was carried out using an Endevco 2265-20 accelerometer and an amplifier built in the ISVR. A Butterworth low pass filter was incorporated in the measuring system, its output being - 3dB at 100 Hz. The subject scores were corrected for the effect of this filter which, for measuring purposes, reduced the high frequency vibration of the table. The measuring system was calibrated at intervals throughout the experiment: the variation being $\pm$ 4%.

The calibration of the vibration measuring system was also compared with a B & K Calibration exciter No.4290, cathode follower and spectrometer type 2112. The percentage error being $\pm$ 5% in the frequency range 50 - 100 Hz.

Furthermore, a Wayne Kerr vibration meter type B731A was used to measure the displacement on the wooden surface on which the subject was sat or stood. Comparing these results with the measuring system (accelerometer mounted inside the aluminium plate) showed a percentage error of -0, + 10% in the frequency range 10 - 100 Hz.

The DC calibration of the measuring system was checked simply by inverting the accelerometer, its change in output being equal to a change of 2g.

A5. RESULTS AND ANALYSIS

A5.1. Results for perception in a large group of subjects.

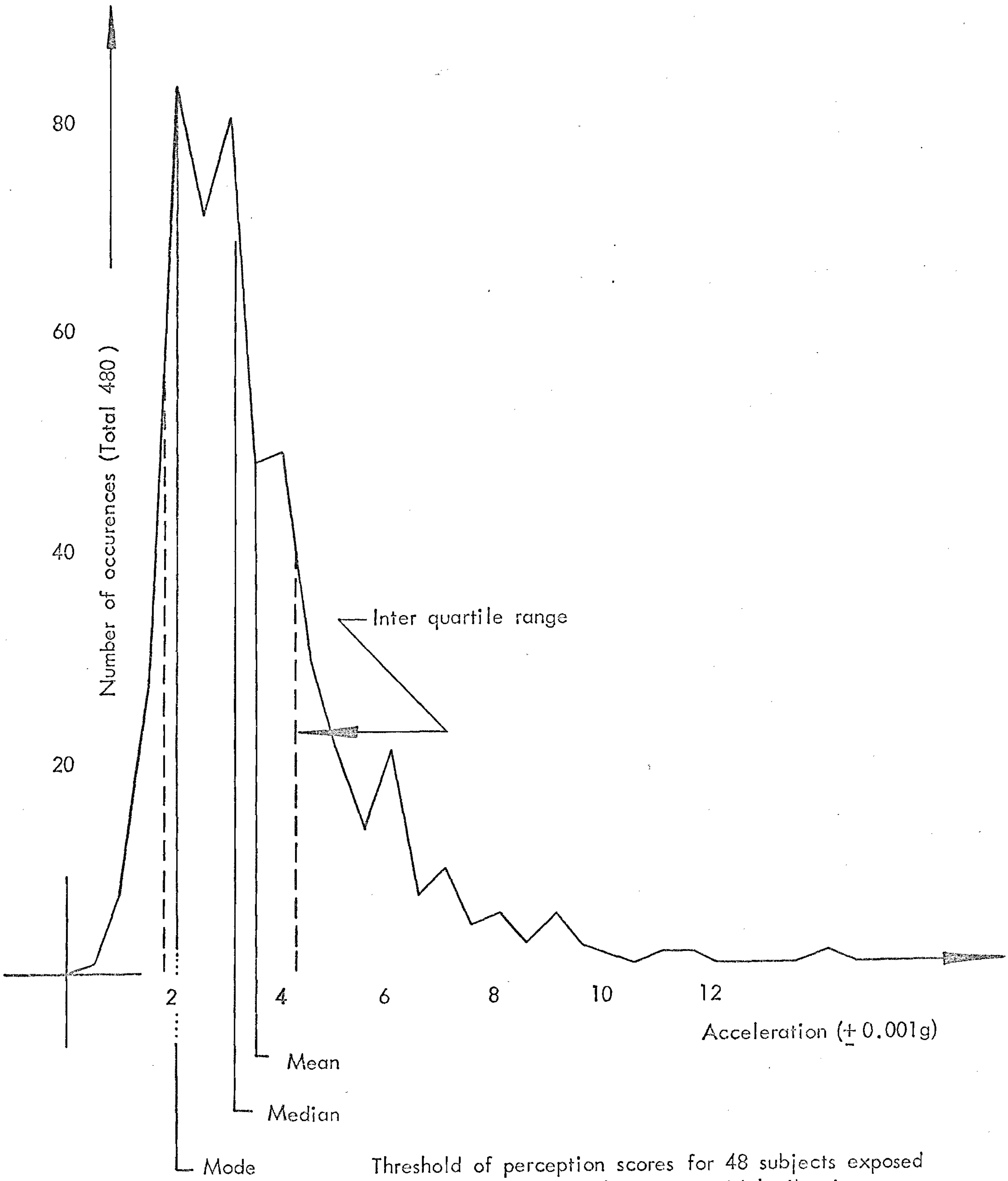
A5.1.1. Distribution of subject threshold scores.

The distribution of all subject threshold scores, regardless of posture, sex, vibration frequency and test presentation is shown in Fig.5. The distribution appears to be positively skewed and a test for normality showed this to be so. Figs. 5 and 6 also show the difference between median (50th percentile), mode (most frequent score) and mean.

A5.1.2. Median and interquartile range.

The central tendency (median) and dispersion (interquartile range: 25th and 75th percentile) are presented in Fig. 7. There is a trend of decreased sensitivity at the higher frequencies which is statistically significant. There is a minimum at 6.5 Hz; this point being significantly below the curve at 4 and 15 Hz. The curve does not therefore have a similar shape to other vibration data (Meister: Ref. 14, ISO: Ref. 12).

The interquartile range containing 50% of the scores forms a broad band around the median with an indication that the distribution of scores is more skewed at the higher frequencies. In other words, a small number of subjects tended to detect the higher vibration frequencies at relatively high levels of acceleration.



Threshold of perception scores for 48 subjects exposed to whole body, vertical and sinusoidal vibration. These data include all vibration frequencies.

FIG. 5 DISTRIBUTION OF SUBJECT THRESHOLD SCORES.

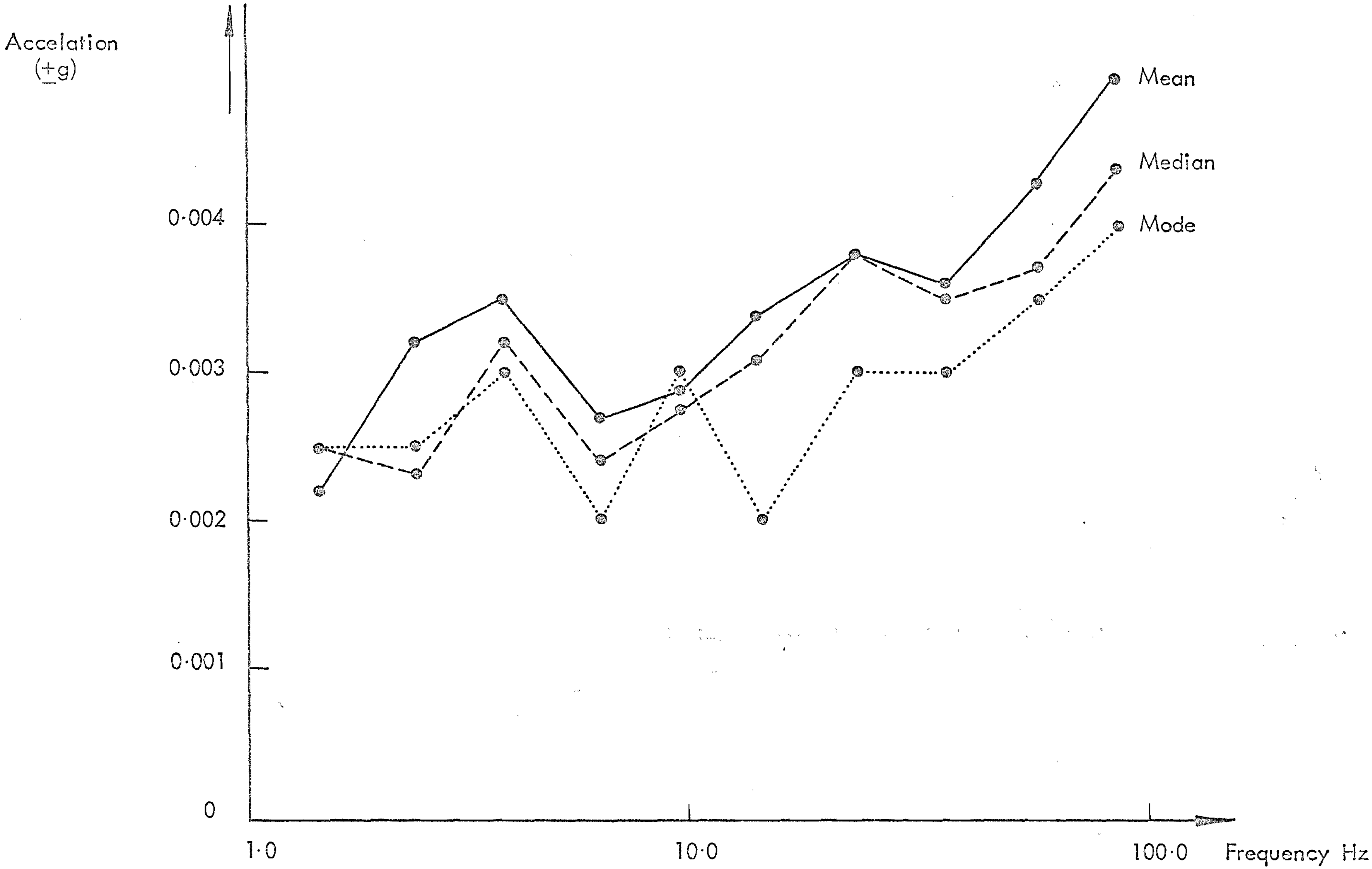


FIG. 6 THRESHOLD OF PERCEPTION : MEAN, MEDIAN AND MODE COMPARED (BASED ON 48 SUBJECTS)

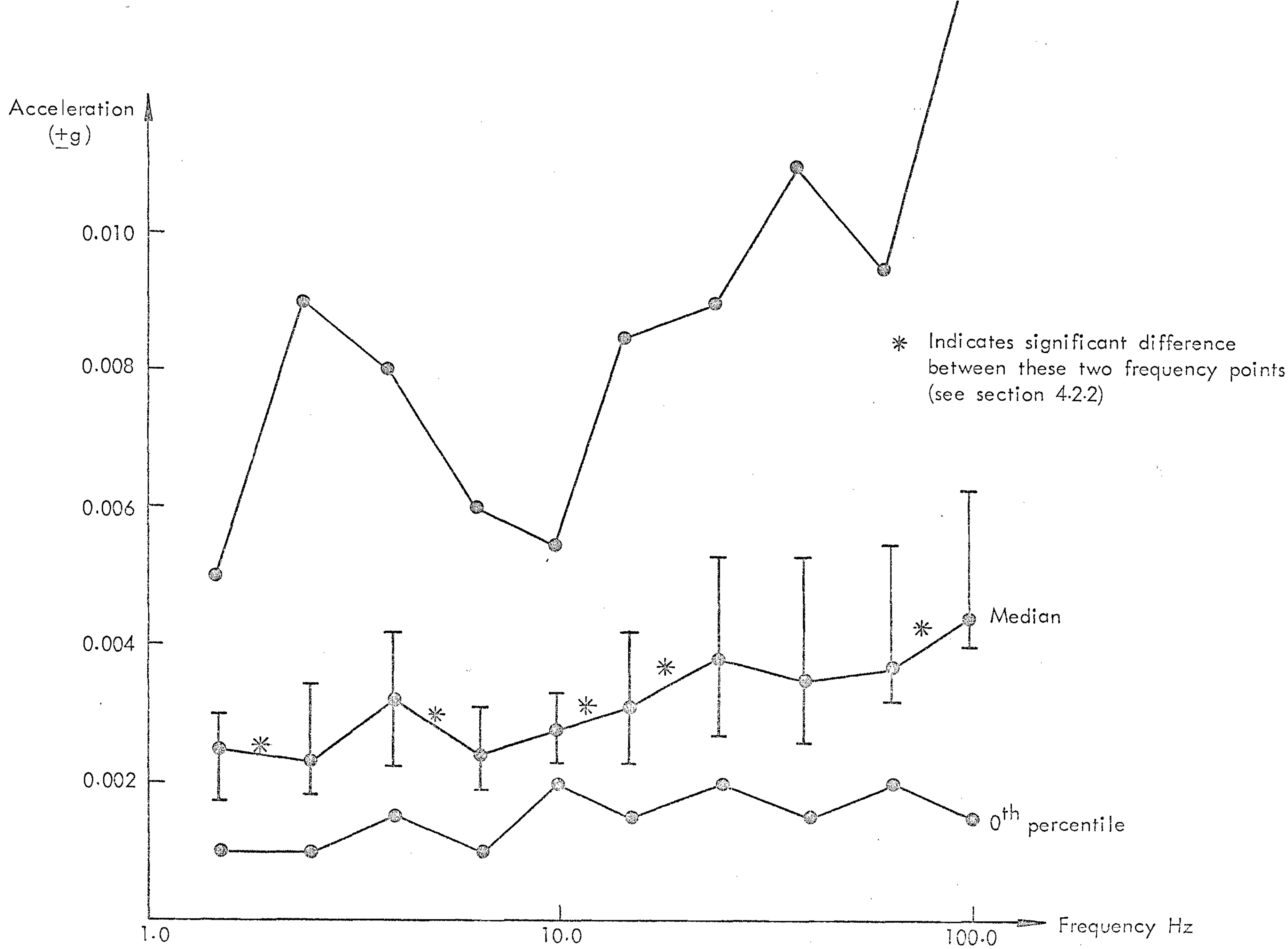


FIG 7 THRESHOLD OF PERCEPTION : MEDIAN SCORES AND INTERQUARTILE RANGE BASED ON 48 SUBJECTS

A5.1.3. Differences between standing and sitting subjects.

Fig. 8 compares the results of the 24 subjects who sat (12 male, 12 female) with the 24 subjects who stood (12 male, 12 female) on the vibration platform. Subjects were generally more sensitive whilst seated on the platform: this trend was statistically significant at the two lowest vibration frequencies. In the region 15 - 25 Hz, the trend was reversed: there being a significant difference at 15 Hz.

A5.1.4. Differences between male and female subjects.

Fig. 9 compares the results of the 24 male subjects (12 sitting, 12 standing) with the 24 female subjects (12 sitting, 12 standing). Males were generally more sensitive, this trend being statistically significant at 6.5 and 15 Hz.

A5.1.5. Differences between two limits of perception.

A comparison was made between two definitions of the limit of perception. One of these was the lowest level of acceleration at which two positive judgements were made (2 of 3). Fig. 10 compares this threshold with a curve based on the first judgement only made by each subject (1 of 1). Not surprisingly, the (2 of 3) threshold is below the (1 of 1) curve, this trend being statistically significant at 2.5, 4, 6.5, 10, 25, 40 and 65 Hz.

A5.1.6. Informal subject reaction to the test.

An informal post test interview of subjects was made. The aspects considered were duration of test, acoustic noise in the laboratory, mode of sensory perception, rhythm of presentation and other comments. These results are presented in Section 4.1.4 for convenience, alongside each question. The noteworthy findings being that:

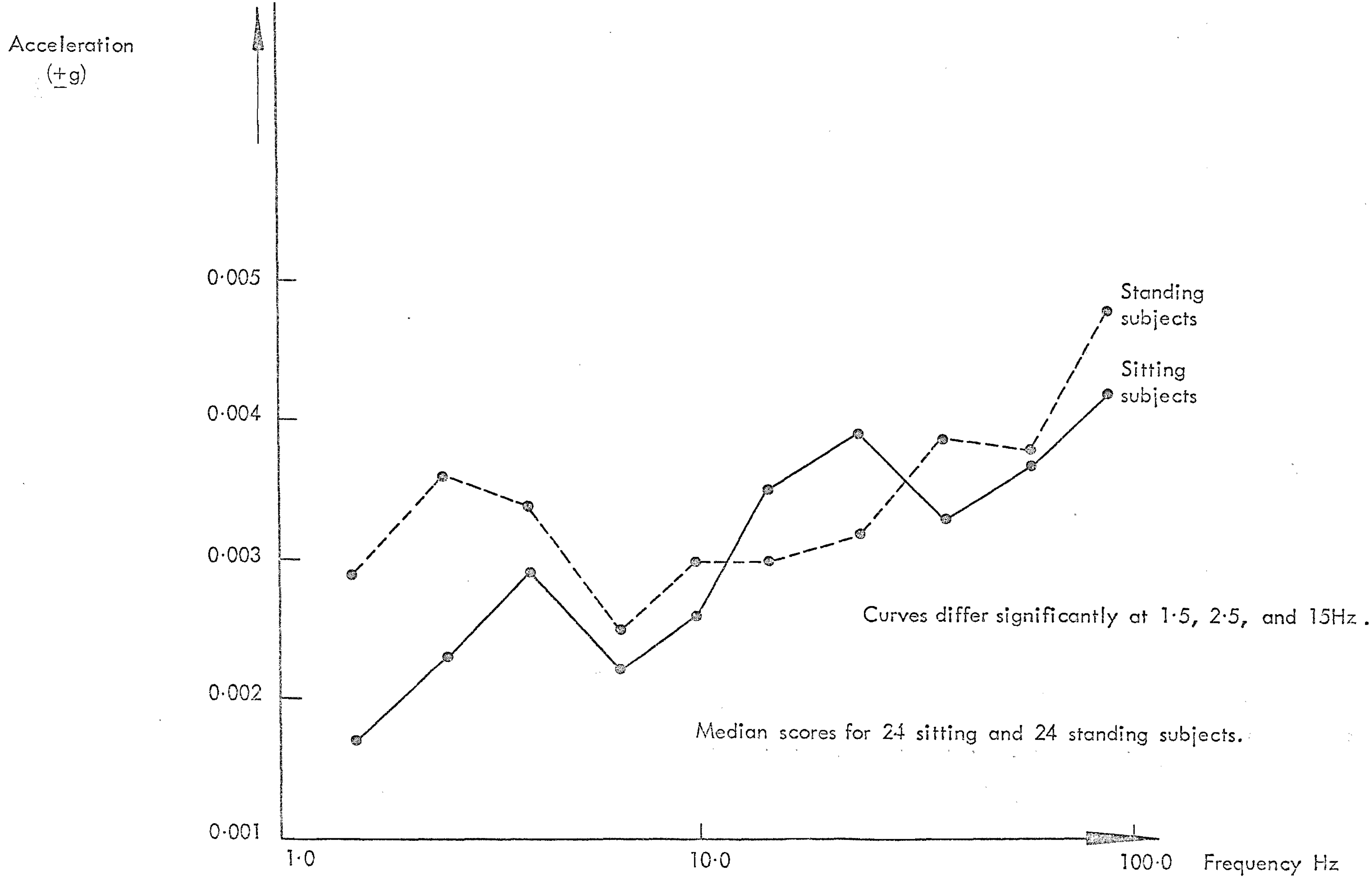


FIG.8 THRESHOLD OF PERCEPTION : SITTING AND STANDING SUBJECTS COMPARED.

