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Article title:

Difference thresholds for intensity perception of whole-body vertical vibration: effect of frequency and magnitude

Name of authors:

Miyuki Morioka and Michael J. Griffin

Affiliation:

Human Factors Research Unit

Institute of Sound and Vibration Research

University of Southampton

Southampton SO17 1BJ

England

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Whole-body vibration perception

ABSTRACT

Difference thresholds for seated subjects exposed to whole-body vertical sinusoidal vibration have been determined at two vibration magnitudes (0.1 and 0.5 ms^{-2} r.m.s.) and at two frequencies (5 and 20 Hz). For twelve subjects, difference thresholds were determined using the up-and-down transformed response method based on two-interval forced-choice tracking. At both frequencies, the difference thresholds increased by a factor of five when the magnitude of the vibration increased from 0.1 to 0.5 ms^{-2} r.m.s. The median relative difference thresholds, Weber fractions ($\Delta I/I$), expressed as percentages, were about 10% and did not differ significantly between the two vibration magnitudes or the two frequencies. It is concluded that for the conditions investigated the difference thresholds for whole-body vibration are approximately consistent with Weber's Law. A vibration magnitude will need to be reduced by more than about 10% for the change to be detectable by human subjects; vibration measurements will be required to detect reductions of less than 10 %.

(158 words)

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INTRODUCTION

The human body is exposed to many sources of vibration: in all types of transport, in buildings, and from the operation of industrial equipment. People react to the vibration according to their perception, which depends, in part, on the vibration magnitude. The magnitude of the vibration to which the body is exposed can be expressed in terms of physical measurements (e.g. the displacement, velocity or acceleration). However, the sensations experienced by people must be obtained using psychophysical measures (e.g. ratings of perceptibility, comfort, annoyance or pain). While the physical magnitude of the motion may be quantified on well-known ratio scales (e.g. in metres, metres per second, or metres per second per second), psychophysical measures may have nominal, ordinal, interval or ratio characteristics according to how they are obtained (Stevens, 1975). The interpretation of physical measurements, and the construction and interpretation of psychophysical scales requires knowledge of how the perception of vibration varies with vibration magnitude.

Absolute thresholds for the perception of whole-body vibration have been determined in several experiments (e.g. Parsons and Griffin, 1988; see also review by Griffin, 1990). These show average absolute thresholds for the perception of vertical sinusoidal vibration at about 0.01 to 0.02 ms^{-2} r.m.s. over the range 5 to 20 Hz, but with appreciable differences between experimenters and between subjects.

Several studies have shown that for vibration magnitudes well above threshold (e.g. Miwa 1968; Howarth and Griffin, 1988), increases in the magnitude, φ, of whole-body vibration results in increases in judgements of the sensation magnitude, ψ, which are approximately in accord with Steven's Power Law:

$$\psi = k \cdot \varphi^n$$

where *n* is the 'growth function' and *k* is a constant that depends on the system of units. Studies have found some values of *n* for vibration stimuli: 0.95, 0.81 and 0.62 at frequencies of 60, 120 and 240 Hz, respectively for the fingertip (Stevens, 1959,1968); 0.89 over the frequency range 25 to 350 Hz for the thenar eminence (Verrillo, 1970); 1.04 to 1.47 in the frequency range 4 to 60 Hz for whole-body vibration (Howarth and Griffin, 1988). This suggests that the sensation magnitude increases in approximately linear proportion to the acceleration magnitude.

For practical purposes, it is useful to know how much a vibration must be reduced for it to be perceived as being less uncomfortable. Attempts to reduce vibration discomfort for whole-body vibration have proceeded over recent years on the assumption that lower magnitudes of vibration will result in reduced discomfort. It has been assumed that, after applying a frequency weighting to allow for differences in sensitivity to different frequencies, reductions at any frequency that result in the same reduction in vibration magnitude will have the same beneficial effect. It has not been known when a reduction in vibration magnitude will not result in a noticeable improvement in discomfort.