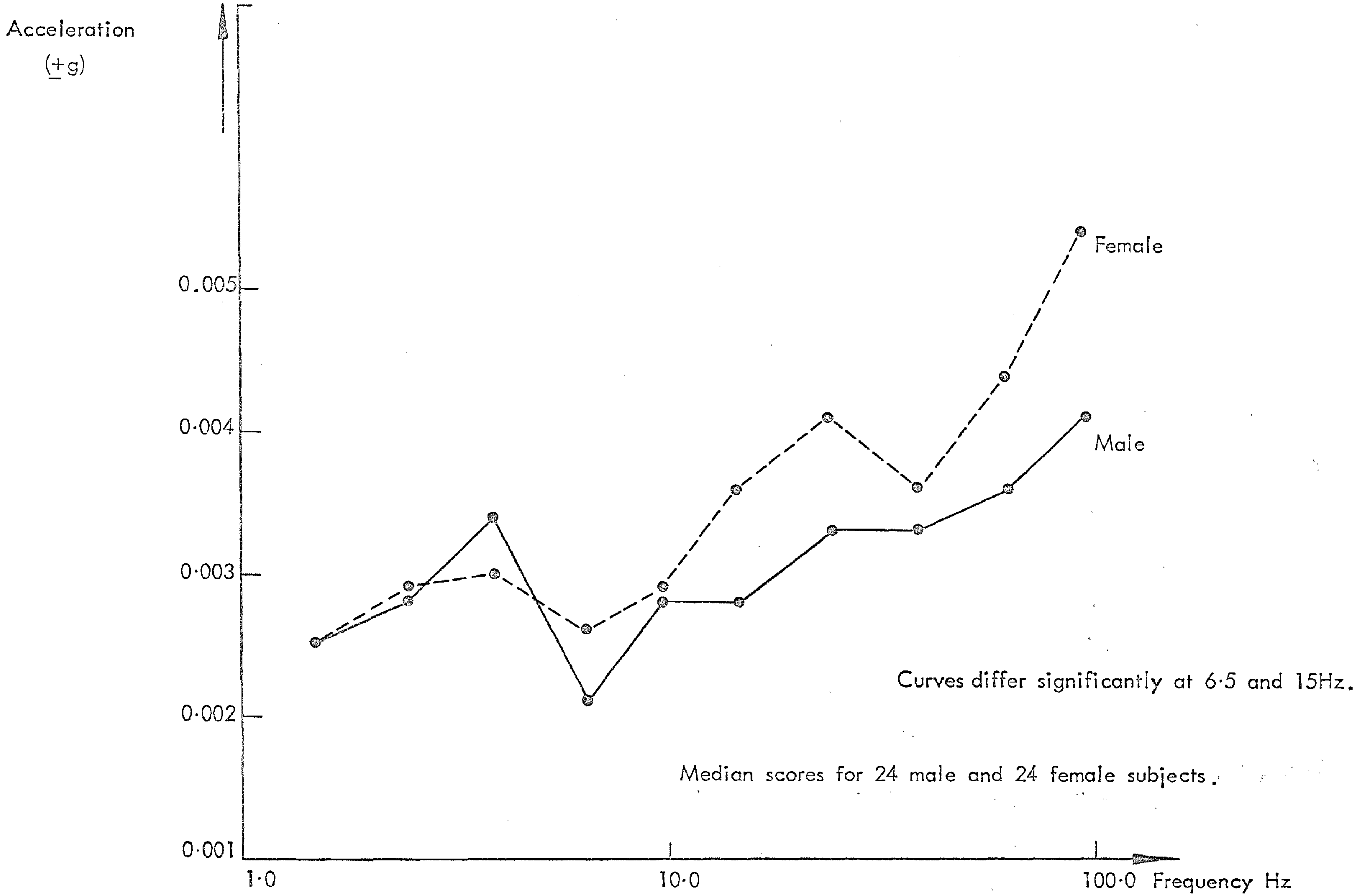


FIG. 9 THRESHOLD OF PERCEPTION : MALE AND FEMALE SUBJECTS COMPARED.

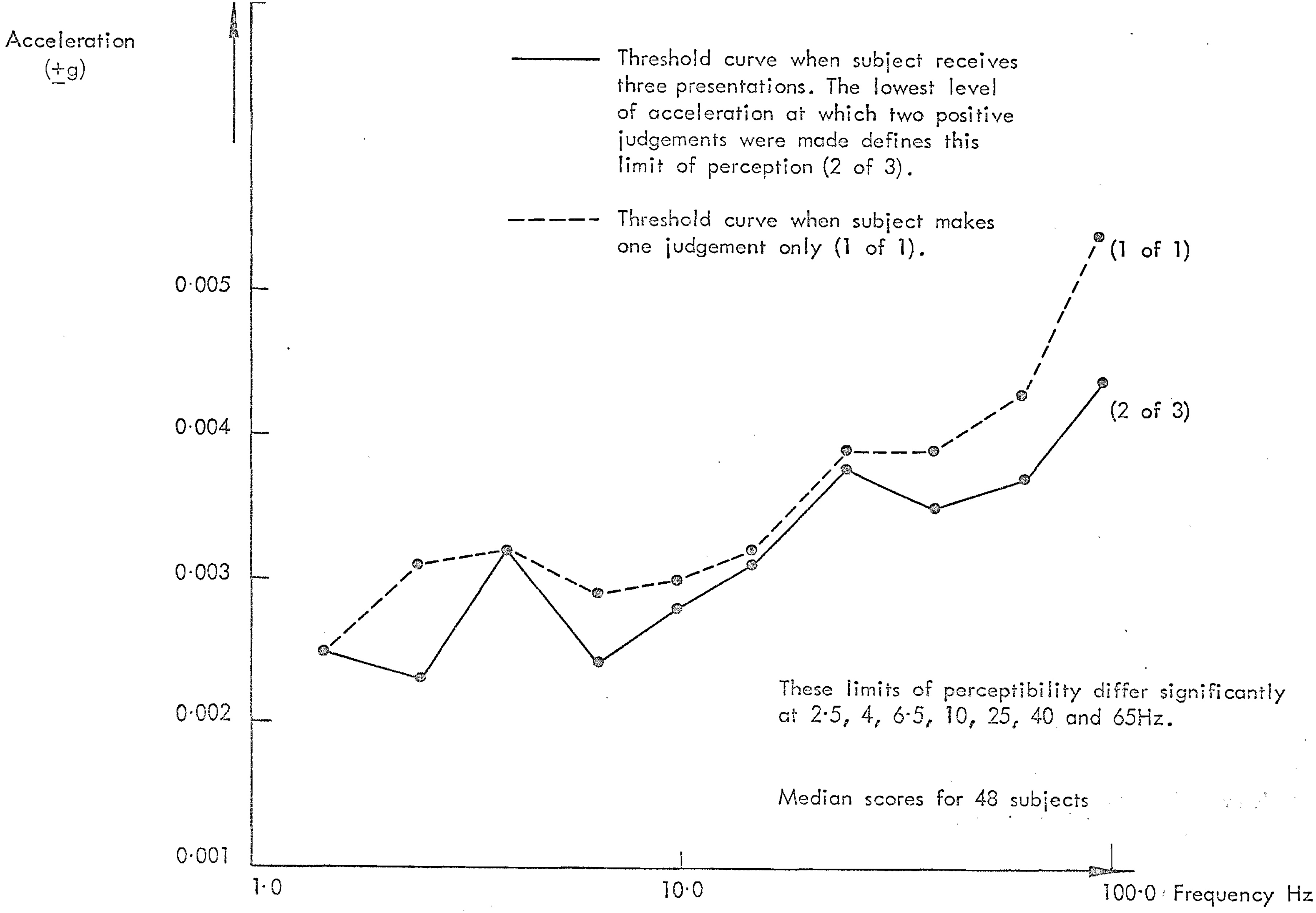


FIG. 10 THRESHOLD OF PERCEPTION : TWO LIMITS OF PERCEPTION COMPARED

half the subjects found the laboratory noise (56 dBA) distracting and 18 subjects found the start and stop of the vibration more noticeable than the stimulus itself. This suggests that the subject is more sensitive to a change in the stimulus; that he quickly adapts to a stimulus of constant intensity and consequently, an intermittent vibration may be more noticeable.

A5.2. Methods for determining thresholds of perception.

Fig. 11 illustrates for comparison the several methods for determining perception.

The (1 of 1) judgements are shown to give significantly reduced sensitivity (p=.01) than the (2 of 3) judgements. This confirms the finding shown in Fig. 10, which used a very much larger sample.

When stimulus level increases continuously rather than in stepped increases presented in separate bursts, sensitivity is again reduced but this trend was not significant. Exactly the same comment applies, when the subject rather than the experimenter is in control of the stimulus. Incidentally the method generally used by subjects was to reduce the vibration below a level which could be perceived and then increase and oscillate about the selected level. Most subjects elected to use the ON/OFF switch in conjunction with the continuously variable attenuator control. None of the subjects, when questioned after the test noticed a difference between continuously varying and burst stimulus presentations.

For a detection probability of 0.75 the 2AFC method leads to a threshold significantly lower (p=.01) than the (2 of 3) method. Some subjects preferred to have to give an answer even when possibly wrong. Other subjects, perhaps conditioned by the (2 of 3) experiment completed previously, disliked having to make

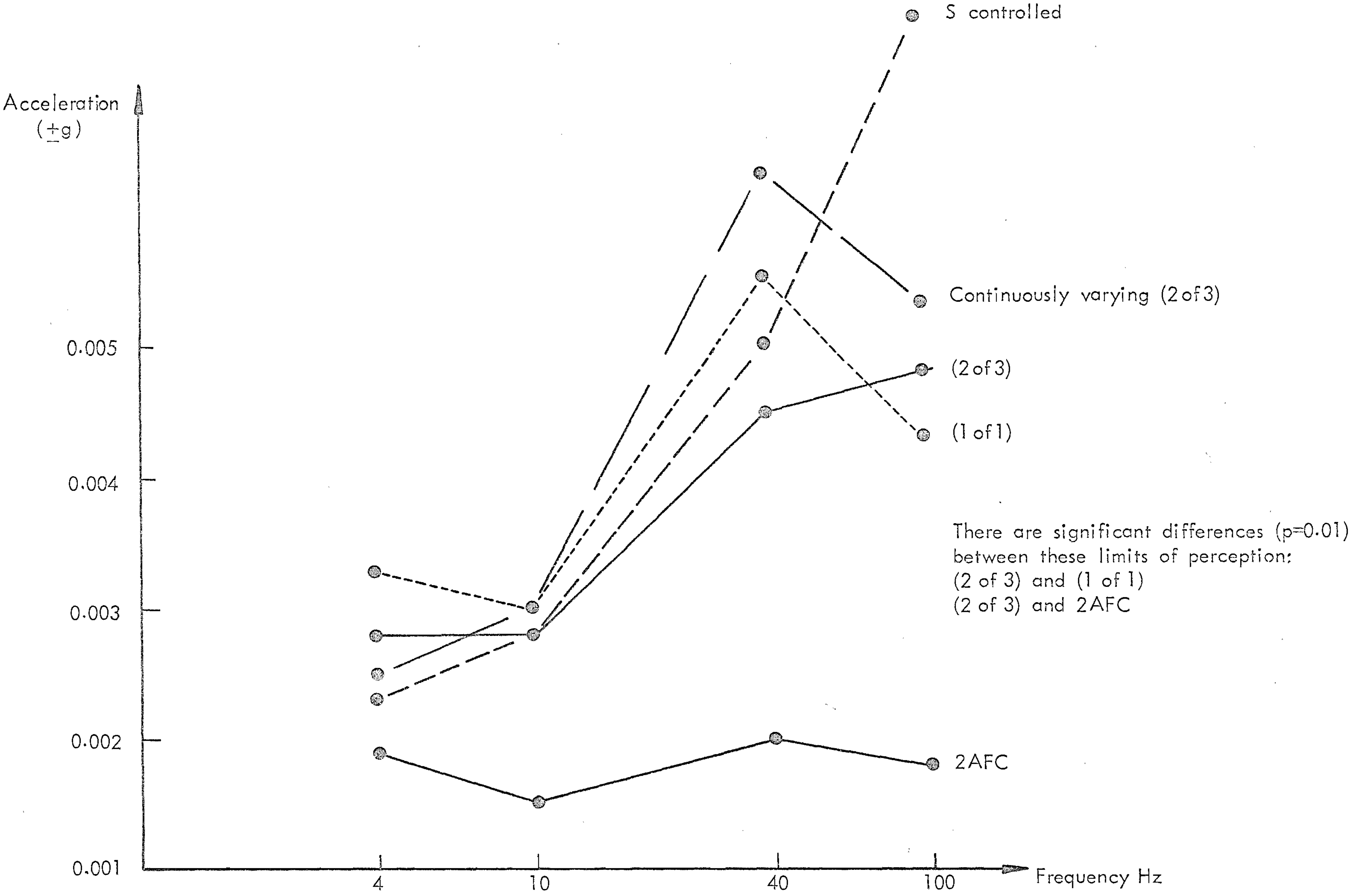


FIG 11 A COMPARISON OF METHODS FOR DETERMINING PERCEPTION

guesses. They may have been reluctant to change their definition of perception and often suggested that a third "don't know" button would be helpful. Such a suggestion would obviously have defeated the purpose of the experiment.

One explanation for the increase in sensitivity shown for the 2AFC method is that both increasing and decreasing stimulus intensities were used. Preliminary experiments, showed that, using the same response criterion, thresholds are lower for decreasing than for increasing intensity. This point is discussed further in Section A6.1.

A5.3. Variance of one subject for repeated tests.

The median score and interquartile for one subject tested on 12 different occasions over a period of ten weeks (six hours total experimentation time) is shown in Fig. 12. Fig. 13 shows the same phenomenon as a function of each test occasion.

The most important comparison to be made is between the interquartile ranges of the main group and this single subject. This latter variance is shown to be smaller at all vibration frequencies. The relative position of these two variances is frequency dependent: the interquartile range for the single subject falling above, below and within the main group variance.

A comparison of the two frequency presentation methods (increasing from and decreasing to 1.5 Hz) used for this subject was made. There was a trend towards lower scores where the 1.5 and 100 Hz tests were completed last rather than first but this trend was not statistically significant.

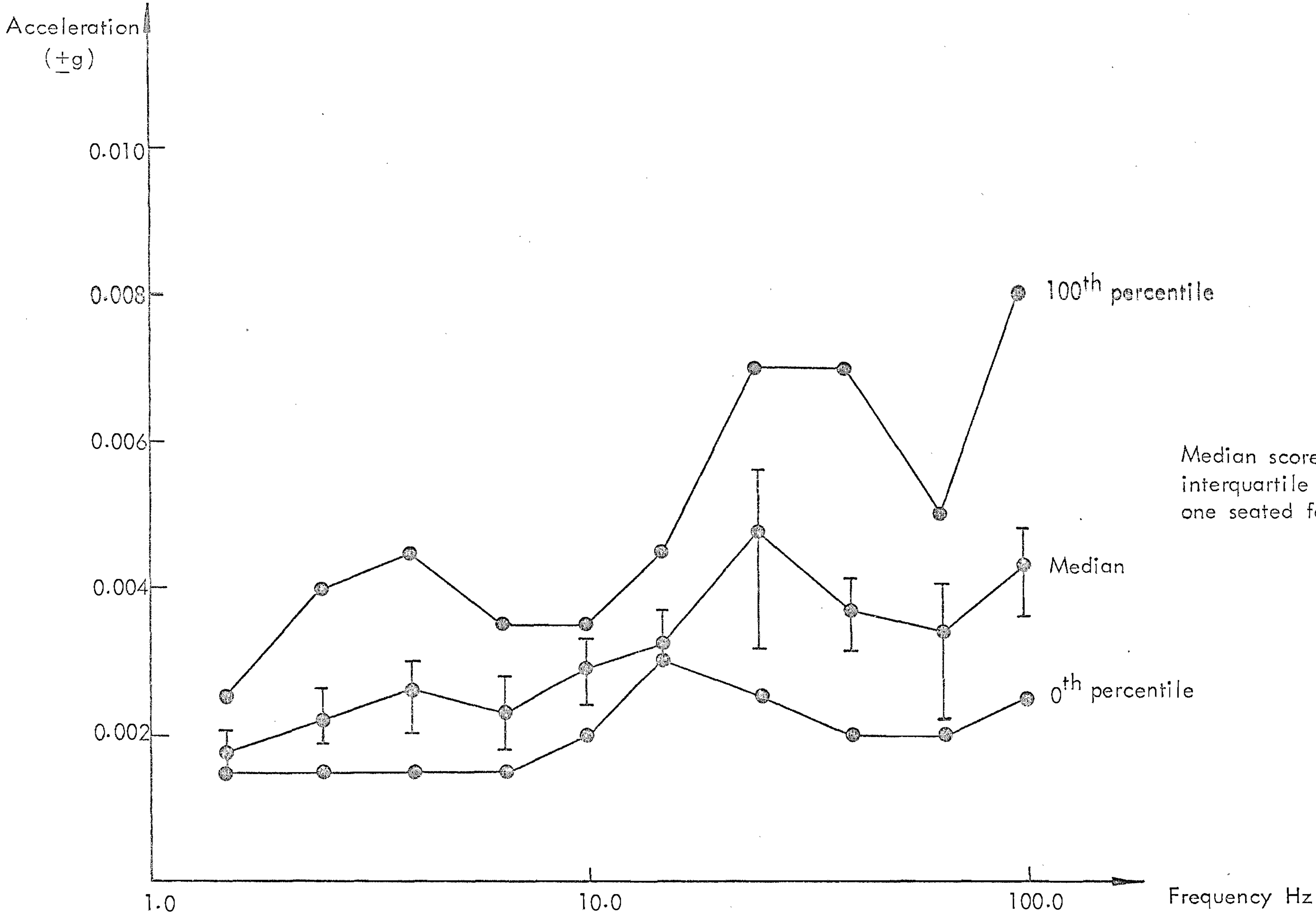


FIG 12 THRESHOLD OF PERCEPTION: VARIANCE IN ONE SUBJECT TESTED ON 12 OCCASIONS

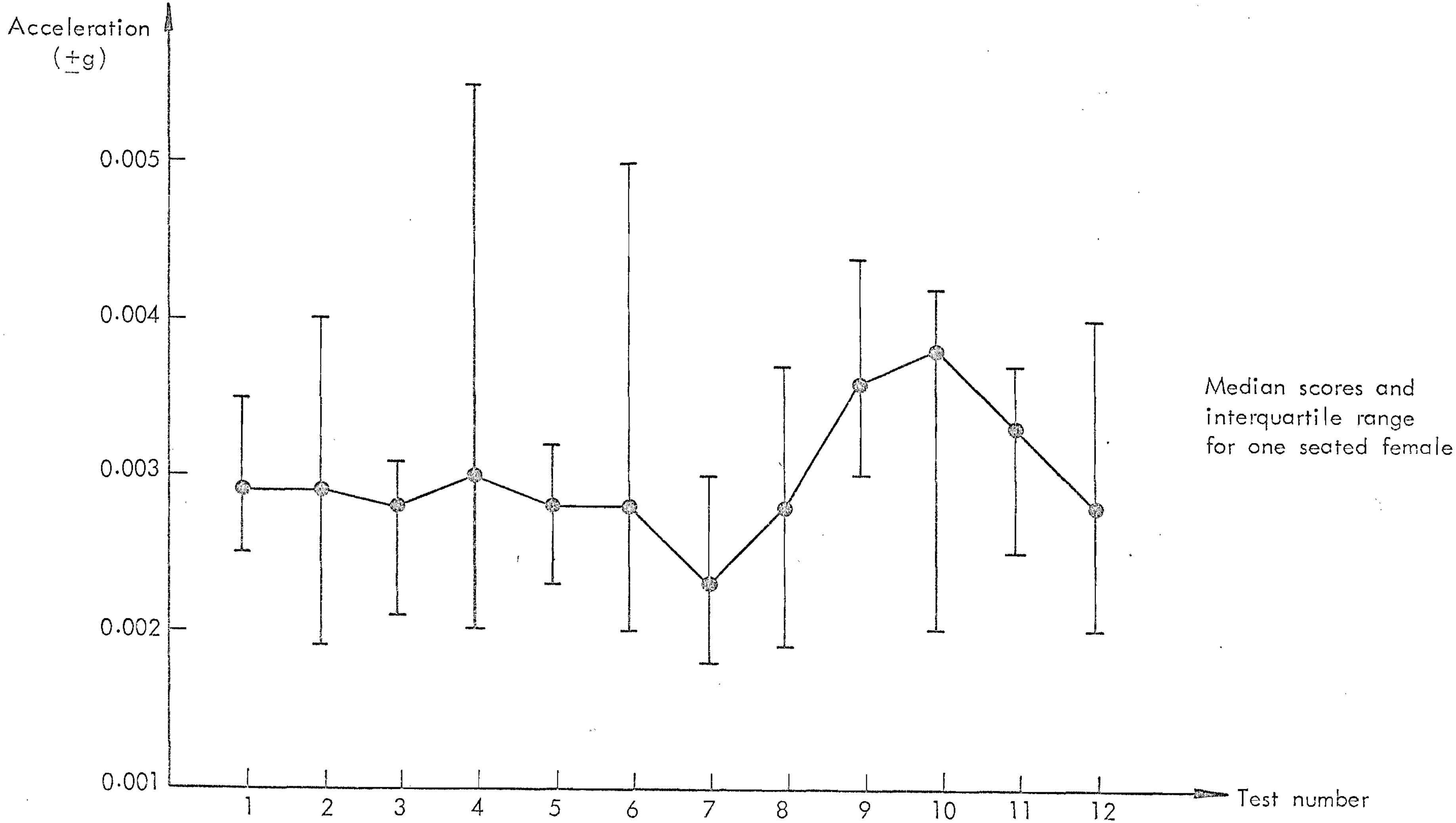


FIG 13 THRESHOLD OF PERCEPTION : VARIANCE FOR ONE SUBJECT AND 12 REPEATED TESTS

The results of the first six tests for this subject were compared with her results for the last six tests: there were no significant differences at all frequencies. In confirmation of this, the subject stated that the threshold judgements did not become easier to make as the series progressed.

A5.4. Whole body vibration including lower limbs and feet.

Fig. 14 shows the differences between seated vibration postures which include and exclude support for the feet, vibrating in an identical way. Differences were found to be statistically significant (p=.05) at the two lowest vibration frequencies (1.5 and 2.5 Hz). Overall frequencies the differences were not significant.

A5.5. Footwear.