For various stimuli, the ‘difference threshold’ (sometimes called the ‘difference limen’, DL) has been measured: this quantifies human ability to differentiate between stimuli of different magnitudes. The difference threshold is defined as the change in a stimulus required for a human observer to recognise a ‘just noticeable difference’ in the stimulus (Guilford, 1954).

The German psychologist, E.H. Weber proposed that the size of the difference threshold is a constant ratio of the stimulus magnitude. Weber's law can be formulated as:

$$\frac{\Delta I}{I} = \text{constant}$$

where ΔI represents the increment in stimulus intensity and I is the stimulus intensity; the ratio is called the Weber ratio, which varies according to the type of stimulus.

Two studies reported since the conduct of the present study have investigated difference thresholds for whole-body vibration. Mansfield and Griffin (1999) determined difference thresholds for whole-body vertical vibration using a car seat, examining three vibration magnitudes (i.e. 0.2, 0.4 and 0.8 ms^{-2} r.m.s.) and two vibration waveforms recorded in a car driven on 'tarmac' and 'pavé' surfaces. On average, an increment of about 13 % in stimulus intensity was just perceptible; this was independent of both the vibration magnitude and the vibration waveform when the stimulus was appropriately frequency-weighted. Pielemeier *et al.* (1997) determined difference thresholds on a car seat using a low level of stimulus: three types of narrow-band random vibration (i.e. centre frequencies at 4, 8 and 15 Hz) at 8 m*g* r.m.s. (0.08 ms^{-2} r.m.s.). The difference thresholds were in the range 0.6 to 1.8 m*g* r.m.s. (7.5 to 22.5 % of the stimulus magnitude).

There is a demand for a reduction of vibration not only in vehicles but also in other situations (e.g. in buildings, aircraft, ships) where the vibration contains a variety of characteristics. It is therefore desirable to identify perceptual sensitivity for a range of vibration stimuli so as to allow general predictions of the extent to which reductions in vibration magnitude will be perceived.

The present study involved the determination of difference thresholds for seated subjects exposed to *z*-axis (i.e. vertical) sinusoidal vibration. "The Effect of vibration frequency (at 5 and 20 Hz) on difference thresholds was examined with reference to two vibration magnitudes (0.1 and 0.5 ms^{-2} r.m.s.)"

I. EXPERIMENTAL METHOD

A. Subjects

Twelve male volunteers, staff and students at the University of Southampton, participated in the experiment. All subjects were free of injury or history of relevant illness. They were aged between 21 and 30 (mean 23.5) years with an average stature of 181.2 cm and an average weight of 75.1 kg. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton. Subjects were provided with written instructions (see Appendix) prior to participating in the experiment.

B. Apparatus

Whole-body sinusoidal vertical vibration was produced using a Derritron VP85 (6LA) electrodynamic vertical *z*-axis vibrator powered by a 1,000 W amplifier. Subjects sat on a rigid flat wooden surface secured to an aluminium plate, 405 mm by 405 mm and 15 mm thick, attached to the vibrator. Subjects were positioned at the centre of the seat surface; there was a stationary adjustable footrest but no backrest. Sinusoidal vertical vibration was generated and measured using *HVLab* software and a digital computer. The signals were generated at 300 samples per second and passed through 25 Hz low-pass filters. Vibration waveforms and the levels of the input and output signals were monitored on an oscilloscope. The vibration acceleration on the wooden seat surface was recorded during the presentation of every ‘test’ motion using the *HVLab* system.

During the experiment the ambient noise levels were in the range 55 to 60 dB(A), this noise was mainly caused by the vibrator cooling fan. So as to mask the ambient sounds of the vibrator, subjects wore ear defenders with integral speakers producing white noise at 70 dB(A), measured using a Knowles Electronics Manikin for Acoustic Research, KEMAR. They were exposed to this level for a maximum 60 minutes. Both the subject and experimenter were within easy reach of emergency buttons capable of stopping the motion of the vibrator.