Fig. 15 shows the differences for a group of subjects who wore normal footwear and later wore no footwear at all. Differences between the two curves were not significant at individual or overall vibration frequencies.

A5.6. Activity of the subject.

Fig. 16 shows the differences between a curve derived when subject's attention was devoted primarily to reading and when devoted primarily to the detection of vibration. These curves are significantly different at the p=.001 level with a tendency to reduced sensitivity whilst reading. Note that when reading the subject received only one series of increasing stimulus intensities at each frequency. And this result is compared with the (1 of 1) curve derived from this groups' main experiment results.

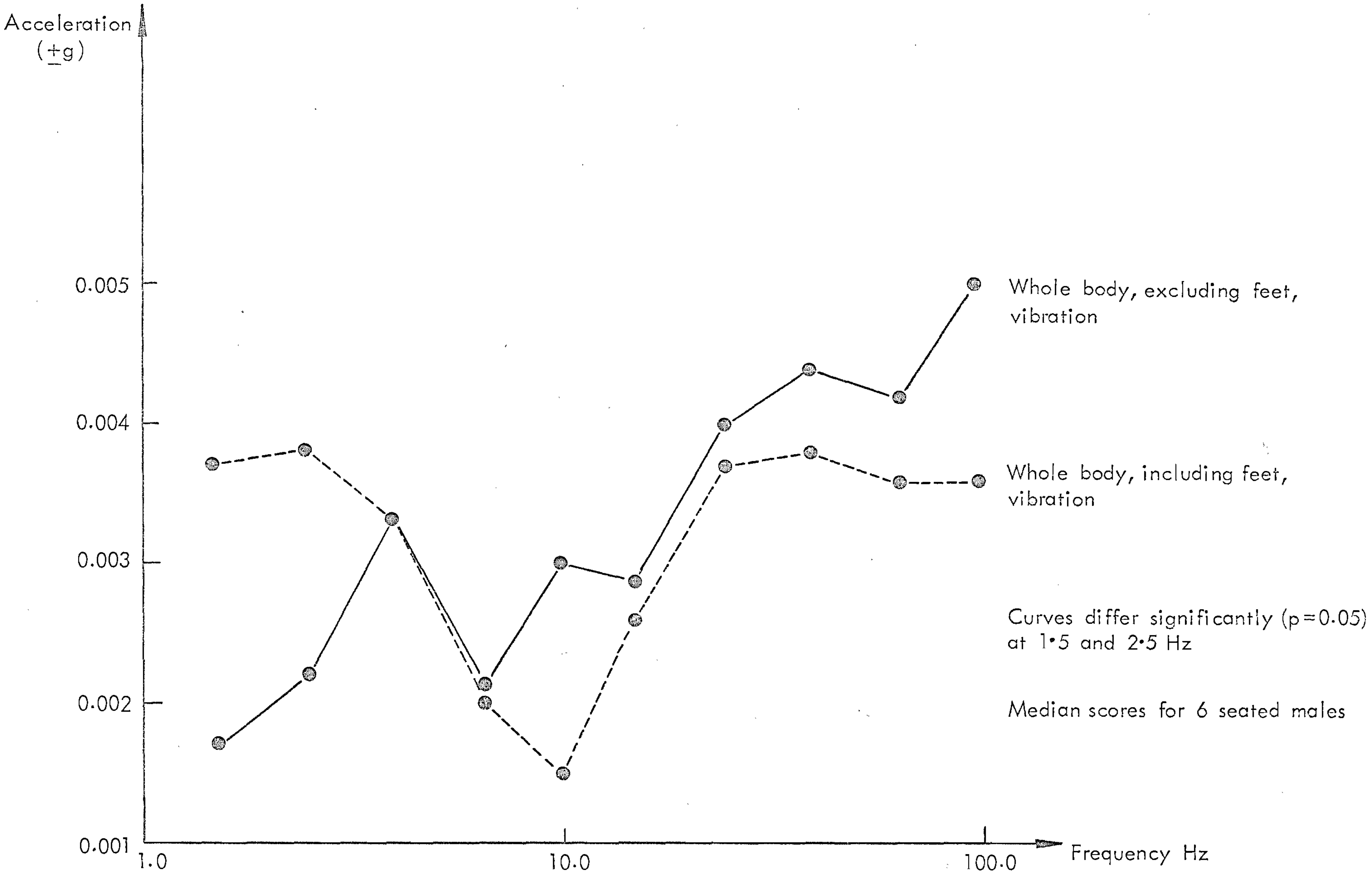


FIG 14 THRESHOLD OF PERCEPTION : FEET INCLUDED AND EXCLUDED FROM VIBRATION

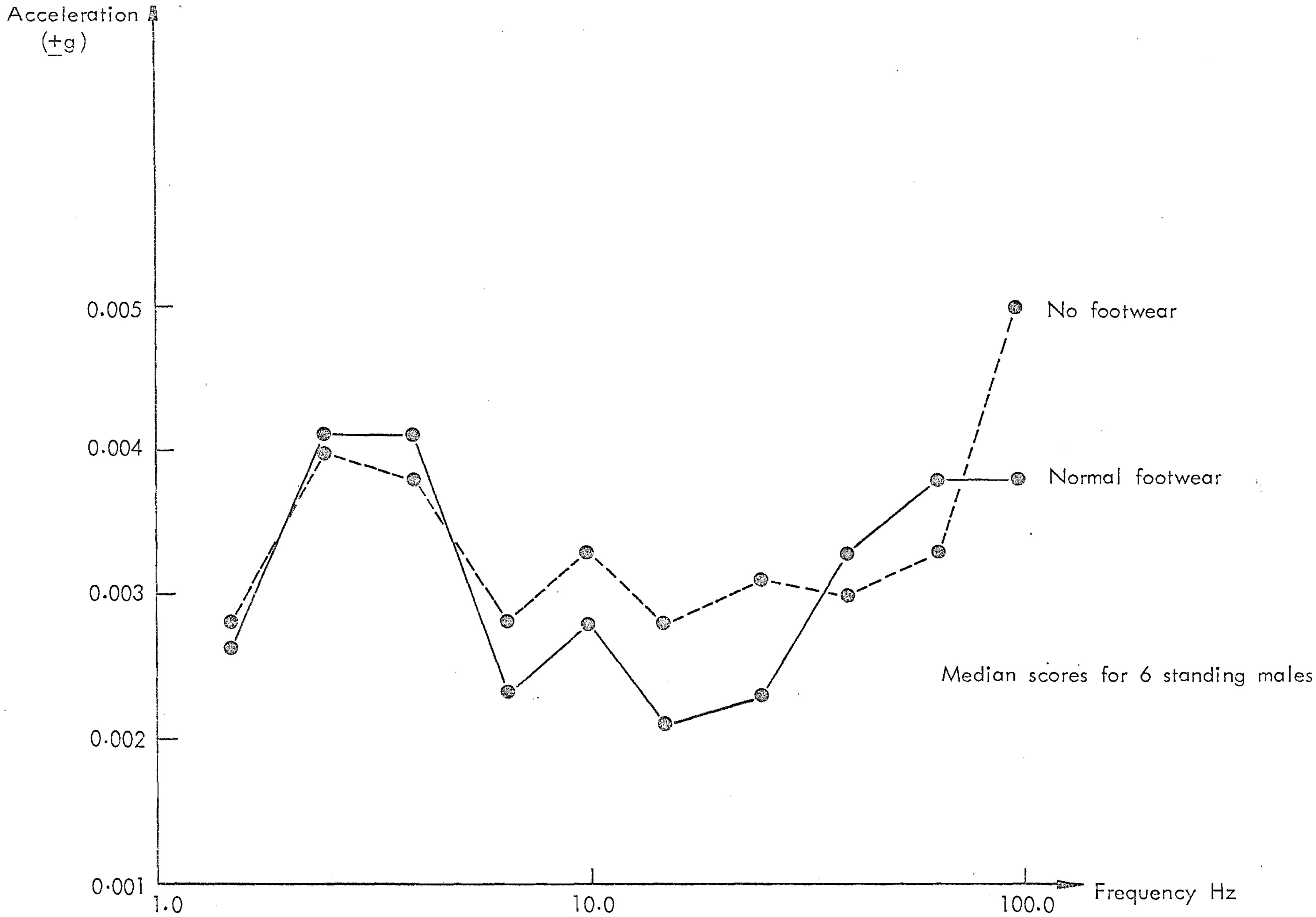


FIG 15 THRESHOLD OF PERCEPTION: COMPARISON OF SCORES FOR NORMAL FOOTWEAR WITH NO FOOTWEAR

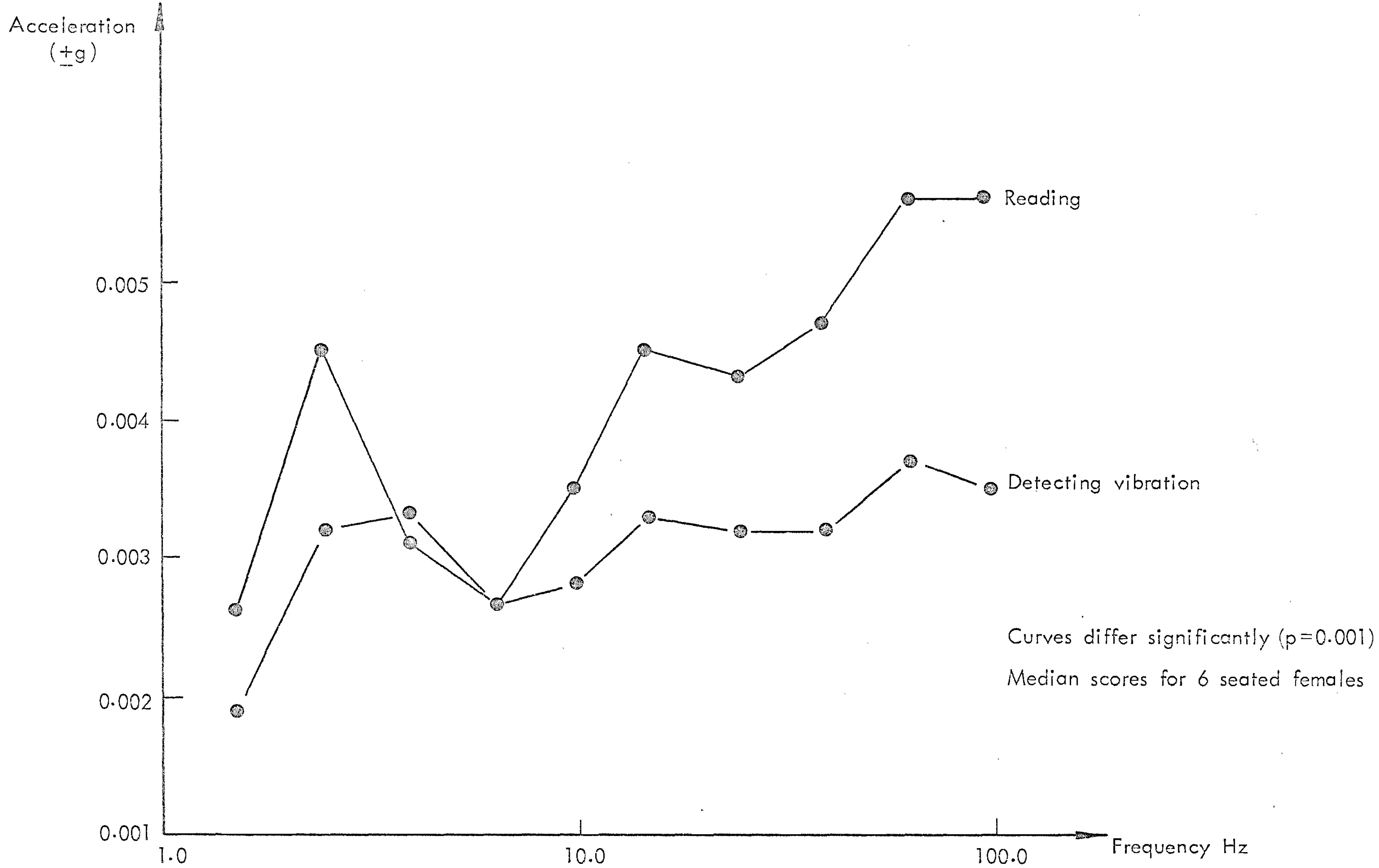


FIG 16 THRESHOLD OF PERCEPTION: A COMPARISON OF TWO TYPES OF SUBJECT ACTIVITY

A5.7. Vision.

Fig. 17 shows the effect of blindfolding standing subjects in comparison with their results under normal vision. The threshold is shown to be significantly increased (p=.05) when normal vision is prevented at the two lowest vibration frequencies (1.5 and 2.5 Hz). Several subjects commented during the blindfold test that, whilst standing, the normal body sway evoked similar feelings to the low frequency vibration and as a result they felt that the sway might mask the perception of vibration. Fig. 17 supports their comments.

A5.8. The acoustic environment.

Fig. 18 shows the effect of increasing acoustic noise from 56 to 85 dBA. The differences tending towards reduced sensitivity in the presence of higher noise just failed to be significant (p=.09).

A5.9. Minimum or background vibration level.

Figs. 19 and 20 show a threshold of perception as a function of the background or minimum vibration level present at the subject's seat; all equipment running, but at minimum output levels.

The threshold was derived in the presence of four different levels of background vibration. For the two lower levels ($\pm$ 0.001 (B_2) and $\pm$0.0003 (B_1) g) subjects were asked to respond to any vibration of the seat. The two resultant threshold curves (T_1 and T_2) were not significantly different at either individual or overall frequencies (15-100 Hz).

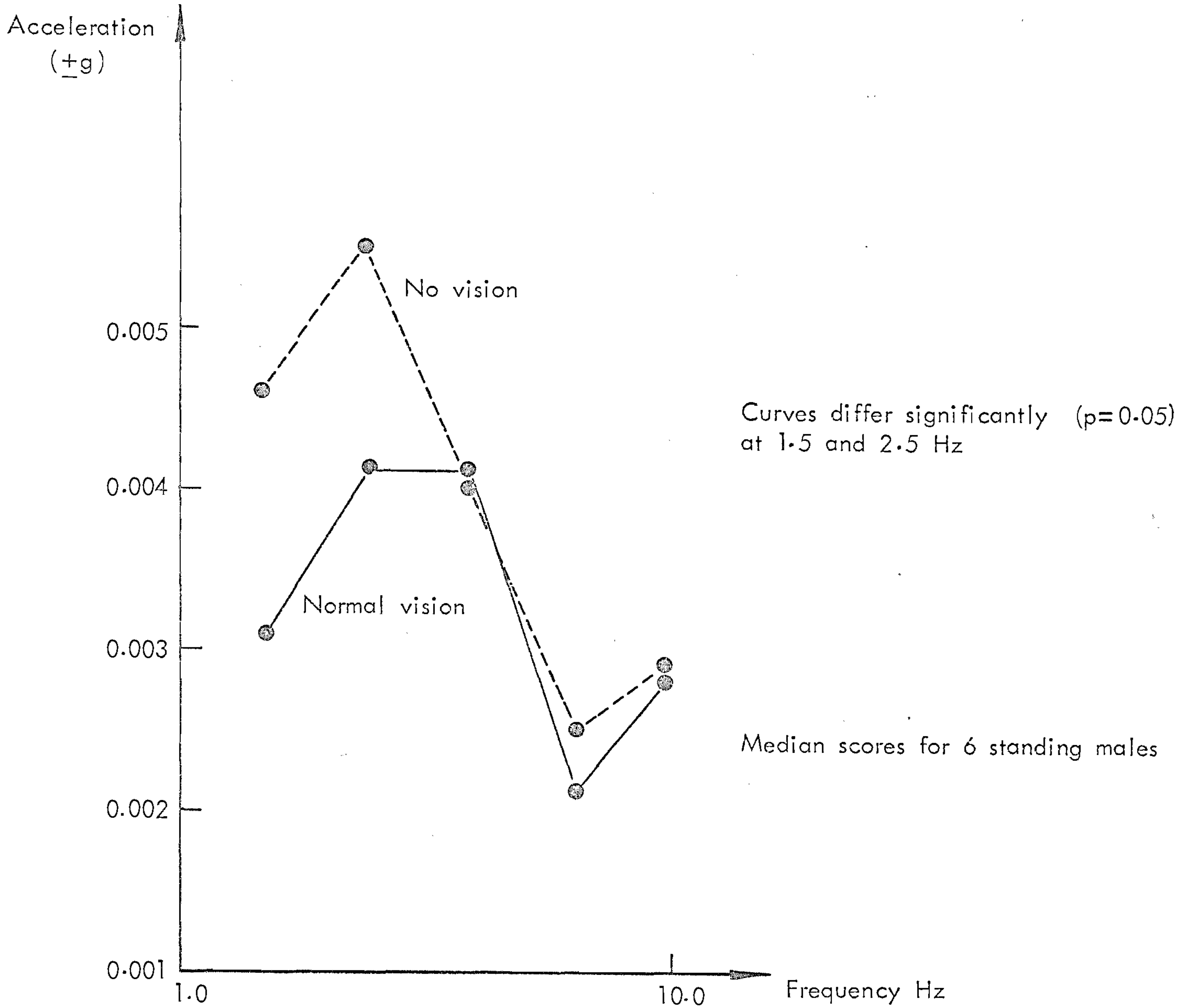


FIG 17 THRESHOLD OF PERCEPTION: NORMAL VISION COMPARED WITH NO VISION

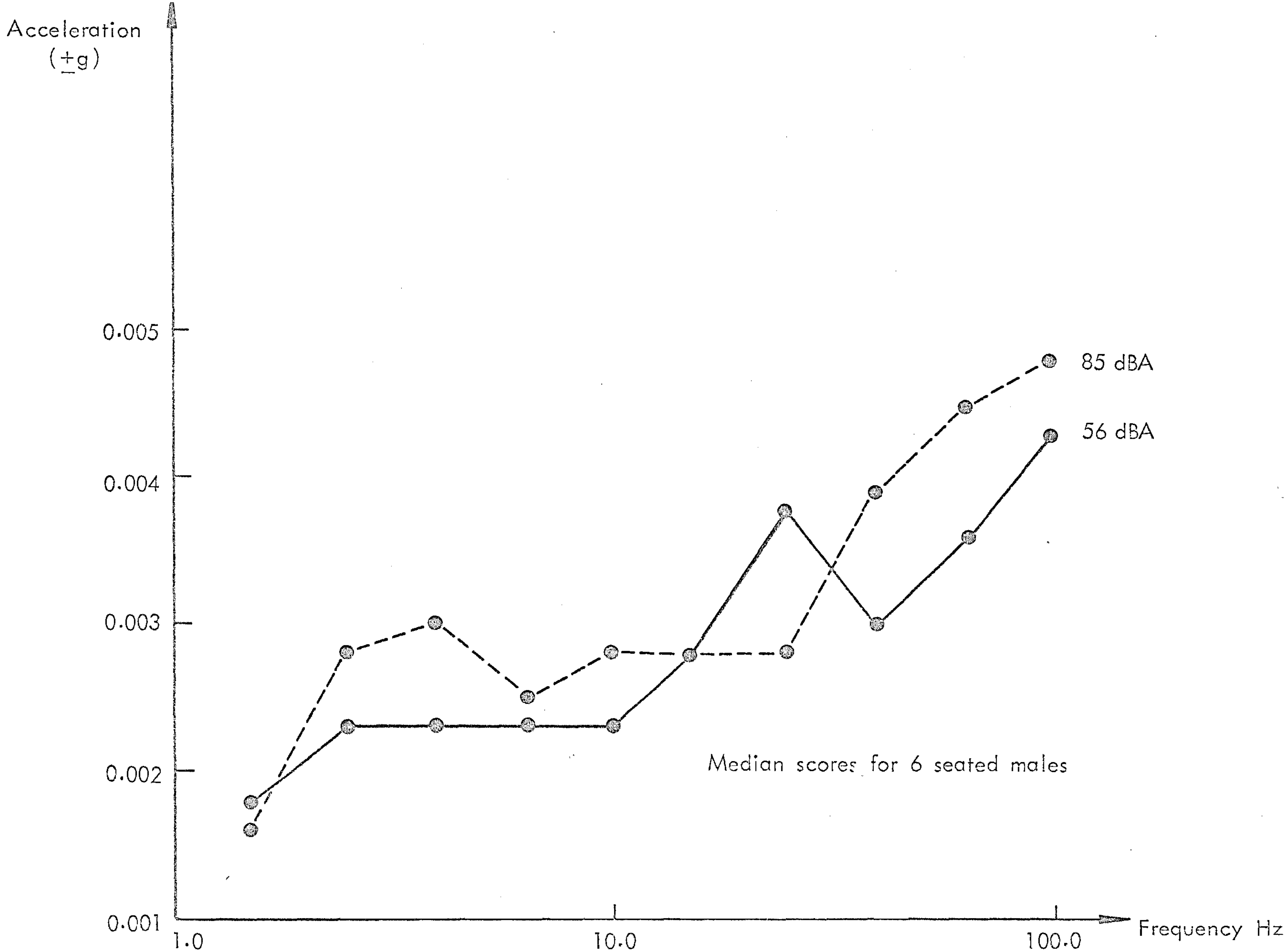


FIG 18 THRESHOLD OF PERCEPTION : 56 AND 85 dBA TESTS COMPARED

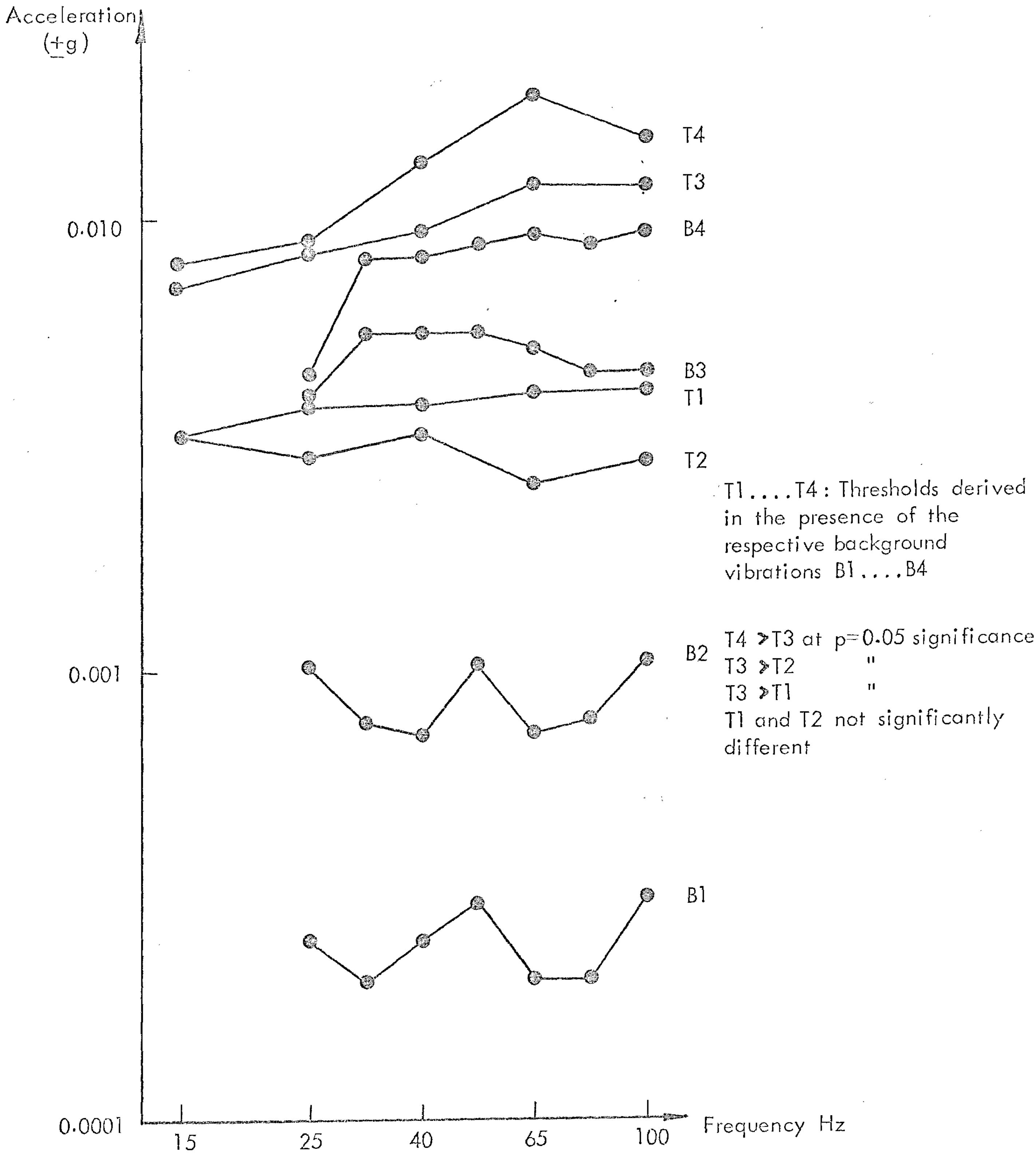


FIG 19 THRESHOLD OF PERCEPTION AS A FUNCTION OF BACKGROUND VIBRATION

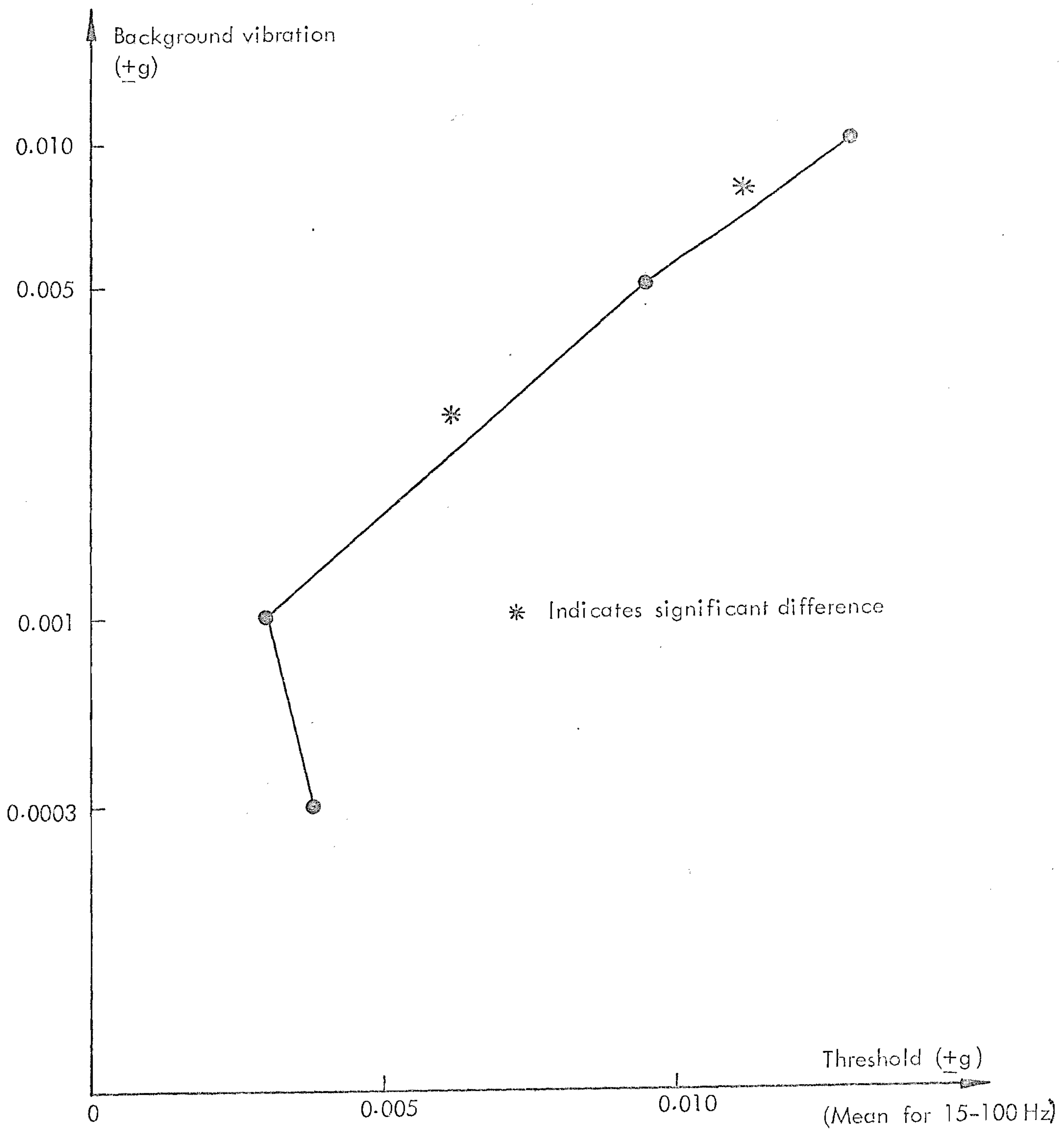


FIG 20 THRESHOLD OF PERCEPTION AS A FUNCTION OF BACKGROUND VIBRATION

For the two higher levels of background vibration ($\pm$ 0.005 (B_3) and $\pm$ 0.010 (B_4) g) the subject responses were necessarily in two parts. For both these levels, when asked: "press the button in response to any vibration"; all subjects would do so whether additional vibration was presented or not. The subjects' response was therefore split into two parts. First, when asked to respond to <u>any</u> vibration, all subjects said yes throughout exposure to a background of $\pm$ 0.005 (B_3) and $\pm$ 0.010 (B_4) g. Secondly, they were asked to indicate the duration of any vibration signal which they could detect in the presence of these backgrounds. The two thresholds derived (T_3 and T_4) are shown in Fig. 19.

T_1 and T_2 were not significantly different. However, T_3 was significantly ($p=.05$) higher than both T_1 and T_2 and furthermore T_4 was significantly higher ($p=.05$) than T_3. Subjects could perceive backgrounds B_4 and B_3 but not B_1 or B_2.

Presumably for B_3 and B_4 the threshold is raised because the background is above a normal threshold.

A5.10. Analysis.

A5.10.1. Analysis of distribution.

A chi-squared test for normality applied to all subject scores (regardless of posture, sex, test presentation and vibration frequency) showed the probability of this distribution being normal to be = 0.001. Consequently non parametric methods of analysis were required.

As regards measures of central tendency, the median (50th percentile), rather than the mean is the preferred indicator, being ~~more~~ less sensitive to extreme values (Ref. 15). And similarly, the interquartile range (25th and 75th percentiles) and not standard deviation is the most appropriate measure of dispersion from the median. The numerical values of the median, mean, mode and interquartile range are given in Table V.

TABLE V. Threshold of perception : median and interquartile range.

Frequency (Hz)	Median	Interquartile range		Mean	Mode
		25th percentile	75th percentile		
1.5	2.5	1.7	3.0	2.2	2.5
2.5	2.3	1.8	3.4	3.2	2.5
4.0	3.2	2.2	4.2	3.5	3.0
6.5	2.4	1.9	3.1	2.7	2.0
10	2.8	2.3	3.3	2.9	3.0
15	3.1	2.3	4.2	3.4	2.0
25	3.8	2.7	5.3	3.8	3.0
40	3.5	2.6	5.3	3.6	3.0
65	3.7	3.2	5.5	4.3	3.5
100	4.4	4.0	6.3	5.0	4.0
All frequencies	3.1	1.8	4.2	3.5	2.0

Units are $\pm$ 0.001g_z. Data are summated over posture, sex and frequency configuration for 48 subjects.

A5.10.2. Analysis of effects of vibration frequency.

The characteristics of the data were assumed to achieve ordinal scaling as defined by Siegel (Ref. 20). For the purpose of determining the effects of different vibration frequencies the samples were related since thresholds were compared where subject, sex and posture remained identical. The Wilcoxon Signed Rank test was therefore selected as the most appropriate test. The results are given in Table VI below.

TABLE VI. Analysis of effects of vibration frequency.

Frequency points compared (Hz)	Probability of no difference between thresholds (two tailed 'p')
100 - 65	0.01
65 - 40	not significant
40 - 25	not significant
25 - 15	0.01
15 - 10	0.01
10 - 6.5	not significant
6.5 - 4	0.01
4 - 2.5	0.10
2.5 - 1.5	0.01

A5.10.3. Analysis of posture, sex and presentation order effects.

Ordinal scaling was assumed but samples were unrelated because the results of one individual were compared with those of another. The Mann Whitney-U test was therefore selected to test posture and sex effects.

First, the data was averaged over all vibration frequencies: posture ($p = .06$) and sex ($p = .08$) failed to be significant variables and for this reason posture and sex differences were compared at each vibration frequency (see Table VII).

TABLE VII. Analysis of posture and sex effects.

Vibration frequency (Hz)	Probability of no difference between male and female thresholds (two tailed 'p')	Probability of no difference between standing and sitting thresholds (two tailed 'p')
100	NS	NS
65	NS	NS
40	NS	NS
25	NS	NS
15	.01	.05*
10	NS	NS
6.5	.03	NS
4	NS	NS
2.5	NS	.02
1.5	NS	.001

(not corrected for ties except at *)

Subjects received one of three different frequency presentation orders: decreasing from 100 Hz, increasing to 100 Hz and a random order of frequencies. The Kruskal-Wallis test was used for comparison, there being three independent samples. When the data was averaged over all vibration frequencies the probability of there being no difference in the threshold for each presentation order was $0.20 > \text{two tailed 'p'} > 0.10$. In addition, a comparison was made between the two presentations : decreasing from 100 Hz and increasing to 100 Hz, at two of the vibration frequencies (1.5 and 100 Hz, these being the more "sensitive" vibration frequencies). There were no significant differences between these two frequency presentations.

A5.10.4. Analysis of two limits of perception.

The two definitions of perception (1 of 1) and (2 of 3), defined in Section A5.1.5, were compared using the Wilcoxon Signed Rank test: the two samples being related. The results of this test are presented in Table VIII.

TABLE VIII. Analysis of two limits of perception.

Vibration frequency (Hz)	Probability of no differences between the two limits (two tailed 'p')
100	0.10
65	0.05
40	0.05
25	0.01
15	not significant
10	0.01
6.5	0.01
4	0.05
2.5	0.01
1.5	not significant

A5.10.5. Other analyses.

The Wilcoxon signed rank test was used to test the significance of differences between the various methods for determining perception. Summing over all vibration frequencies, the (1 of 1) curve was again found to be significantly greater (one tailed $p = .01$) than the (2 of 3) curve which in turn was significantly greater (one tailed $p = .01$) than the 2AFC curve. At neither individual nor overall frequencies were the differences significant, between experimenter and subject controlled stimulus presentation. The same applies to differences between stimulus intensities continuously varying and presented in bursts.

The Wilcoxon signed rank test was also used to test the significance of differences for the experimental variables shown in Table IX. If differences were not significant (NS) over all frequencies of vibration then the same test was applied at each frequency.

TABLE IX Experimental variables - significance of differences.

Variable	All frequencies	Each frequency
12 tests of threshold: First 6 compared with last 6	NS	NS
Including compared with excluding feet from whole body vibration	NS	1.5*, 2.5*.
Normal compared with no footwear	NS	NS
Reading compared with detecting vibration	***	
Normal compared with reduced vision	NS	1.5*, 2.5*.
85 compared with 56dBA noise	(p=.09)	2.5*.
Background vibration		
Thresholds (T_1&T_2) compared in backgrounds B_1&B_2	NS	NS
" (T_3&T_1) " " " B_3&B_1	**	
" (T_3&T_2) " " " B_3&B_2	**	
" (T_3&T_4) " " " B_3&B_4	**	

* two tailed p = .05

** two tailed p = .01

*** two tailed p = .001

A6. DISCUSSION AND CONCLUSIONS.

A6.1. Discussion.

This study has made a twofold approach to perception: first, an investigation of the nature of perception and secondly it has applied one particular threshold to the study of experimental variables.

The belief in a step like psychometric function for the perception of vibration has been the tradition for those who have studied the human response to vibration. This belief has been shown to be without foundation, although much depends on the accuracy of measurement. Using one particular level of accuracy, it has been shown that perception does not change from NO to YES at a discrete level of vibration. It was demonstrated that there is a range, of which this discrete level is a part, and over this range, the probability of detection varies between 0 and 1.0. The inference should not be that the threshold curve reported here is correct and other thresholds are wrong: obviously, they are all right. But one reason why they do differ is because the measurement is of different parts of the perception function.

Also described in this thesis are a series of investigations into the magnitude and direction of the effects of a number of experimental variables. One particular method for defining the threshold was used. The results of this study are compared with previous investigations in Fig. 21. Not surprisingly, the results fall in the region between existing extremes: Chaney (subjects had reduced visual cues) and Meister (curve drawn below all threshold scores). Also plotted, however, are the two extremes (100th and 0th percentile)

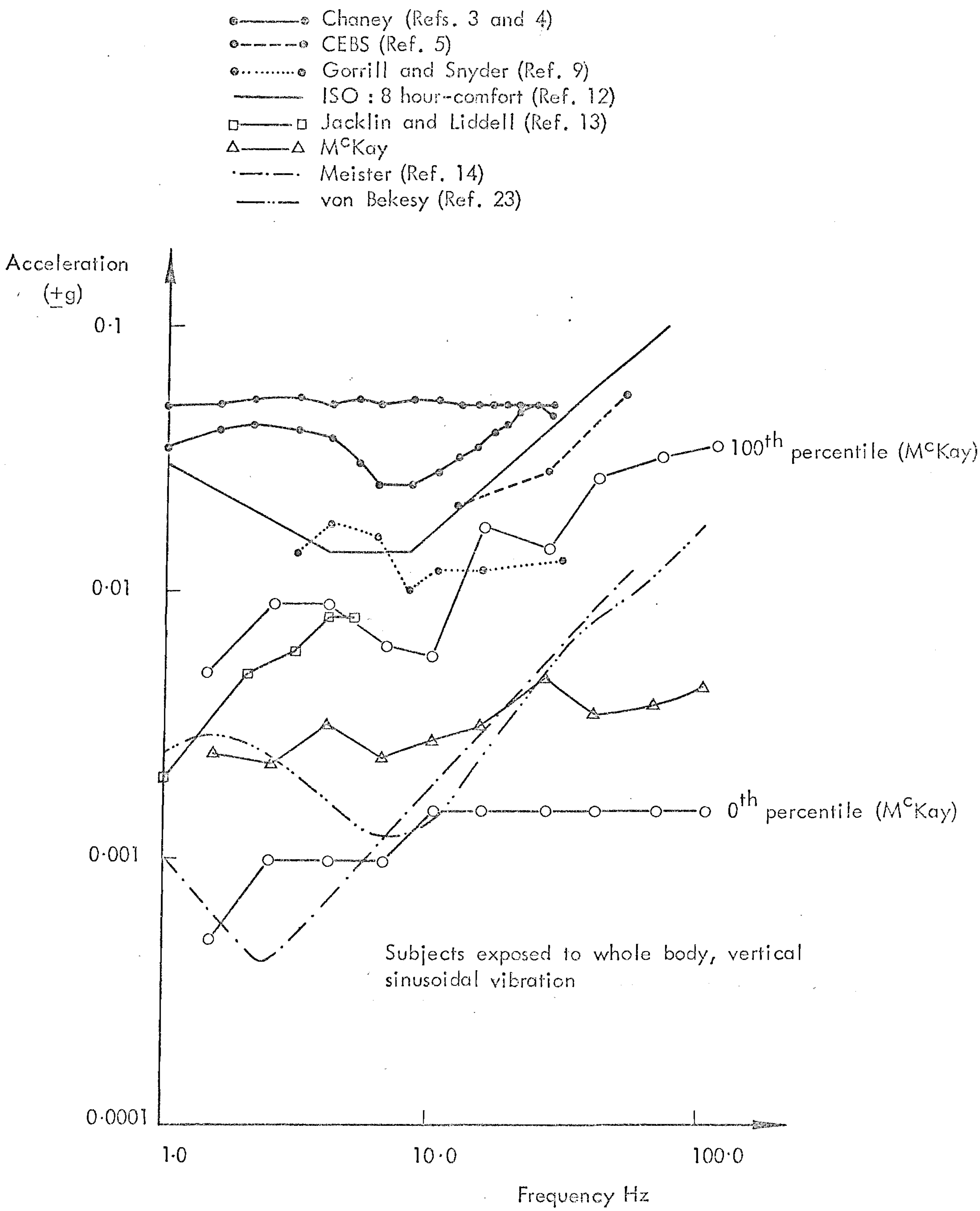


FIG. 21 THRESHOLD OF PERCEPTION : COMPARISON OF PREVIOUS DATA WITH THE RESULTS OF THIS STUDY.

derived from all the authors' own experiments. These two curves show that variations in the experimental circumstances will contribute at least 40dB, this being the range of existing reported thresholds. It is regretable that the importance of the experimental circumstances has only just been confirmed especially in view of the gaps in existing reports so clearly shown in Table I. The sources of variance which have been investigated by the author on a statistical basis are shown in Table X.

The two existing extremes are Chaney and Meister and the experimental differences are as follows: acoustic noise, vision, analysis, stimulus presentation and stimulus control. These two extremes, being about 40dB apart at 2.5 Hz, would have been closer by 1.5, 2.5, 7, 1 and 1 dB respectively: a total of 13dB. However, inadequacies in experimental techniques and/or reporting by both authors (Meister's reports being the least comprehensive) could lead to these experimental differences: background vibration, footwear, subject response criterion, variance within and between subjects. Their respective contributions have been shown to be of the order of 20, 1, 9.5, 6 and 14 dB.

TABLE X. Sources of variance in a threshold of perception.