C. Design and procedure

The difference thresholds were determined with vertical sinusoidal vibration in four conditions: two vibration frequencies (5 and 20 Hz) each presented at two different vibration magnitudes (0.1 and 0.5 ms^{-2} r.m.s.). The forced-choice tracking procedure, originally applied by Zwislocki *et al*. (1958) in auditory detection, was employed in the study in conjunction with the two-alternative forced-choice procedure. Subjects were exposed to a number of trials (about 35 to 60 trials per threshold determination); a trial consisted of a 4 second 'reference' stimulus, followed by a 1 second pause, followed by a 4 second 'test' stimulus. The order of the ‘reference’ and the ‘test’ stimuli was randomised. The magnitude of the 'reference' stimulus was constant at either 0.1 or 0.5 ms^{-2} r.m.s., depending on the condition being investigated. The ‘test’ stimulus was presented at a greater magnitude than the ‘reference’ stimulus with 0.25 dB (i.e. 2.9 %) increment steps. The maximum magnitude of the 'test' stimulus was 3 dB (i.e. 41 %) greater than the ‘reference’ stimulus. After each exposure to a pair of vibration stimuli the subject responded to the question:

“Did you judge the first or second to be the greater?”

For the sequence of producing the ‘test’ stimuli, the up-and-down transformed response method (UDTR method), proposed by Wetherill and Levitt (1965), was employed in the experiment. This method enables the estimation of observation probabilities other than the 50 % level on a psychometric function, it has been used in some studies of absolute vibration perception thresholds at the finger (e.g. Maeda and Griffin, 1995; Maeda and Morioka, 1997) and on the hand (Morioka and Griffin, 1998), also to determine difference thresholds for whole-body vibration (Mansfield and Griffin, Awaiting publication) and hand-transmitted vibration (Morioka, 1998). The UDTR method has several alternative sequence patterns for obtaining thresholds at different probability levels (see Levitt, 1971). In the experiment, a three-down one-up rule (i.e. a decrease in the stimulus magnitude after three consecutive correct responses, an increase in the stimulus magnitude after one incorrect response) was selected because this gives thresholds at 79.4 % correct response: close to half-way between a chance response (i.e. 50 %) and certainty (100 %).

A typical set of data from the experiment is illustrated in Figure 1. The ‘test’ stimulus commenced with the same magnitude as the 'reference' stimulus. In the example, an incorrect response was given after trial ‘1’, so the magnitude of the following ‘test’ stimulus was increased to the next level. After trial ‘2’, a correct response was given, so the following stimulus was presented at the same level as in trial ‘2’. Subsequently, after trial ‘3’, three correct responses had been given consecutively, so the magnitude for trial ‘7’ was decreased. A measurement was terminated after ten reversals (a point where the stimulus level reversed direction: either a peak or a trough). The four measurement runs were conducted with each subject on the same day, each requiring 10 to 15 minutes of experimentation.

FIGURE 1 ABOUT HERE

D. Algorithm for determining difference thresholds

To determine difference thresholds, only the acceleration data at the reversal points (peaks and troughs) were used. Thresholds were calculated from the mean of the peaks and the troughs. Levitt and Rabiner (1967) suggested that the data from the first two reversals should be omitted from the calculation of the estimate in order to reduce starting errors, so difference thresholds were obtained by subtracting the 'reference' value from the threshold value calculated from the average of the last four peaks and the last four troughs:

$$\text{Difference threshold} = \frac{\left[\sum_{i=2}^{i=5} p_i + \sum_{i=2}^{i=5} t_j\right]}{N} - R$$

where p_i is the vibration magnitude of peak i, and t_j is the vibration magnitude of trough j; N is the number of reversals (i.e. 8); R is the reference magnitude.

II. RESULTS

A. Difference thresholds

Figure 2 shows the absolute difference thresholds obtained for all 12 subjects at the two magnitudes and the two frequencies. The difference thresholds ranged from 0.0064 to 0.0237 ms^{-2} r.m.s. with the 0.1 ms^{-2} r.m.s. reference magnitude and ranged from 0.015 to 0.132 ms^{-2} r.m.s. with the 0.5 ms^{-2} r.m.s. reference magnitude. It is clear that the difference thresholds were greater with the higher reference magnitude. Overall, the difference thresholds obtained with the four reference stimuli were significantly different (Friedman, $\chi^2 = 29.8$, $p < 0.0001$), whereas there was no significant difference between difference thresholds obtained with the 5 and 20 Hz reference stimuli at 0.1 ms^{-2} r.m.s., or between these two stimuli presented at 0.5 ms^{-2} r.m.s. (Wilcoxon, $p > 0.3$). From these results, it is concluded that there was no significant difference in the difference thresholds at the two vibration frequencies (i.e. at 5 Hz and 20 Hz).