	Notation
Increase in sensitivity, lowering of threshold	-
Decrease in sensitivity, raising threshold	+

Source	Differences (dB)					
Frequency (Hz)	Mean for 1-25Hz	1.0	1.5	2.5	10	25
Chaney (Ref.3) - Meister (Ref.14)	+29	+34		+42	+29	+20
Results due to McKay						
1. Vision: (normal - blindfold)	-1.5		-3.5*	-2.5*	0	-
2. Acoustic noise: (85-56 dBA)	0		-1	+1.5*	+1.5	-2.5
3. Footwear: (normal - bare foot)	+1		+0.5	-0.5	+1.5	+2.5
4. Sex: (females - males)	+0.5		0	0	0	+2
5. Posture: (standing - sitting)	+2		+4.5*	+4*	+1	-2
6. Whole body vibration: (exclude - include feet)	+1.5		+7*	+4.5*	-6	+0.5
7. Attention: (Reading - detecting vibration)	+2.5		+2.5*	+3*	+2*	+2.5*
8. Analysis: (50th-0th percentile)	+6		+8*	+7*	+3*	+6.5*
9. Analysis: (1 of 1)-(2 of 3) judgements	+1		0	+2.5*	+1*	+0.5*
10. Stimulus presentation: (continuous - bursts)	+1					
11. Stimulus presentation: (subject - experimenter control)	+1		Frequencies used were 4, 10, 40 and 100 Hz.			
12. Methods: ((2 of 3) - 2AFC)	+6					
13. Background vibration: (±.010-±.001g)	+20		-	-	-	+20*
14. Subject's response criterion: (100-0)% detection	+9.5		(4,10,40 and 100 Hz only)			
15. Variance within one subject: (100th - 0th) percentile	+6		+4.5*	+8.5*	+2*	+9.5*
16. Variance between subjects: (100th - 0th) percentile	+14		+14	+19	+9	+13

*significance at p = .05 level.

Why should these particular sources of variance affect an experiment in the perception of vibration? Consider first, the two parameters of the stimulus which were investigated: vibration frequency and background vibration.

The introspective comments confirm that the sensory processes which perceived vibration were frequency dependant and that the site of sensation i.e. type of sensory receptor, was related to frequency. It is not surprising, therefore, that overall sensitivity was a function of frequency. However, the relationship for a threshold in terms of acceleration and frequency was found to be non-linear and not of a form similar to that promulgated by Meister & ISO.

When the level of background vibration exceeded $\pm$ 0.001g, thresholds of perception could be raised. Either the subject may notice the continuous background in the presence of which a signal of similar strength goes undetected or, if asked to ignore the background and respond only to additional vibration, the threshold will lie at a higher level.

Only one feature of the experimental environment was investigated: acoustic noise. In the main experiment, many subjects had commented on the difficulty of making judgements in 56 dBA of acoustic noise. They reported distraction and/or masking of the vibration by noise. A higher level of acoustic noise raised the threshold confirming the suspicions of these subjects. The implication is that lower threshold scores would be expected in quieter environments and presumably the converse may also hold: that vibration is buildings is less noticeable in the presence of certain kinds of noise.

With regard to experimental method it was somewhat surprising to find that for subject controlled stimulus presentation, sensitivity was reduced; surprising because the subject would know when to expect a stimulus. Subjects do tend to be conservative in their judgements i.e. use a response criterion with a high probability of detection. This may be accentuated when they control presentation or it may be that they are influenced by being asked to make adjustments starting from a high level ($\pm$ 0.010g) (see Section B2.2.1.).

A higher threshold was also derived when stimulus level was continuously increasing rather than in steps and bursts. This trend in sensitivity was expected in view of the finding that subjects tended to respond, at theshold levels, to the onset and offset of the vibration stimulus. The implication is that intermittent vibration is more noticeable than continuous vibration of the same intensity.

The comparison between methods for defining the threshold illustrates the importance of the limit and/or methods used. The trend for the (2 of 3) scores to be lower than the (1 of 1) scores is probably a result of the greater number of exposures. The forced choice procedure yielded an even lower threshold confirming the findings of others (Swets Ref. 29). They attribute this result to the subject making conservative judgements i.e. employing a strict limit of perception, when not forced to make a decision.

Nine sources of variance in the subjects' physical or behavioural characteristics were investigated on a statistical basis. Sensitivity was significantly reduced when normal vision was prevented at low vibration frequencies. In this region, larger displacements ($\frac{1}{32}$ ins.) are needed to evoke perception and vision may therefore play a part although very few subjects commented that visual cues were advantageous. It is possible that females adopt a more conservative limit of perception but there is no obvious explanation for the significant difference between the sexes. When the feet and lower limbs vibrate together with the whole body, sensitivity was again significantly reduced at the low frequencies only. This may be explained by the larger relative movement which occurs between stationary lower and moving upper body where frequency is low and displacements large. Standing subjects were significantly less sensitive but this was not due to their footwear which was not a significant source of variance.

Where the subject's attention was diverted from the task of detecting vibration, sensitivity was significantly reduced. This result was expected. It has also been shown that the subject may use varying degrees of certainty in making decisions and this will lead to probabilities of detection varying from zero to 1.0.

Lastly, the extent of within and between subject variance has been illustrated. Using the (2 of 3) method, overall frequencies, temporal variability of the threshold was as large as the variability between individuals. But at each frequency, temporal variation was always the lesser. Even so the threshold when tested on different occasions will vary over a relatively wide range and particularly so at the higher frequencies. This may, of course, be a consequence of this particular method for determining a threshold or it may be a function of inherent subject variability. However, the method derives considerable support from its sensitivity to the many experimental variables described above.

Examining the post test subject comments, revealed an absence of comment on the vibration exposure. And yet there is ample evidence of nuisance and distress to building occupants at these levels (Daily Telegraph, June 23, 1971). The dichotomous nature of this evidence underlines the importance of the psychological circumstances of the experiment and points out the serious limitations of laboratory research into this subject.

Perhaps the most important conclusion is that the threshold should not be considered as a discrete value but rather, it should be considered as a range, this being from $\pm$ 0.001 to $\pm$ 0.010g_z, with a large number of sources of variance. For some individuals, in certain situations, the threshold of perception will lie outside this range.

A6.2. Conclusions.

Section A of this thesis reviews existing information on the threshold of perception for whole body, vertical, sinusoidal vibration and discusses the limitations of this information. Experiments are described, the aims of which were to make a more definitive study of the threshold, its variability and the most appropriate experimental techniques used to define the threshold.

It is suggested that this information is relevant to man's perception of vibration in buildings and may therefore be of use to building designers and where complaints of vibration intrusion are made by the occupants of buildings.

The traditionally held belief in a step-like psychometric function for the perception of vibration was shown to be misleading. A threshold of perception in a group comprising twenty-four male and twenty-four female subjects had a median of $\pm$ 0.003g and interquartile range of $\pm$ 0.002 to $\pm$ 0.004g. A considerable number of experimental variables affecting perception were investigated. These were the stimulus characteristics: vibration frequency and background vibration. The laboratory acoustic noise was studied as was the experimental method: subject versus experimenter presentation of the stimulus, burst versus continuously varying stimulus presentation, analysis and methods for determining thresholds. Subject variables were: vision, footwear, sex, posture, attention, response criterion, vibrating and stationary footrests, within and between subject variance. Many of these sources of variance were statistically significant.

The relevance of this work to the human response to vibration in buildings is discussed.

Section B STARTLE

BI. INTRODUCTION.

Man may be exposed to a variety of sudden vibratory forces: the origin of such excitation might include blasting, sonic booms and construction equipment. Despite the occurrence of these forces, there has been very little previous research which has examined the effects of short duration, whole body vibration at levels typical of those found in buildings excited by impulsive forces. At these levels, Magid (Ref.30) has probably used the shortest experimental duration of between 0.3 and 3 minutes, otherwise impact research has been at higher levels with specific reference to the design of aircraft ejection seats (Ref. 31).

The human response may well depend on the unexpected quality of the stimulus and presumably this unexpectedness or startle response may be more acute in buildings where their purpose, whether residential or occupational, is unrelated to the vibration source. Both von Gierke (Ref.32) and Rice (Ref.33) have underlined the need for research into man's response to sonic boom induced building vibrations.

The startle reaction has been the subject of a large number of previous investigations. Many of these used a psychophysiological approach and have been reviewed by Oldman (Ref.34). May (Ref.35) has reviewed and experimented in task performance under startle. Lukas (Ref.36) has used simulated sonic booms with both an acoustic and vibratory component and he has investigated their joint effect on performance and electromyography (EMG) measurements. These references have shown that measurable changes in psychophysiological, in performance and in subjective assessments are attributable to a sudden external (usually acoustic) stimulus.

However, these measurements are of specific components of a generalised orienting or startle reaction in man which is consequent on suddent stimulation. The question therefore arises of how best to define, the characteristics of these generalised reactions. Having done so, it will then be possible to decide which specific indices are the most appropriate in the context of a sudden vibration stimulus.

BI.I. Nature of the startle reflex.

Sokolov (Ref.37) has stated: ".....stimulus and the reinforcement that follows evoke:

a. an orienting reflex (OR)- a non specific, generalised reaction of activation of the organism that includes motor, vascular, respiratory and bioelectrical components.

b. adaptational reflex (AR) - a localised specific response for a given analyser reaction of adaptation to the acting stimulus.

c. a defensive reflex (DR) - a total defensive reaction of the organism which is evoked where the stimulus reaches a destructive intensity".

Not only does stimulus intensity play a role in the evocation of the DR but also, number of repetitions. Moderately intense stimuli may produce a DR for the first few trials and then the OR or the reverse depending on the nature of the stimulus and its value to the receiver.

Considerable effort has gone in elaborating the definitions of the OR and DR and in methods by which these two responses may be distinguished. The characteristics of the OR have been summarised as follows Lynn (Ref.38):

i. increases in sensitivity of sense organs

ii. a characteristic response of the musculature, including a general increase in muscle tone and EMG.

iii. changes in electroencephalogram (EEG)

iv. vegetative changes for example, in vasoreaction, galvanic skin reflex (GSR) and heart rate (HR).

In some of these functions, stimulation may evoke qualitative or quantitative changes and these may be used to distinguish the OR from the DR. Sokolov believes that the two are most easily identified in the vasoreaction: with the OR, there is vasodilation in the head and vasoconstriction in the limbs. With the DR vasoconstriction occurs in both head and limbs. For thermal stimuli, as Zimny and Miller (Ref. 39) point out, the vasoreaction is somewhat different especially with the AR, but this need not concern us here.

Raskin et al (Ref.40) hold the opposing view to Sokolov, namely that it is not possible to distinguish the OR and DR on the basis of vasomotor activity in the forehead skin. Raskin suggests that the OR and DR may be distinguished in the HR response and a short latency deceleration may characterise the OR. Graham and Clifton (Ref.41), Germana and Klein (Ref.42) and Uno and Grings (Ref.43) agree and disagree on various phases of the post stimulus HR response pattern. Clearly there is a need for a better understanding of the cardiovascular response before further detailed study of habituation. And quite clearly these autonomic components, the HR and vasoreaction to a vibration stimulus are worthy of further investigation.

Considerable support for Sokolov's theory was produced in experiments conducted by Zimny and Schwabe (Ref.44) using measures of both vasoreaction and GSR. Although the GSR, unlike the vasoreaction, does not exhibit a qualitative change dependent on the stimulus, it is true that previous studies (Ref.38) have used the GSR in response to electric shocks and acoustic stimulation. These have demonstrated support for Sokolov's theory. And, furthermore, we know that the GSR is sensitive to stimuli generated by the subject, both internally and externally. Indeed, Montagu (Ref.45) has stated: "...GSR is the most sensitive physiological indicator of psychological events available". There is good reason therefore to use the GSR in whole-body vibration experiments; a field of study in which it has not yet been applied.

Similar evidence and reasoning supports the use of EEG and EMG measures but these two are subject to special consideration in the context of whole body vibration experiments. First, the perception and cortical response to body vibration, unlike audition, is non-specific in man. As a result, no one cortical site responds to a vibration. In the case of EMG measurements, the difficulty is of a more practical nature. Namely that by virtue of the physical vibration causing movement, much of the body musculature will be active irrespective of the orienting reaction which occurs at a higher autonomic level, together with specific EMG orienting components.

BI.2. Measurements proposed in the context of vibration and startle.

So far then, evidence has been presented or referred to which suggests that in the context of short duration, vibration experiments the HR, vasoreaction and GSR are indices worthy of investigation. This conclusion is based on a mixture of considerations from what is technically possible and physiologically sound. On these same grounds EEG and EMG have been found inappropriate to short duration vibration exposures. Performance and startle due to vibration is being investigated elsewhere (Ref.36) and was not included in this investigation.

To complement the use of these objective indices, it was thought to be worthwhile making an assessment of the subjective feelings of startle caused by the vibration stimulus. Subsequently, it would be possible to compare the two complementary aspects of human behaviour: on the one hand "consciously controlled feelings" with subconsciously controlled vegetative indices on the other hand.

Several investigators have attempted the subjective measurement of startle with varying degrees of success. May (Ref.35) used a simple method of magnitude estimation in response to pistol shots and actual sonic booms. He showed habituation and correlation with a performance measure. There are considerable difficulties inherent in the measurement of subjective startle. It is in the nature of startle that subjects' response are "one off", that he cannot make comparisons with a standard unless it is imaginary or (probably) long forgotten. Section B2.2 discusses these difficulties in relation to potential methods of subjective assessment.

B2. ARTIFACTS AND METHOD

B2.1. Artifacts in electrophysiological recording.

In whole body vibration experiments, there are a number of possible sources of artifact in the recording of electrophysiological events. Prior to these experiments, considerable effort was spent in delineating the circumstances in which artifact could occur in the GSR, HR and vasoreaction under conditions of whole body vibration. The four sources of error which were considered to be possible under vibration were as follows:

i. Movement of the electrodes relative to the skin site.

In all three physiological functions, this artifact has a discrete, identifiable and transient effect on the recording. In other words, the effect of "loss of contact" is a characteristic one.

By observing the raw waveforms, as distinct from a treated waveform such as the HR, it was always possible to identify where this error had occurred. In fact it was fairly infrequent. However, when this did occur it was always possible to null its effects on the results, by paying very close attention to the time history of events. The stimulus duration for these experiments (see Section B3) was one second which is usually less than the latency of these physiological functions, so that the stimulus offset and "loss of contact" due to relative electrode/site movement had already taken place before any physiological changes occurred.

ii. Movement of the electrode leads only: Poor electrical connections and pick up induced by movement through stray electrical fields are demonstrated when the leads vibrate or move. The first problem is easily rectified but the second is not. However, no effects on the measured functions were observed for gross lead movements probably because each of the three preamplifiers was fitted with a low pass filter.

iii. Movement of the electrode/site combination. Voluntary and vibration induced movement of both the individual limbs and the whole body were considered. Using two subjects and a dummy resistive load no effects were observed in the GSR. (The GSR arises from changes in skin resistance which is mediated by the sweat glands only.) Using three subjects and a dummy light source, the PPG was unaffected by transducer/site movements.

For EKG and HR the result was different. The EKG is determined by the changes in potential measured on the surface of the skin. Placed in EKG lead position II, the electrodes detect potentials generated by the activity of the heart muscles, these being tansmitted to the surface of the skin by various body fluids and tissue. Where movement is induced whether voluntary or otherwise, there may be a response of the musculature and changes in potential generated by the limb muscles (EMG) will occur.

When the limb muscles are active, the EKG may therefore be compounded of the potentials generated by both the heart and limb muscles.

iv. Artifacts in physiological functioning.

As explained above, the GSR and PPG, being dependent on resistance and light changes, are unaffected by voluntary or vibration induced movements provided there is no relative movement between the electrode and site.

On the other hand, the EKG may become contaminated by limb muscle potentials. This EMG is of higher frequency than the EKG and the use of a low pass filter is therefore beneficial. Close observation of the raw EKG identifies the occasions on which this artifact occurs. Its effects can be further nullified by paying close attention to the stimulus onset and offset in relation to the HR changes which occur.

In conclusion, it is essential to ensure the best possible electrode/site contact. "Loss of contact" and EMG artifacts can be identified by observation of raw waveforms and their effects can usually be nullified by close attention to the time history events where exposure durations are of the order of one second.

B2.2. Subjective method

Consider first the constraints imposed by the nature of the experiment on the subjective methods which could be used. The subject's task is to report his feelings of startle: a feeling which is obviously mediated by the characteristics of the stimulus and its relationship to previous stimuli. Obviously then, a comparison or reference stimulus is impractical where startle is concerned although annoyance or discomfort are another matter. It may be that the subject uses the feelings evoked by the first stimulus as his reference or he may use some imaginary standard, self generated. But prescribed modulus, pair comparison or magnitude production techniques are not applicable in the context of startle where other stimuli may have a substantial effect.

A second and more practical constraint is imposed by the limited degree of physical movement which subjects would, be allowed to make in communicating their response to the experimenter.

These considerations gave rise to the choice of the simple method of magnitude estimation described in section B3.3. Subjects were asked to say a number which was proportional to their feelings: the absolute value of the first response being unimportant but subsequent responses were required to show proportionally in relation to the first. Stevens (Ref.48) describes a series of experiments in some of which, subjects used a standard and in others they did not. One of his conclusions was: "....in making quantitative estimates of sensory magnitudes, the typical subject seems able to describe his sensations in a consistent quantitative language. At least he seems able to do so whenever the experiment gives him a fair and unbiased opportunity to do so".

The absolute value of the subject's response to the first stimulus is obviously of little significance, what is important is the relationship of subsequent responses to the first. Moreover, in the laboratory situation, the practical value of absolute judgements is nil; the importance lies in interelationships: between stimuli, repetitions and orders.

Consideration was also given to the word which is used to describe feelings of startle. Possible synonyms include: surprise, frighten, catch unaware, make jump and shock. The word startle was eventually used because although it is less commonly used than some of the others, it was closest to the meaning which was to be expressed.

B2.2.1. Limitations of the subjective method.

Having selected the most appropriate subjective method for these experimental purposes, consider now the limitations of this method so that the results are seen in proper perspective.

i. Asymmetry of response range.

Some subjects may underestimate the low and overestimate the high intensity stimuli. Or as Stevens puts it: "subject's judgement is dependent not only on the ratio of the stimulus to standard (real or imagined) but also on the absolute level of the stimulus". Some subjects may be afraid to "use up" low numbers or may misconceive the proportionality of numbers in other ways.

ii. Some may use an ordinal and not a ratio scale. That is they can order feelings greater or less than but not in proportion to the standard.

iii. Context error.

The subject may make his judgement on the basis on previous stimuli, usually the prededing one and not necessarily the first. This type of error is inherent in the method adopted, discarding as it does the use of an external standard.

iv. Past experience.

The subject may be influenced by his previous experience in either vibration or subjective rating experiments.

v. Validity.

Stevens writes: "...the quantitative estimation of subjective magnitudes is not an easy task. Sensations do not come with numbers written on them,... It is no wonder that subtle constraints and biases can influence the results... the outcome is a function of method". Obviously the absolute value of the method used has no validity, but the reader must decide on the validity of relative judgements.

vi. Some subjects may confuse the startle feelings evoked by the stimulus with the magnitude of the stimulus itself.

B2.3. <u>Psychophysiology: stimulus, pseudo stimulus and arbitrarily chosen responses.</u>

The purpose of this investigation was to examine the psychophysiological responses to sudden vibration. In order to validate these responses it is necessary to compare them with the normal (possibly random) variations in the same physiological index under resting i.e. no vibration conditions. The stimulus response (SR) was therefore compared with a control response (CR) selected on an arbitrary basis. In practice, this was the mid point between stimuli and two and a half minutes before the first stimulus.

An alternative approach is the comparison of SR with a pseudo stimulus or spontaneous fluctuation. Such events, usually generated from within the subject but occasionally arising from external laboratory noise for example, are readily observable in the GSR. Internal sources of fluctuation include respiration and sinus arrhythmia in heart rate. When using the pseudo stimulus method of analysis the experimental purpose is investigation of the different type of response: to the experimental stimulus and to spontaneous (usually mild) stimuli generated internally or externally to the subject. By chance, it could occur that the arbitrary response was selected during an on-going spontaneous fluctuation but such occurrences were rare.

This distinction between spontaneous fluctuations and control response as a method of analysis, is important and intimately related to the experimental purpose. Arbitrary responses were chosen in analysis of heart rate and vasoreaction because the aim was to make use of the physiological tools as distinct from investigating their properties.

B3. EXPERIMENTAL METHOD.

B3.1. Vibration equipment.

The method for generating and measuring the vibration was the same as that described in section A4.10. Two vertical vibration levels of $\pm$ 0.1 and $\pm$ 1.0g were used.