There were no significant correlations between difference thresholds and subject age or body size (i.e. height and weight) (Spearman, $p > 0.05$).

FIGURE 2 ABOUT HERE

B. Weber fraction

In order to investigate the percentage change in magnitude required for a subject to notice that the vibration magnitude had changed, the ‘absolute difference thresholds’ were expressed as ‘relative difference thresholds’ using the Weber fraction, $\Delta I/I$ (i.e. the absolute difference threshold, ΔI, divided by the reference magnitude, I). Table 1 shows the relative difference thresholds, expressed as a percentage, for the four stimuli and the twelve subjects. The thresholds varied between subjects over the range 3.2 to 23.2 %, with median thresholds of 11.6 % at the low reference magnitude and 9.2 % at the high reference magnitude. The analysis showed no significant difference in the Weber fractions between the four stimuli (Friedman $p > 0.5$). The percentage of relative difference thresholds were slightly lower than those presented by Mansfield and Griffin (Awaiting publication) (i.e. 11.8 to 14.1 %) and much lower than those for hand-transmitted vibration presented by Morioka (1998) (i.e. about 15.6 to 18.6 %).

TABLE 1 ABOUT HERE

III. DISCUSSION

The difference thresholds increased as the stimulus magnitude increased, with no frequency dependence: at both 5 and 20 Hz the difference threshold was almost five times greater at 0.5 ms^{-2} r.m.s. than at 0.1 ms^{-2} r.m.s. When the difference threshold was expressed as a fraction of the vibration magnitude there was no significant difference between the two magnitudes. It seems that the difference thresholds for some types of whole-body vertical vibration are about 10 % (between 8.1 and 12.3 %) of the stimulus intensity. Although there was a trend for the Weber fractions to reduce with increasing vibration magnitude, the results are approximately consistent with Weber's law.

The results from the experiment may not be sufficient to predict detection sensitivity for other vibration stimuli. Figure 3 summarises the median relative difference thresholds of the twelve subjects. Trends observed over the four stimuli may assist the extension of the results. At both frequencies, the relative difference threshold decreased (by about 2 %) when the stimulus magnitude was increased from 0.1 to 0.5 ms^{-2} r.m.s. A similar phenomenon has been observed in some studies of difference thresholds at the thenar eminence where vibration intensity discrimination at 25 and 250 Hz is enhanced as intensity increases (Gescheider *et al.*, 1990). Discrimination sensitivity at 20 and 100 Hz has been found to be U-shaped or V-shaped, with a maximum enhancement at about 20 dB sensation level (Delemos and Hollins, 1996), which results in a "near miss" to Weber's Law.

Although the present results show no statistically significant change in the difference thresholds between 5 and 20 Hz, lower difference thresholds with the higher frequency were found at both magnitudes. This trend could indicate that detection sensitivity of vibration stimuli is greater at 20 Hz than at 5 Hz. This implication does not support the use of frequency weightings that assume vertical vibration at 5 Hz is produces significantly greater discomfort than vertical vibration at 20 Hz. Mansfield and Griffin (1998) concluded that the W_b frequency weighting from British Standard 6841 (1987) provided useful predictions of difference thresholds with different spectra of vertical vibration. The present results suggest that difference thresholds and Weber fractions of frequency-weighted stimuli may not be equal as the vibration frequency changes. However, the weighting W_b from BS 6841 (1987), which gives a high weighting to frequencies around 20 Hz relative to that in the old International Standard 2631 (1985) and the new International Standard 2631 (1997), may be sufficient if the vibration frequency is primarily within the range between 5 Hz and 20 Hz.