However, differences in seated body weight and mechanical impedance between the subjects could affect the seat acceleration. For these reasons, an attempt was made to control subject posture. Furthermore it was not possible to predict and preset the vibration exposure of each subject as this would reduce the startle qualities of the stimulus. The appropriate amplifier gain settings were preset on the basis of 12 subjects not used in the actual experiment who provided the data for drawing up a graph of seated body weight against gain settings to give the nominal acceleration of $\pm$ 1.0 and $\pm$0.1g. Typical vibration exposures of the experiment itself are shown, as recorded on Devices M2 equipment, in Appendix D; across subjects the mean accelerations were $\pm$ 1.03 and $\pm$ 0.1g with standard deviation of 0.09g and zero respectively. For details of the stability, repeatability, distortion and duration of the acceleration exposures see Appendix D.

The vibration frequency was 20 Hz with duration of one second. The stimulus parameters ($\pm$ 1.0, $\pm$ 0.1g, 20 Hz and 1 sec) were selected on the basis of sonic boom induced building vibration measurements (Ref.46). Appendix E gives a summary of these measurements: the range of peak vertical accelerations recorded on residential house floors was $\pm$ 0.02 to $\pm$ 0.29g with a mean of $\pm$ 0.13g.

Predominant frequencies were 20 Hz with durations between half and one second.

B3.2. Subjects.

Twelve males in normal health and aged between 20 and 31 years gave written consent to take part in the experiment. All the subjects had taken part in only one previous vibration experiment, namely the one described in section A. They were chosen from the students, research and technical staff of the University. The duration of each test was about thirty minutes but no payments were made to any subject. The Audiology Group's Safety and Ethics Committee gave prior approval for the experiment to take place.

B3.3. Subject instructions.

The subjects sat on the vibration platform with hands resting in their lap. Their feet were placed on a stationary foot rest, whose height was adjustable so that the underside of the thigh was not in contact with the platform. The angle between thigh and table being approximately 10°; from below the knee, the leg was vertical. All subjects wore the clothing and footwear which they used in their normal occupations. The written instructions for subjects were as follows:

"I am going to make your seat vibrate a number of times.
Your task is to tell me how startling each vibration is,
by assigning a number to each.
Please wait until you are asked for your impressions;
this will be a short time after each vibration. Give
your feelings of startle a number - any number you

think appropriate but try to make the numbers you use proportional to your feelings of startle.

I appreciate that being seated without a back rest for about twenty minutes, may be uncomfortable. Try to adopt a reasonably upright but relaxed posture at the outset and see if you can maintain this throughout."

On completion of the experiment, subjects were asked, in an informal way a number of questions concerning their subjective judgements. These included their imagery, whether they preferred the freedom of judgement inherent in the method, if they believed their judgements to be consistent and how many different acceleration levels there were. The noteworthy findings were complaints about the lack of a standard or reference although most subjects believed their judgements were consistent. Most believed there were at least four different acceleration levels but it was obvious that some subjects rated the stimulus magnitude and not their feelings. For further discussion of these results see section B4.5.

B3.4. Methods of psychophysiology.

The electrocardiogram (EKG) and heart rate (HR) were recorded using a Devices ACI preamplifier, ratemeter and M8 recorder. The four surface electrodes were connected in EKG lead position II and held in contact with the subjects' limbs by means of rubber straps. The two GSR electrodes were attached to the subject's left forearm and middle finger of the left hand and connected via a bridge coupling unit to a DC2 preamplifier in the M8 recorder. Cambridge electrode jelly was used for both the GSR and EKG electrodes.

A Devices photoplethysmograph (PPG) comprising a light source and photo-detector was used to monitor the vasoreaction. Mounted in the centre of the forehead this photocell was sensitive to light reflected from the local tissue and vascular bed. The principle of the PPG relies on the tissue density remaining constant so that the changes in light reflected are inversely proportional to the volume of blood (i.e. more blood = less light reflected). In fact there are two cardiovascular components: the blood volume (BV) and pulse amplitude (PA). Decreases in these two components give rise to an increase in light reflected and output from the photocell which is fed to the M8 recorder via a preamplifier.

B3.5. Procedure.

On entering the vibration laboratory, each subject was asked to sign a form consenting to take part in the experiment. Their fitness to take part was assumed on the basis of a satisfactory reply to the list of contradictions, included in a U.K. Safety Guide (Ref.47).

Subjects were then asked to be seated on the vibrator and whilst the various electrodes were attached, each subject read the sheet of printed instructions. Curtains and a clinical screen were then arranged around the subject to form a small room and recording began after the 2 to 3 minutes required to adjust and calibrate recordings.

After five minutes of resting recording, each subject received the first stimulus, thereafter stimuli followed at 2, 4, 3, 2 & 4 minute intervals: a total of six stimuli. There were two orders of stimulus intensity as follows (Table XI):

TABLE XI. Order of stimulus intensities.

Subjects	Stimulus intensity ($\pm g$)					
	1	2	3	4	5	6
Group 1 = 1, 3, 5, 7, 9, 11	1.0	0.1	0.1	1.0	0.1	1.0
Group 0.1 = 2, 4, 6, 8, 10, 12	0.1	1.0	1.0	0.1	1.0	0.1
Time interval (mins.)	5	2	4	3	2	4

At about thirty seconds after each stimulus, subjects were asked for their subjective responses and these were noted by the experimenter.

B4. RESULTS AND ANALYSIS.

B4.1. Heart rate.

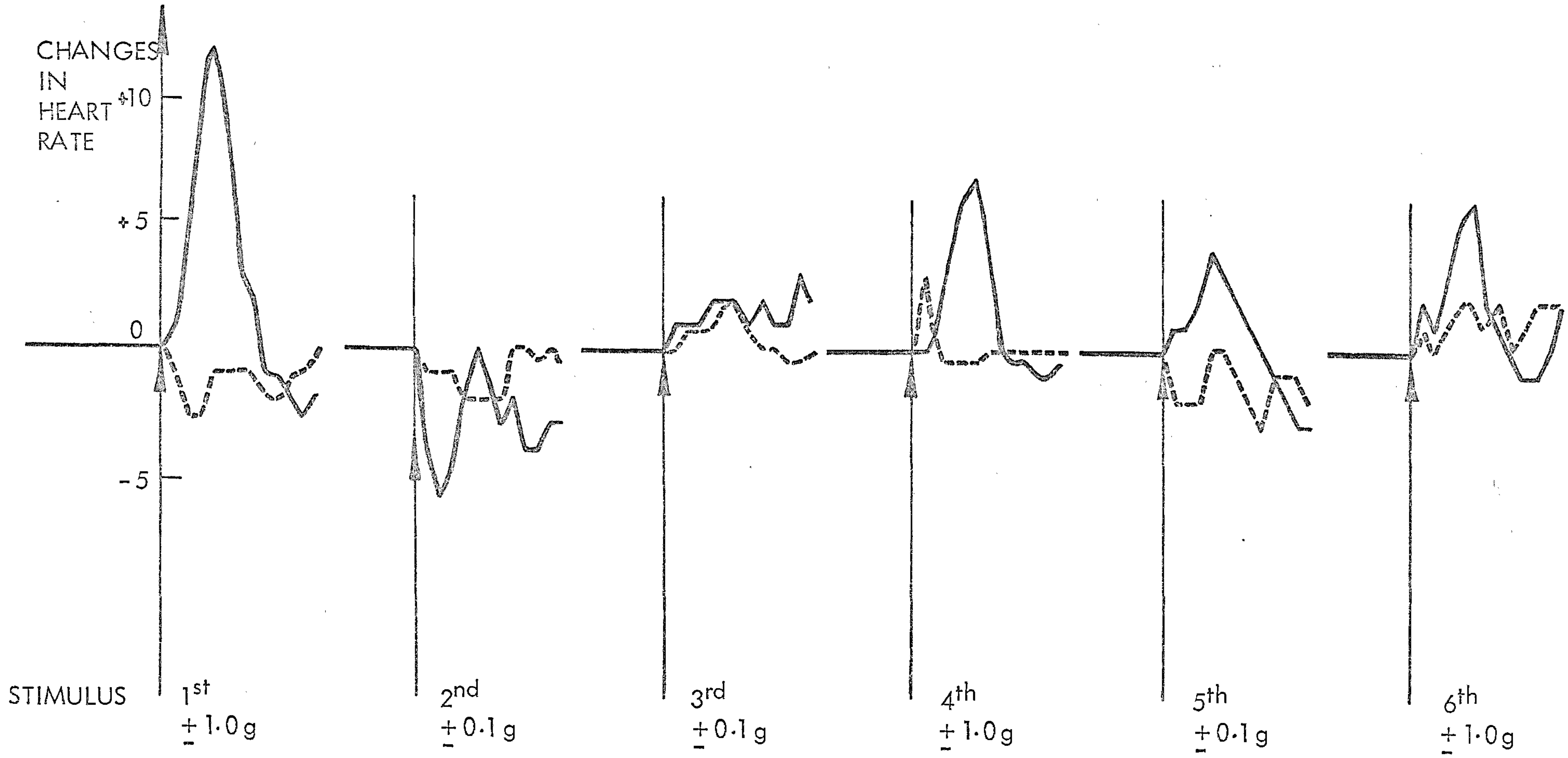
Beat-by-beat analysis of both the stimulus responses (SR) and arbitrarily chosen control responses (CR) from pre-stimulus beat three to post stimulus beat twelve was carried out. For the group receiving the large stimulus first (group I), the changes in heart rate for both CR and SR are shown in Fig. 22. Group 0.1 responses are presented in Fig.23. Fig. 24 shows in detail the responses to the first stimulus only for group I.

* What is the probability of the SR and CR in heart rate being the same?

The distribution of the stimulus heart rate response was assumed not to meet the criteria of parametric tests of significance. Consequently, the Kolmogorov-Smirnov test was used as the data were independent and assumed to achieve ordinal scaling as defined by Siegel (Ref.20). This test compares distributions being sensitive to central tendency, dispersion and skewness.

TABLE XII. Probability of SR and CR heart rate responses being drawn from same populations.

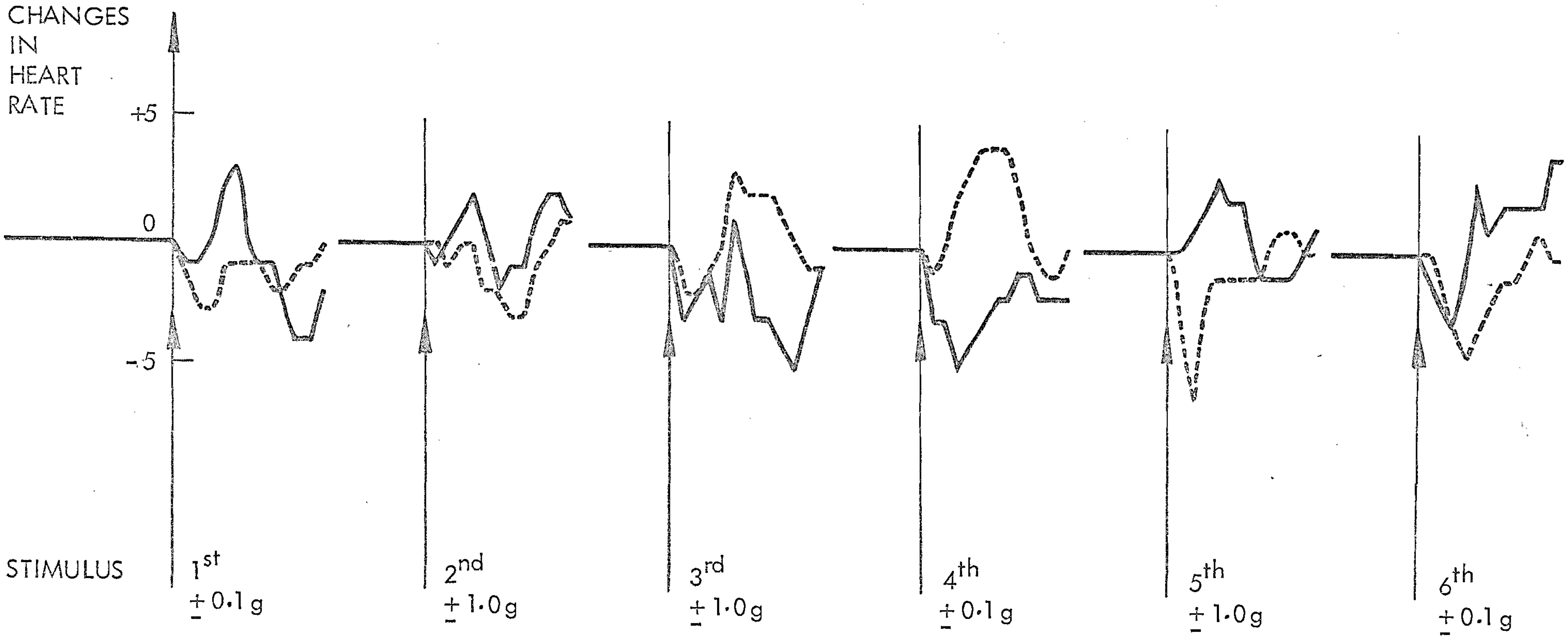
Stimulus	1st	2nd	3rd	4th	5th	6th	Subjects
Intensity ±g	1.0	0.1	0.1	1.0	0.1	1.0	Group I
Probability	.001	.001	.01	.005	.05	NS	
Intensity ±g	0.1	1.0	1.0	0.1	1.0	0.1	Group 0.1
Probability	.001	NS	.05	.001	NS	.05	



——— STIMULUS RESPONSE (SR) : CHANGES IN RATE FOR 12 POST STIMULUS BEATS.

– – – – – CONTROL RESPONSE (CR) : CHANGES IN RATE FOR 12 BEATS FOLLOWING THE MID POINT BETWEEN STIMULI.

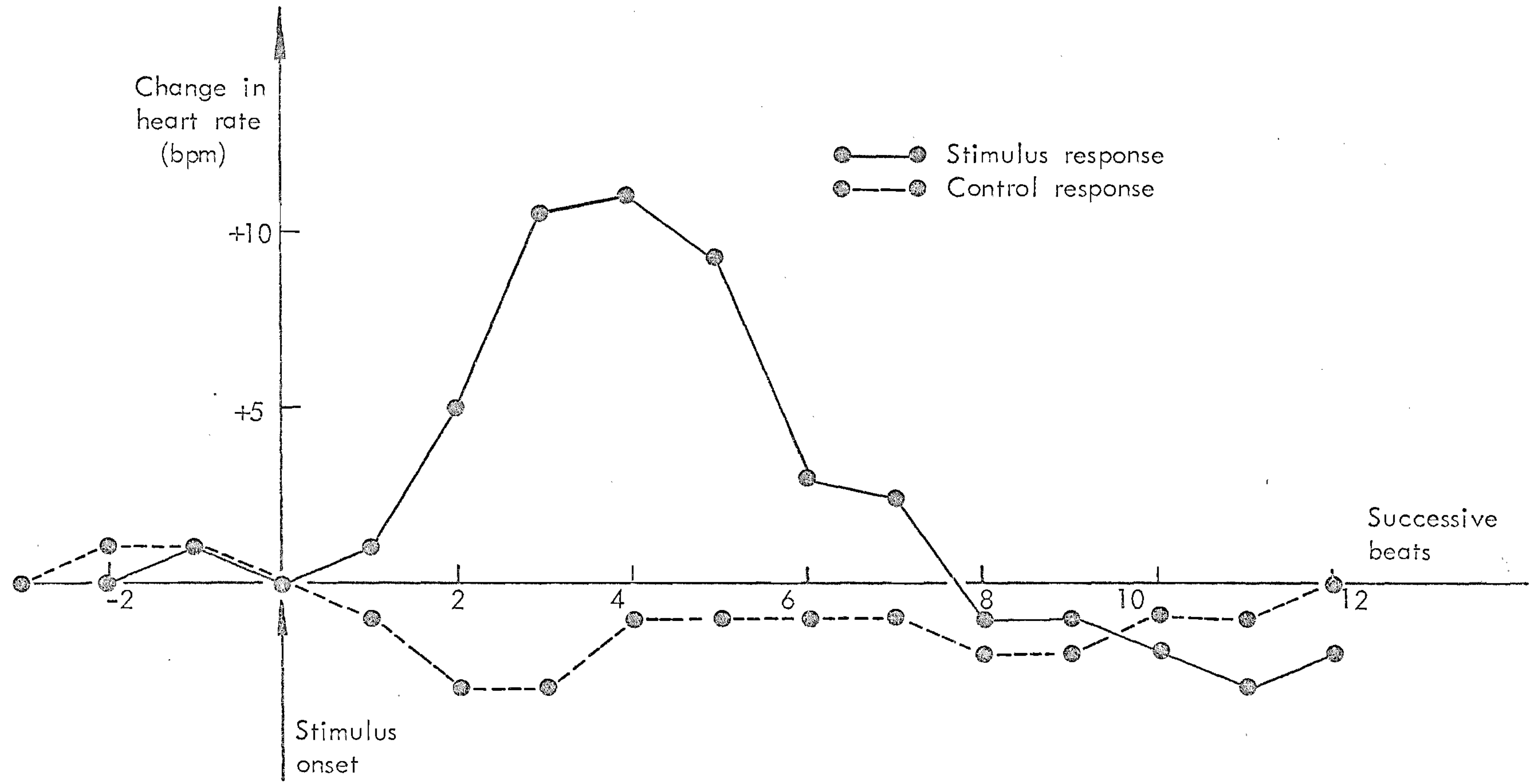
FIG 22 CHANGES IN HEART RATE - MEAN FOR SIX SUBJECTS (GROUP 1)



——— STIMULUS RESPONSE (SR) : CHANGES IN RATE FOR 12 POST STIMULUS BEATS.

– – – CONTROL RESPONSE (CR) : CHANGES IN RATE FOR 12 BEATS FOLLOWING THE MID POINT BETWEEN STIMULI.

FIG 23 CHANGES IN HEART RATE – MEAN FOR SIX SUBJECTS (GROUP 0·1)



Mean score for six males exposed to ± 1·0 g as the first stimulus

FIG 24 CHANGES IN HEART RATE: DETAIL OF ONE RESPONSE

Table XII confirms that most of the differences are significant between the heart rate SR and CR responses. By itself, this result is of little value, unless the nature of the arbitrarily chosen control response is more clearly defined. This consideration leads us to the next question.

* What is the nature of the CR in heart rate?

Fig. 25 shows that the distribuion of these scores is relatively normal and use of the analysis of variance technique is probably justified. An F test showed no significant differences between subjects (12) and repetitions (6). In other words, these fluctuations are essentially random. The normal change in heart rate had a mean of -0.17 and standard deviation of 4.12 beats/minute.

So far, it has been shown that for most repetitions the stimulus heart rate response is distinct from normal fluctuations in heart rate and these show no consistent changes across subjects or with time. Trends in habituation may now be considered.

* What is the probability of the SR to the first stimulus being the same as the reponse to the last stimulus of the same intensity?

The Kolmogorov-Smirnov test was again used: results are shown in Table XIII.

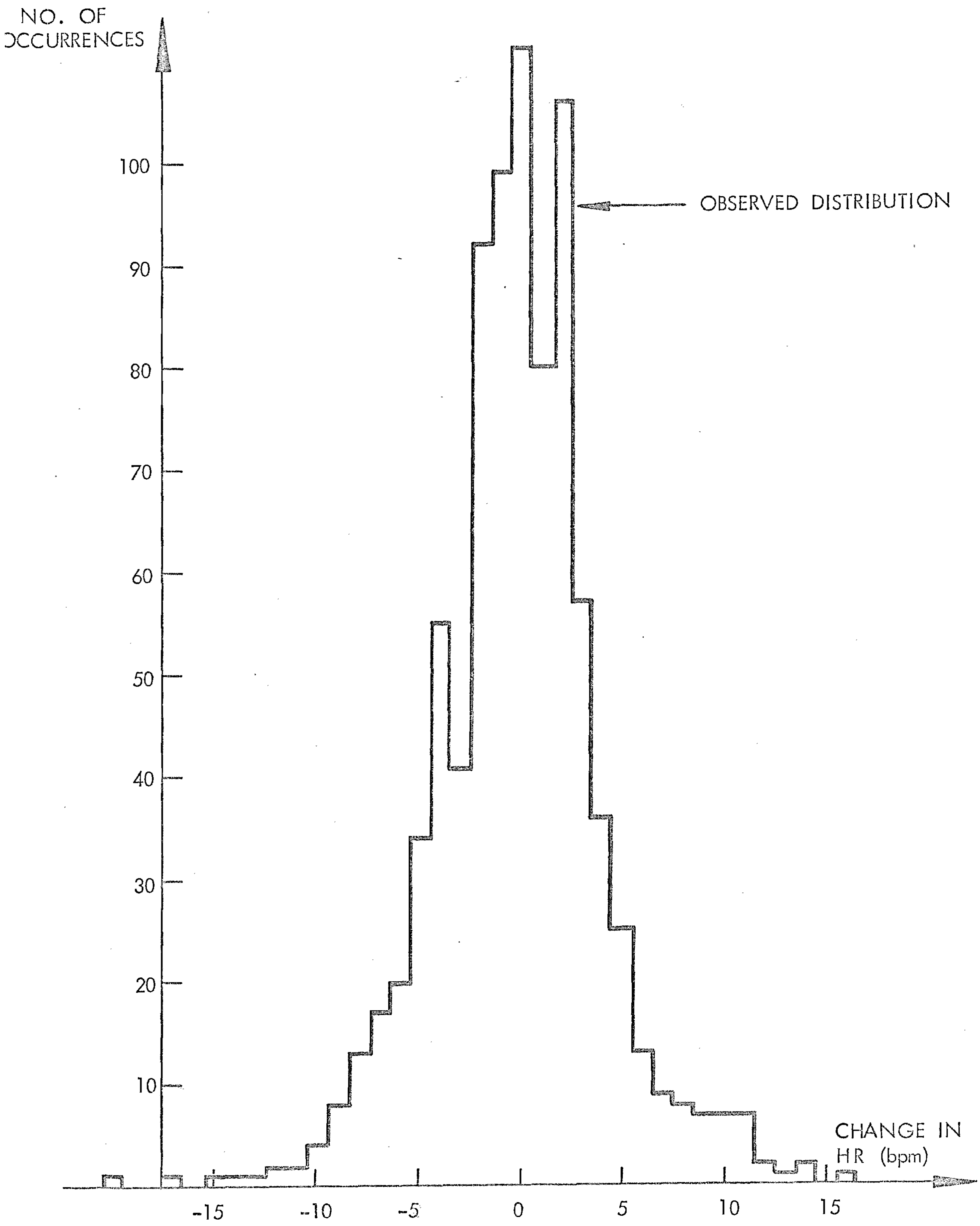


FIG 25 DISTRIBUTION OF RAW SCORES - CONTROL RESPONSE DATA ONLY

TABLE XIII. Comparison of the responses to the first and comparable last stimuli.

Stimuli	Ist and 6th compared	2nd and 5th compared
Intensity (±g)	1.0	0.1
Probability	0.05	0.005
Intensity (±g)	0.1	1.0
Probability	0.05	NS

Table XIII shows that there are significant changes across repetitions in the stimulus response patterns. In addition, the same statistical test was used to compare the responses of the group who received the large stimulus first and the group who received the smaller stimulus first.

* What is the probability of similar response patterns in groups who received different stimulus magnitudes first. Using the (SR minus CR) data, this two tailed probability was 0.001.

With regard to the nature of the response patterns, Figures 22 and 23 are informative. In addition a beat by beat analysis over post stimulus beats 1 through 12 was also made where the SR and CR were compared. For the six subjects who received the large stimulus first, there was a significant increase in the SR for 5 beats. On repetition this response did not recur and neither did the other group (receiving the small stimulus first) show a similar trend. However, this latter group showed a significant decrease for post stimulus beats 9 and 10. This same pattern was repeated for only one other repetition: in the group who received the smaller stimulus for their second presentation (i.e. Group I).

Footnote

The HR pattern change is intimately related to and dependant on the HR level at pre stimulus beat 3. This choice is validated on the grounds that the effects of stimulus onset in relation to the respiration induced rhythmic variations in heart rate (sinus arrhythmia) is averaged out over subjects and repetitions. Since subjects acted as their own control, interindividual differences in pre stimulus HR level, did not materially affect the results.

B4.2. Galvanic skin response.

The fundamental question concerns the relationship between the magnitude of the stimulus evoked response (signal GSR) and for control purposes, the number and magnitude of spontaneous GSR's in each subject. The GSR was scored in $K\Omega$(fall) in resistance to the first point of maximum inflection. The smallest signal GSR which occurred being 1.5 $K\Omega$. Subsequently, the number and magnitude of spontaneous GSR's, equalling or exceeding 1.5 $K\Omega$ was recorded and these were compared with the signal GSR's, as in Table XIV.

Transformation of the raw resistance scores to log conductance, the currently popular unit of quantification (Ref.49), was not made. As a result, it should be noted that the results were based on change in skin resistance and were independent of the background level. Justification of this method of analysis is made on the grounds that each subject was used as his own control. In fact the background level varies little intraindividually but substantially interindividually. If this latter comparison were to have been made, then transformation to conductance changes would have been essential.

One further point to note is that the GSR made by all subjects when giving his subjective response some 30 seconds after the stimulus was not included in the analysis.

* What is the probability of the signal GSR's being as small as the spontaneous GSR's taking into account their size and number?

TABLE XIV. Signal and spontaneous GSR's compared.

Intensity ($\pm g$)	1.0 (Group I)						0.1 (Group 0.1)					
Subject	1	3	5	7	9	11	2	4	6	8	10	12
Probability (one tailed)	.002	.001	.05	.002	.01	.002	.05	$1/\infty$	.001	.11	.026	.02

The data for Table XIV were derived using the Mann Whitney U test: ordinal scaling being assumed. The table shows that the signal GSR is clearly distinguishable from the size and number of spontaneous fluctuations in the normal or resting skin resistance.

In constrast with heart rate, the measure of skin resistance showed no trends of habituation whatever. Using the Wilcoxon signed rank test comparisons were made between the 1st and 6th and between the 2nd and 5th responses with no significant differences being detected.

Lastly the GSR scores were examined to see if the response was sensitive to the two different stimulus magnitudes. The Mann Whitney test was used.

* What is the probability that the GSR to the $\pm$ 0.1 and to the $\pm$ 1.0g are the same? This one tailed probability was calculated as 0.004. In other words, the GSR could distinguish the two stimulus magnitudes.

B4.3. Vasoreaction.

Both the blood volume (BV) and pulse amplitude (PA) of the forehead vasoreaction were analysed beat by beat from pre stimulus beat 3 to post stimulus beat 12 for both a stimulus (SR) and control (midpoint) responses (CR). The level of measurement used for this analysis was rather weaker than that used for heart rate and GSR. Namely, that only qualitative changes were used without regard to their magnitude i.e. the response was denoted either constrictive, dilatory or unchanged. The method expressed changes in BV or PA as deviations from pre stimulus beat 3 but where it was not possible to decide if the PA or BV at that beat, was greater or less than the value at pre stimulus beat 3, then the deviation was set equal to zero. The reason for this restriction on the level of measurement was the necessity for compromise in the setting of the gain control. The gain should be as high as possible for study of the response but not so high as to drive the stimulated response "off scale". BV was scored as change from the diastolic level.

* What is the probability of the SR and CR in both BV and PA being drawn from the same populations. Table XV shows the level of significant differences based on the Kolmogorov-Smirnov test.

TABLE XV. Differences between stimulus and normal fluctuations.

Subjects	Stimulus	1st	2nd	3rd	4th	5th	6th	Vasoreaction
Group I	Intensity (±g)	1.0	0.1	0.1	1.0	0.1	1.0	
	Probability	$.001_V$	$.05_D$	NS	NS	NS	NS	PA - pulse amplitude
		$.001_D$	$.005_V$	NS	$.001_D$	NS	NS	BV - blood volume
Group 0.1	Intensity (±g)	0.1	1.0	1.0	0.1	1.0	0.1	
	Probability	NS	NS	NS	NS	NS	NS	PA - pulse amplitude
		NS	$.05_V$	$.05_V$	$.001_V$	$.01_V$	NS	BV - blood volume

Table XV confirms that some of the differences are significant between the vasoreaction stimulus and arbitrarily chosen responses and the blood volume shows greater reactivity than pulse amplitude.

The suffix D indicates that the nature of the difference in SR is dilative and suffix V indicates greater variability in SR i.e. that the test of significance had found a difference in dispersion between SR's and CR's.

To explain these differences further, the arbitrary responses were examined alone.

* What is the nature of the CR's in vasoreaction?

For this CR data, the use of analysis of variance was validated on the same grades as for heart rate. For both BV and PA the nett change over all post stimulus beats, subjects and repetitions was zero. An F test showed no significant differences across subjects or repetitions.

We can now move on to the ability of the vasoreaction to detect trends of habituation. Comparing responses for stimuli 1 and 6 and stimuli 2 and 5 showed no significant differences in either BV or PA. This confirms that this particular vasoreaction does not habituate.

Consider now the sensitivity of the vasoreaction to the two different stimulus magnitudes.

* What is the probability that the BV and PA responses are the same for the group receiving the large stimulus first as for the group receiving the smaller stimulus first? The results of applying the Kolmogorov-Smirnov test gave a two tailed probability of .005 for both PA and BV. In other words the vasoreaction was sensitive to stimulus magnitude.

With regard to the nature of the vasoreaction within beats, Table XV is explanatory: the differences being denoted as either dilative, constrictive or variable. In addition the Wilcoxon test was used to test for any changes at each beat. For only the $\pm$ 1.0g as the first stimulus was there a significant dilation ($p=.05$) of BV and this occurred over post stimulus beats 5 to 10 inclusive. No other responses, within beats, of either BV or PA were significant.

B4.4. Summary of psychophysiological responses.

Figure 26 shows a recording of typical psychophysiological response, both resting and stimulated.

The results of the HR analysis show that unstimulated control responses are normally distributed and show no pattern of differences across subjects

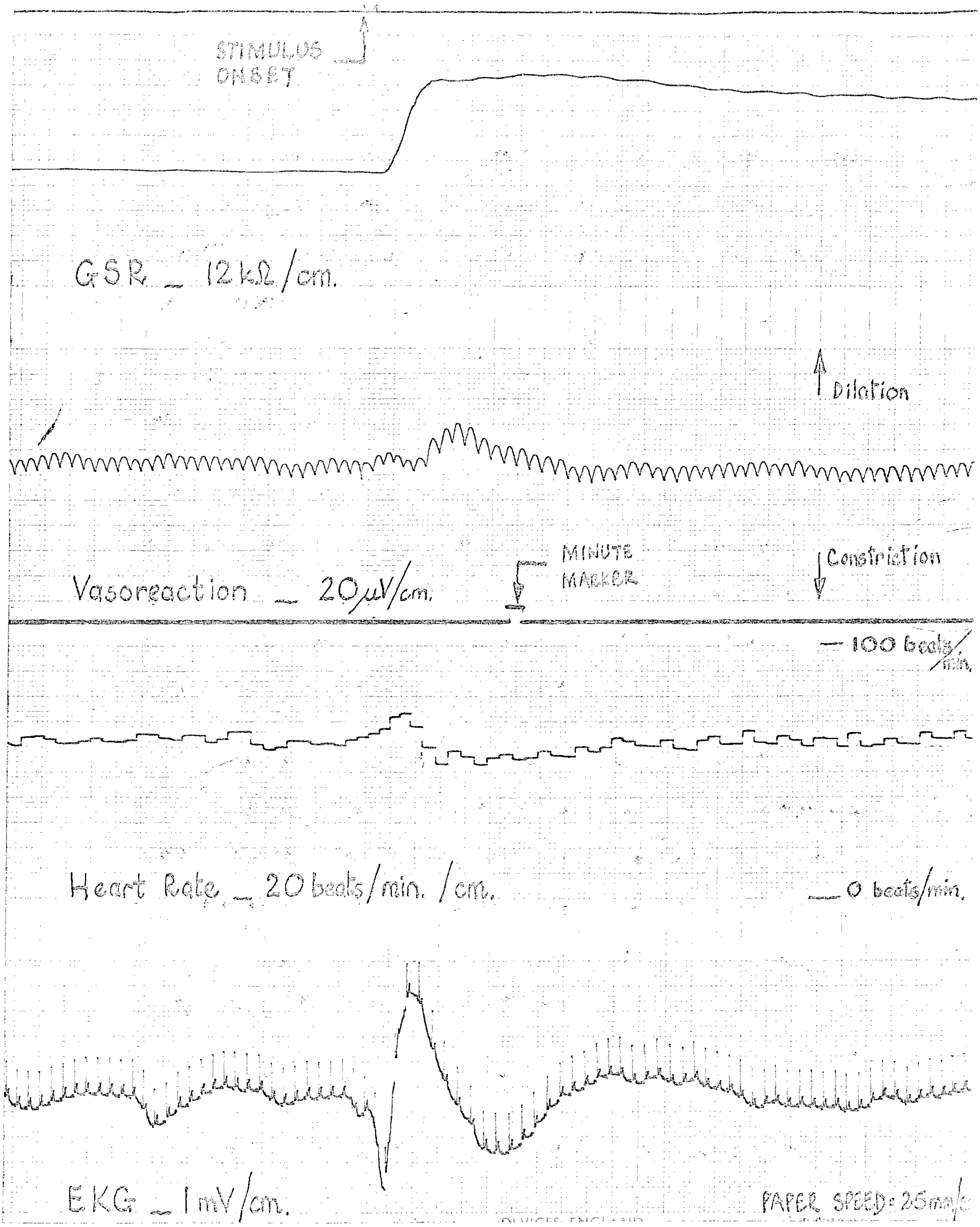


Figure 26. Psychophysiological recordings : an example.

or repetitions. In contrast, the stimulated response is distinguishable from control responses and depends on both stimulus magnitude and number of repetitions. Beat by beat, there is a tendency to increased rate for 6 post stimulus beats and thereafter, especially at beats 9 and 10, a tendency for reduced rate. However, this is not the only heart rate pattern, stimulus magnitude and habituation being depe ndent variables.

Similarly, analysis of the GSR showed that the stimulated response was clearly indlentifiable in the midst of spontaneous fluctuations in the resting GSR. The two stimulus magnitudes evoked different responses but the GSR did not show a tendency to habituation.

The unstimulated forehead vasoreaction, like heart rate, showed essentially random variations which were independent of subjects and limited differences were observed between the stimulus and control responses: blood volume showing greater reactivity than pulse amplitude. No purely constrictive responses were observed, some changes were dilative and some showed greater dispersion than the control response. No trends of habituation were noted in vasoreaction.

B4.5. Subjective responses.

The purpose of the subjective measures, as explained in section BI.2 was to set the physiological measurements against a background of the feelings evoked by successive stimuli. In fact the degree of correlation was found to be disappointing as shown in Table XVI.

TABLE XVI. Correlation (r_s) between autonomic and subjective responses.

Comparison	Subjects	Ratio of stimulus reponses				
		Ist/2nd	Ist/3rd	Ist/4th	Ist/5th	Ist/6th
Subjective/Heart rate	I.0g group	-0.33	0.56	0.37	0	0.2
	0.Ig group	0.85*	0.16	0.55	0.42	0.12
Subjective/GSR	I.0g group	0.55	0.24	0.35	0.72	-0.20
	0.Ig group	0.41	0.59	0.36	-0.37	0.42
Subjective/Blood Volume	I.0g group	-0.1	0.4	-0.47	0.17	-0.48
	0.Ig group	0.05	0.14	-0.53	0.14	0.43
Subjective/Pulse Amplitude	I.0g group	0.17	0	-0.8	-0.21	-0.37
	0.Ig group	-0.35	-0.1	-0.1	-0.03	-0.05

The Spearman rank correlation coefficient was selected: it was assumed that the data achieved ordinal scaling. Because the absolute values of the subjective responses were meaningless, the stimulated autonomic and subjective responses for each subject, were converted into a ratio form, for example Ist/2nd....Ist/6th stimuli. It was these ratios which were tested for correlation. Only one of the above differences was significant at the p = .05 level illustrating very poor correlation between the autonomic and subjective responses. Note that the autonomic response used here was the maximum change for GSR, but the average change for HR and vasoreaction over post stimulus I to 12. In view of the biphasic cardiac response, this method may not have made full use of the data.

Obviously, it was not possible to decide if these data follow Stevens (Ref.48) power law as only two stimulus intensities were used. Assuming however that the law does apply as Shoenberger (Ref.50) has indicated then:

$$\psi = k\phi^n$$

where ϕ is the physical magnitude of the stimulus and ψ is the psychological magnitude. This experiment gave a value of $n = 2.6$. In relation to Steven's experiments, this exponent puts startle due to vibration midway between stimulation by continuous vibration and electric shock.

Consider now the trend of changes in the subjective response. The Wilcoxon test was used to determine the probability that the response to the lst stimulus was the same (or drawn from the same population) as the comparable last stimulus response. No significant differences were detected. This finding may have several implications. First, that no habituation of feelings of startle took place and/or second, that subjects rated the stimulus magnitude and not their feelings of startle and lastly that the method of subjective measurement was not sufficiently sensitive.

On the other hand, the probability of no difference between the magnitude of the subjective response and stimuli was 0.00003. That is the subjective method was sensitive to the two stimulus magnitudes which were used.

With regard to the consistency of subjective responses, the Wilcoxon test showed that there were no significant differences across repetitions or between the two groups of subjects in the response ratios.

B5. DISCUSSION

B5.1. Relevance to psychophysiological theory.

In the introduction, the nature of the orienting reaction (OR) and startle reaction (DR) was presented and discussed: are the psychophysiological results of this experiment sensitive to differences between the OR and DR?

The heart rate (HR), galvanic skin reflex (GSR), vasoreaction comprising blood volume (BV) and pulse amplitude (PA) generally responded in either qualitative or quantitatively different ways to the two stimulus magnitudes, when first received. However, it would be somewhat premature to place the measured responses in the categories of Sokolov's theory. There is evidence of a biphasic HR response consisting of increased rate to post stimulus beat 6. McDonald (Ref.51), Lang (Ref.52), Brener (Ref.53) and Oldman (Ref.54) have noted similarly phased responses. In this experiment, response magnitude is greatest for the larger stimulus but this response, along with that to the smaller stimulus, is quite distinct from normal resting fluctuations in HR. In relation to the other cardiovascular responses, the PA showed less reactivity than BV, whose response was dilatory to post stimulus beat 5, for the larger stimulus received first. For the smaller stimulus received first, there was no significant change of either PA or BV. The inference here is that BV and PA are insensitive to mild stimuli i.e. that stimulus and control responses are not sufficiently distinct and for more intense stimuli the BV along dilates. These findings are in agreement with Raskin (Ref.40) and in direct contradiction to Sokolov's position assuming that the larger stimulus evoked the DR and not the OR.

The GSR was seen to support the cardiac response in as much as it was sensitive to the two stimulus magnitudes and showed differences between stimulus evoked responses and spontaneous fluctuations.

With regard to habituation, HR was the only response to show differences. The nature of these was to reduced magnitude of response and a less distinct biphasic cardiac pattern.

Clearly then there is more than one cardiac response and probably more than one cardiac OR, dependent variables being the novelty and physical characteristicsof the stimulus. Whether or not there are inter-individual differences appears to be as yet unresearched.

One further point with relevance to psychophysiological theory is summarised by Lacey (Ref.55). He writes: " the autonomic response is a function both of the induced magnitude of autonomic activation and of the promptness and vigor of secondarily induced autonomic changes that serve to restrain and limit the effects of the initial disturbance". It is because of this restraint or "mutually antagonistic action of the sympathetic and parasympathetic (nervous systems) that a relationship between prestimulus level and the size of autonomic changes does exist". Wilder (Ref.56) named this phenomenon: "the law of initial values".

Its relevance to this experiment is clear and in psychophysiology either subjects should be used as their own control or for interindividual comparisons, the prestimulus level should be included in the analysis.

B5.2. Relevance to practical situations.

So far, a number of differences between stimulus and control responses have been shown to be statistically significant. Consider now the practical significance of these results.

A stimulus level typical of buildings was used and its physiological effects have been presented. These indicate that the stimulus and control responses are distinct but only in HR do these change with repetition although not so far as to become extinguished. This is in spite of the fact that a high experimental repetition rate was used. If it is to occur in practice, habituation will have longer to do so but the interstimulus interval will be greater for any potential dishabituation.

In some relation to these objective or unconsciously controlled physiological measures, there are the results of the subjective experimentation. The two types of measurement agree in respect of their sensitivity to stimulus magnitude. However, these subjective responses do not, like the GSR and vasoreaction demonstrate habituation. This may indicate either insensitivity to habituation of feelings or no habituation. It may also be a symptom of the fact that subjects, in making their judgements, were really describing the stimulus magnitude rather than the feelings of startle induced by the stimulus.

With regard to the degree of correlation between the subjective and so-called objective measurements, the results are extremely disappointing. Why this should be so is not immediately clear.

It's possible to conclude with an attack on the basic premise of psychophysiology, namely that physiological and psychological phenomena are causally linked. But such a step would be premature for the implication could be that the methods used for each type of measurement: subjective and autonomic, were, in fact, measuring different things. As suggested above, some subjects appeared to describe the stimulus magnitude and not their feelings of startle whereas one assumes that the physiological responses did not make this distinction. We can cast less doubt on the fundamental link in psychophysiology than on the methods used here, in particular the subjective method, to measure the desired aspect of behaviour.

Finally, it should be pointed out that the contribution of the experiment described lies, not in the absolute value of subjective and physiological responses to a laboratory experiment but in the relative information one autonomic index with another and conscious with unconscious response relationships.

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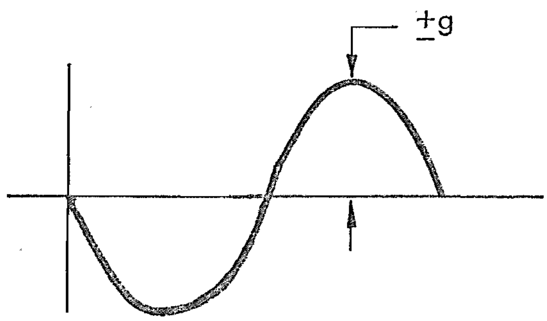
DEFINITIONS.

Acceleration -

The units of acceleration used throughout this thesis are vector, peak or single amplitude acceleration in units of g. Expressed for example $\pm 0.010g$.



Statistical probability -

Several statistical tests of significance are used in this thesis. More usually one distribution is compared with a second and the test applied to determine the probability that they were drawn from the same population. A one tailed probability makes use of one tail of the distribution and leads to a probability of one distribution being as high (OR as low but not both) as the second. Except as noted, this thesis used two tailed probabilities which leads to the probability of one distribution being different from the second (direction being unspecified). NS is not significant i.e. the probability is > 0.05.

APPENDIX A

Vibration waveform

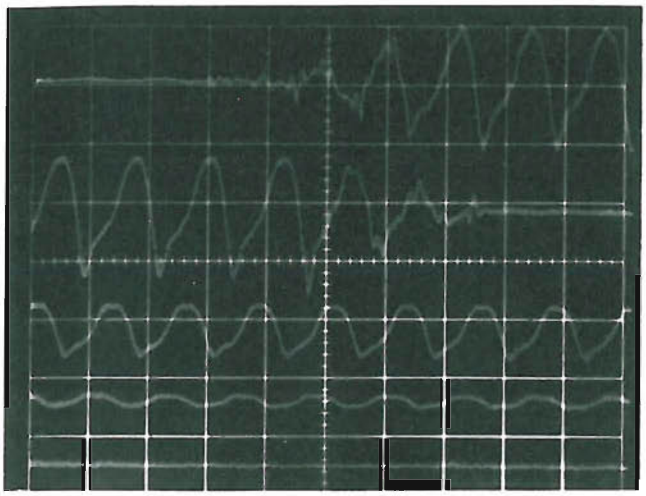
The acceleration waveform showing the nature of the basic waveform and typical rise/fall patterns for all frequencies (1.5 - 100 Hz) are shown in the following pages. All waveforms were recorded with a 160 lb. static load on the vibration platform. In each case the units of the vertical scale are $0.01g_z$/division. For the frequencies 1.5 through 25 Hz, the recorded waveforms have been passed through a low pass filter (-3 dB at 100 Hz). All other frequencies are shown unfiltered.

The acceleration waveforms shown were produced by adjusting the gain control to give $\pm 0.010g_z$ for an attenuator setting of 100 (following the method described in Section A4.10). The rise and fall patterns were then recorded. Subsequently, the attenuator was set at 50, 10 and zero to give the three lower traces; these are supposedly ± 0.005, ± 0.001 and zero g_z.

In some cases the quality of the stimulus leaves much to be desired. The low frequency waveforms are somewhat distorted and the 100 Hz waveform has a high variation in intensity. Although the high frequency vibration (>100 Hz) superimposed on all records was not perceptible to any subjects at any time, the stimulus quality would be much improved had this high frequency vibration been absent.

1.5 Hz nominal

Horizontal scale : 0.5 sec/div



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform

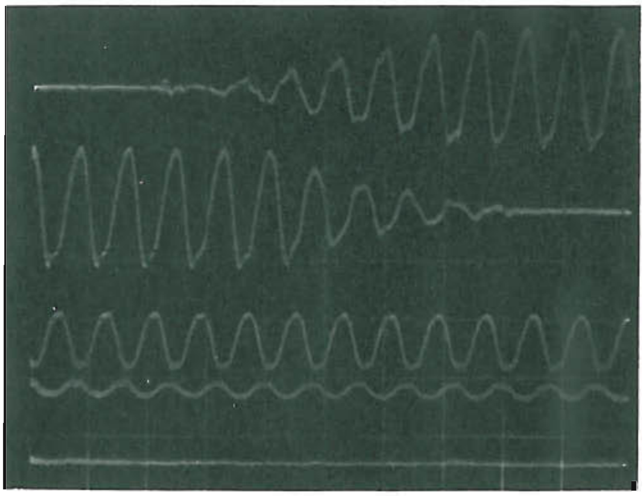
$\pm$ 0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

Zero g_z

2.5 Hz nominal

Horizontal scale : 0.5 sec/div.



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform

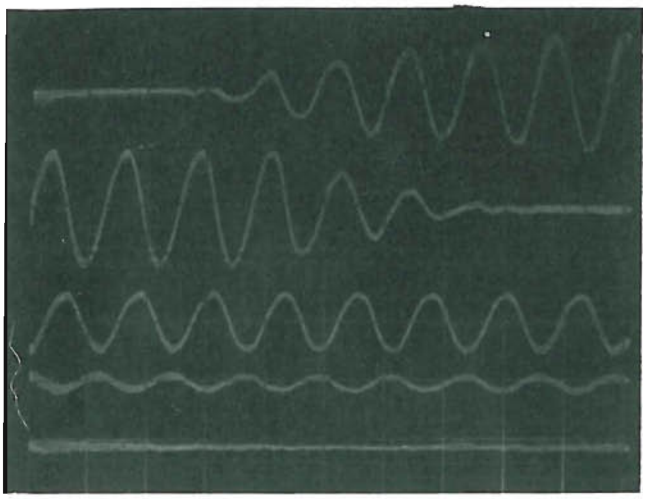
$\pm$ 0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

Zero g_z

4.0 Hz nominal

Horizontal scale : 0.2 sec/div



$\pm 0.010\ g_z$: Rise waveform

$\pm 0.010\ g_z$: Fall waveform

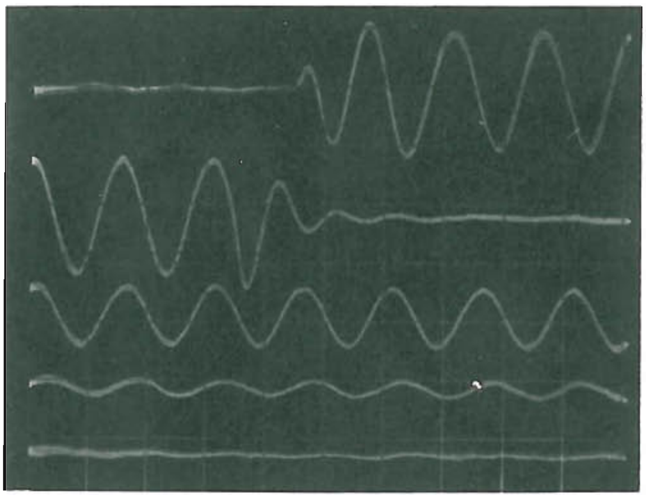
$\pm 0.005\ g_z$: Continuous waveform

$\pm 0.001\ g_z$: Continuous waveform

Zero g_z

6.5 Hz nominal

Horizontal scale : 0.1 sec/div.



$\pm 0.010\ g_z$: Rise waveform

$\pm 0.010\ g_z$: Fall waveform

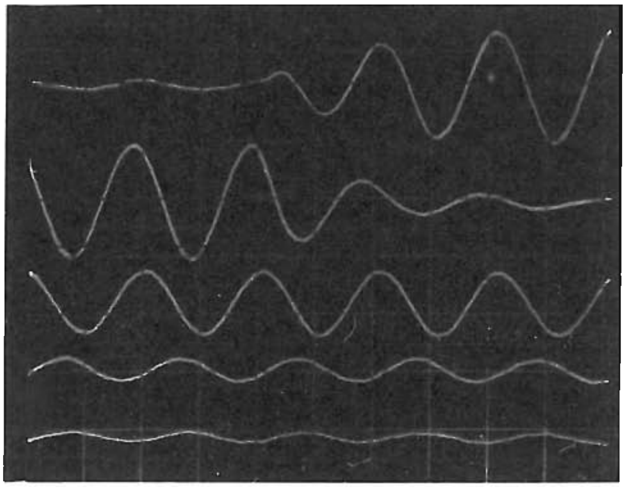
$\pm 0.005\ g_z$: Continuous waveform

$\pm 0.001\ g_z$: Continuous waveform

Zero g_z

10 Hz nominal

Horizontal scale :50msec/div



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform

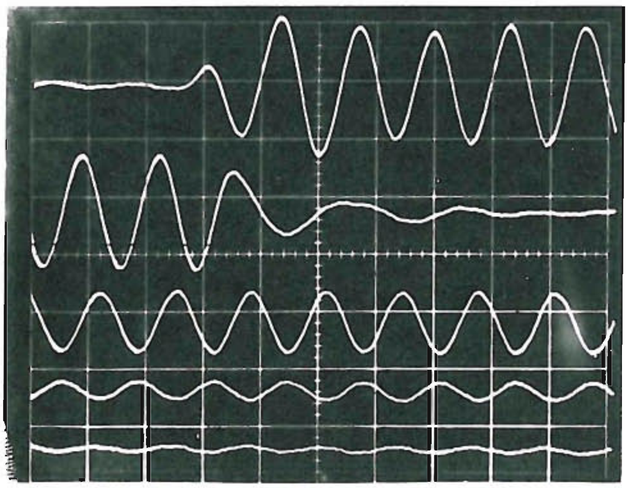
$\pm$ 0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

Zero g_z

15 Hz nominal

Horizontal scale :50 m sec/div.



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform

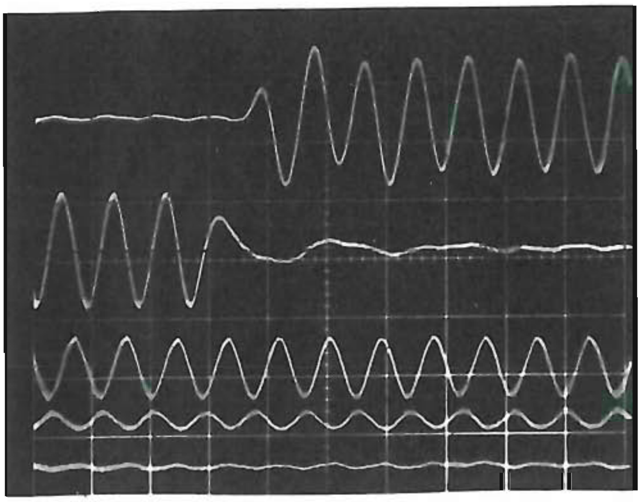
$\pm$ 0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

Zero g_z

25 Hz nominal

Horizontal scale :50 m sec/div



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform

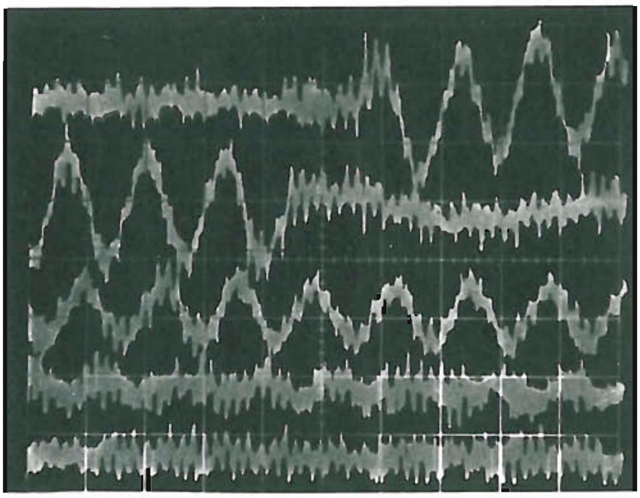
$\pm$ 0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

Zero g_z

40 Hz nominal

Horizontal scale :20 m sec/div.



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform

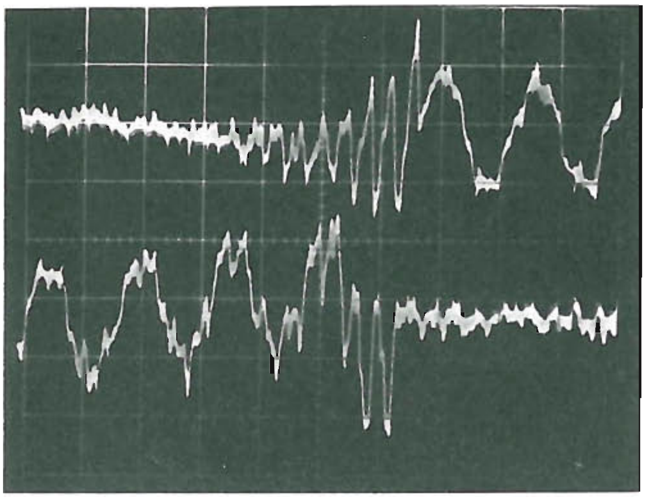
0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

Zero g_z

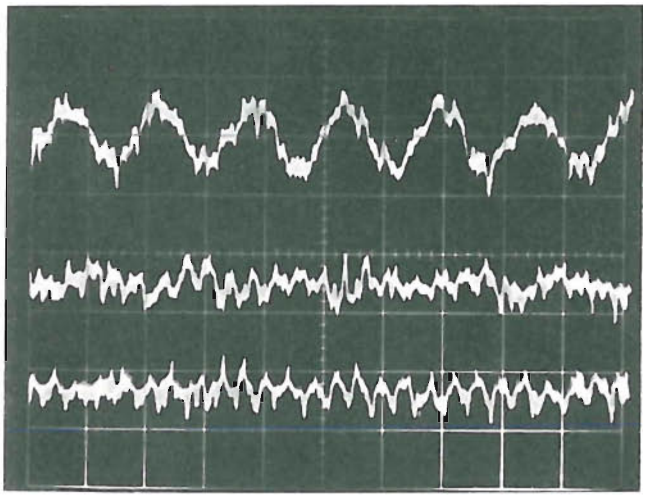
65 Hz nominal

Horizontal scale : 10 msec/div.



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform



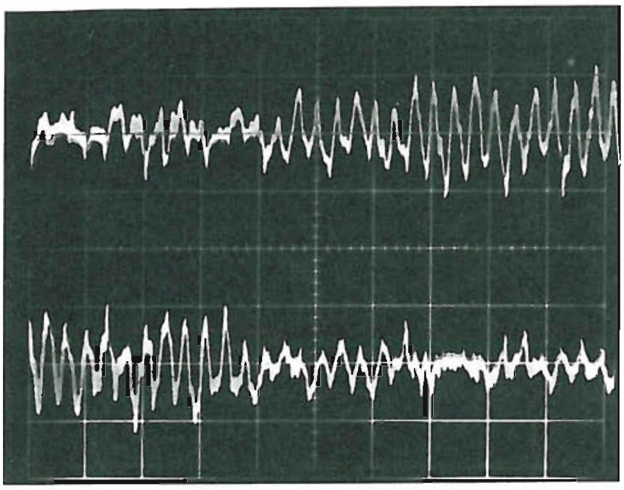
$\pm$ 0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

Zero g_z

100 Hz nominal

Horizontal scale: 10 msec/div.



$\pm$ 0.010 g_z : Rise waveform

$\pm$ 0.010 g_z : Fall waveform

$\pm$ 0.010 g_z : Continuous waveform

$\pm$ 0.005 g_z : Continuous waveform

$\pm$ 0.001 g_z : Continuous waveform

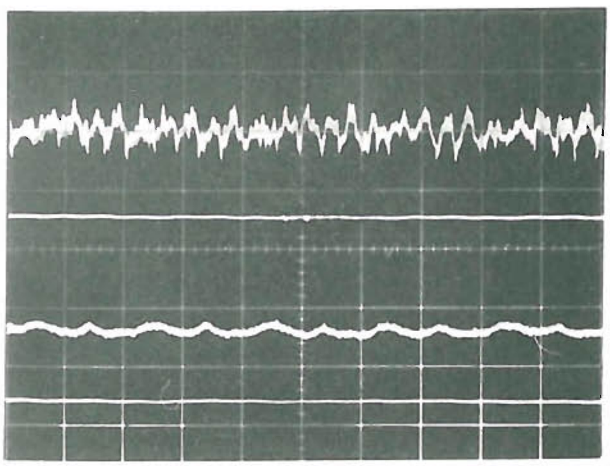
Zero g_z

Appendix B

Minimum vibration levels for main experiment

Vertical scale : $\pm$ 0.01 g / division

Horizontal scale : 10 msec / division



Accelerotion waveform : vibrator switched on and platform at 'zero' g.

Ditto - filtered.

Acceleration waveform : measurement system at 'zero' g.

Ditto - filtered.

APPENDIX C

Notes on the derivation of the perception curves from previous investigations.

Notes for figures 1 and 21

Data from Oshima (Ref. 16) is excluded, as limited frequency range (1.5 - 1.9 Hz) did not warrant inclusion.

Data from Reiher and Meister (Ref. 18) is excluded because its form is inappropriate. Theshold has shape and position similar to Meister (Ref. 14).

Author	Derivation
2. Brumaghin (1967)	As reported
3. Chaney (1964)	Fig. 10 of his report
4. Chaney (1965)	Fig. 9 of his report
5. CEBS (1966)	Fig. shown in the report
9. Gorrill and Synder (1957)	Fig. 8 of their report
11. Helberg and Sperling (1941)	*Hanes (Ref. 10) Fig. 1
13. Jacklin and Liddell (1933 early)	Fig. 18 of their report
Jacklin and Liddell (1933 later)	Fig. 22 of their report
14. Meister (1935)	*Hanes (Ref. 10) Fig. 1
23. von Bekesy (1939)	Fig. 3 of his report
28. Louda (1970)	Fig. 6 of his report

*Hanes (Ref.10) calculations, converting displacement to acceleration, are assumed to be correct.

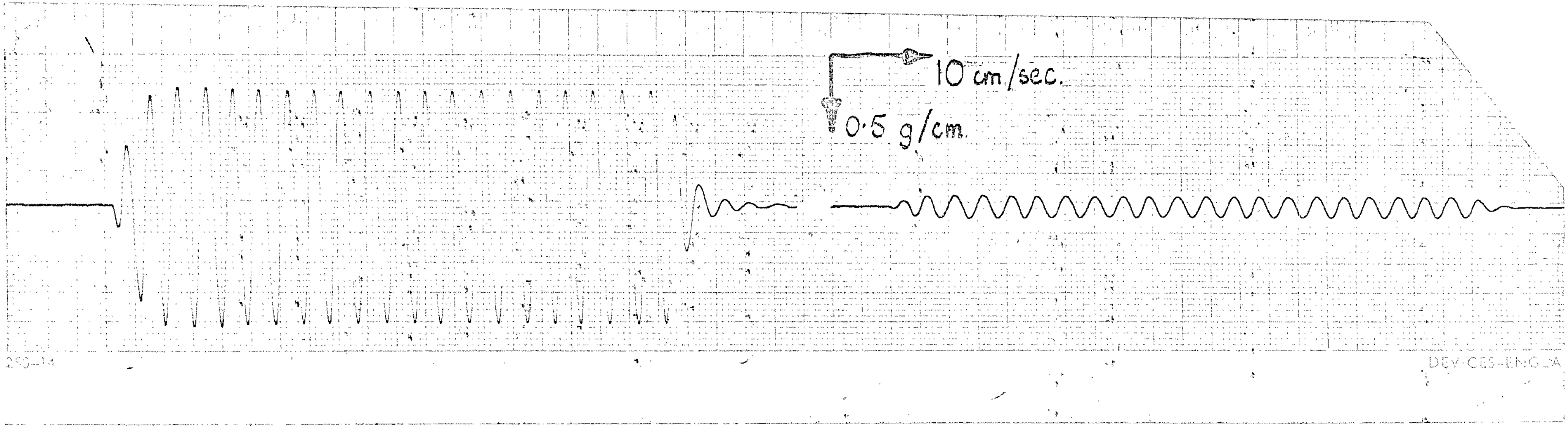
APPENDIX D

Typical vibration exposures.

Acceleration waveforms

Nominal values: ± 1.0 and ± 0.1 g

20 Hz and 1 second duration.



APPENDIX E.

Sonic boom induced building vibration: summary of measurements at Edwards AFB (Ref. 46)

Flight test studies were conducted by the USAF in the vicinity of Edwards, California during June 1966. In two residential structures (E1 and E2), a number of monitoring instruments were positioned including accelerometers mounted on concrete blocks in the middle of several rooms. These accelerometers were sensitive to vertical vibration: a summary of results is given in Table XVII below.

TABLE XVII. Sonic boom induced building vibrations

House Number	Room	Peak Acceleration ($\pm g_z$)		Outside Overpressure lb/ft^2
		Range	Mean	Range
E1	Living room	0.056 - 0.294	0.167	0.97 - 5.50
	Family room	0.026 - 0.246	0.104	
	Bedroom	0.029 - 0.264	0.132	
E2	Dining room	0.009 - 0.230	0.100	0.99 - 5.50
	Bedroom	0.008 - 0.210	0.075	ditto
	Mattress on Bed	0.020 - 0.039	0.025	1.51 - 4.36

Predominant frequency = 20 Hz with durations < 1 sec.