FIGURE 3 ABOUT HERE

During the experiment, some subjects reported they judged the difference between the stimuli by feeling the movement at a particular part of the body which varied according to the vibration conditions, such as movement of the head, knee, shoulder or viscera at 5 Hz and movement of the upper leg or back at 20 Hz. The sensations generated by these two frequencies feel different and are generally perceived to be dominant in different parts of the body (see Whitham and Griffin, 1978). Although vibration may have been felt at different locations on the body this does not appear to have resulted in a large difference in the difference thresholds at the two frequencies.

In accord with previous studies at the finger and the thenar eminence, it may be assumed that difference thresholds for whole-body vibration will depend on the method used for their determination (see Gescheider *et al.,* 1990). Higher or lower values could have been obtained by varying the psychophysical method. Further, difference thresholds probably depend on the interval between the presentation of the pairs of stimuli (see Gescheider *et al.,* 1996): a higher threshold may be expected if the interval is greater than that used here. Variations in the environment (e.g. noise or seating comfort) between two conditions may also be expected to increase difference thresholds. Hence, when comparing the ride in two vehicles, or the ride with two different seats, the present results suggest that changes in magnitude greater than 10 % may be required for detection. However, this does not imply that vibration reductions below threshold are not worth achieving: the sum of several sub-threshold changes can be expected to result in a noticeable improvement. The findings suggest that an improvement of less than 10 % will not be easily detected by subjective testing. Consequently, it is desirable to use objective methods to optimise ride and seating dynamics as these methods can measure improvements less than 10 %.

IV. CONCLUSIONS

Difference thresholds for intensity perception of whole-body vertical vibration have been determined at two magnitudes (0.1 and 0.5 ms^{-2} r.m.s.) and at two frequencies (5 and 20 Hz) using a rigid flat seat. The difference thresholds increased in proportion to stimulus magnitude from 0.1 to 0.5 ms^{-2} r.m.s. The median relative difference thresholds, Weber fractions ($\Delta I/I$), expressed as a percentage, were about 10 % (varying from 8.1 to 12.3 %) and did not differ significantly between the two vibration magnitudes or the two frequencies.

It is concluded difference thresholds of whole-body vertical vibration may be approximately consistent with Weber's Law, but that further information is required in order to confidently predict detection sensitivity with the full range of complex motions in vehicles. It is suggested that reductions in vibration magnitude of more than 10 % will often be required for a change to be detectable by human subjects. Improvements of less than 10 % may be measured by suitable vibration instrumentation.

APPENDIX

Subject Instructions

The aim of this experiment is to determine the difference threshold for vertical sinusoidal whole-body vibration.

1. Before the experiment, the acceleration condition will be calibrated. During the calibration, you will sit in the seat.
2. After the calibration, the experiment will be started. You will feel two vibration stimuli, then you will be asked;

"Did you judge the first or the second to be the greater?

Your task is to answer, either *"FIRST"* or *"SECOND".*

3. Stimuli will be presented several times.

Please maintain the posture and concentrate on the stimuli during the measurement.

Note

FOUR measurements will be performed, it will take about 10 to 15 minutes for each.

Thank you very much for your co-operation.

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TABLE

TABLE I. Relative difference thresholds (Weber fractions) expressed as percentages (%) with four reference stimuli for twelve subjects.

Subjects	Reference stimulus conditions			
	$0.1\ ms^{-2}$ r.m.s.		$0.5\ ms^{-2}$ r.m.s.	
	5 Hz	20 Hz	5 Hz	20 Hz
S1	8.51	11.16	6.40	4.86
S2	9.81	14.03	7.60	7.34
S3	10.49	7.41	6.42	5.82
S4	14.73	20.28	9.24	24.86
S5	20.40	6.96	11.40	9.14
S6	10.98	16.87	11.54	14.34
S7	16.01	6.84	14.70	6.89
S8	7.33	13.58	8.59	8.92
S9	14.69	13.57	15.49	23.18
S10	11.57	10.82	5.86	3.20
S11	13.40	10.55	24.52	14.63
S12	12.94	7.39	11.47	6.05
Median	12.25	10.99	10.32	8.13
Inter-quartile range	4.73	6.52	7.20	8.68

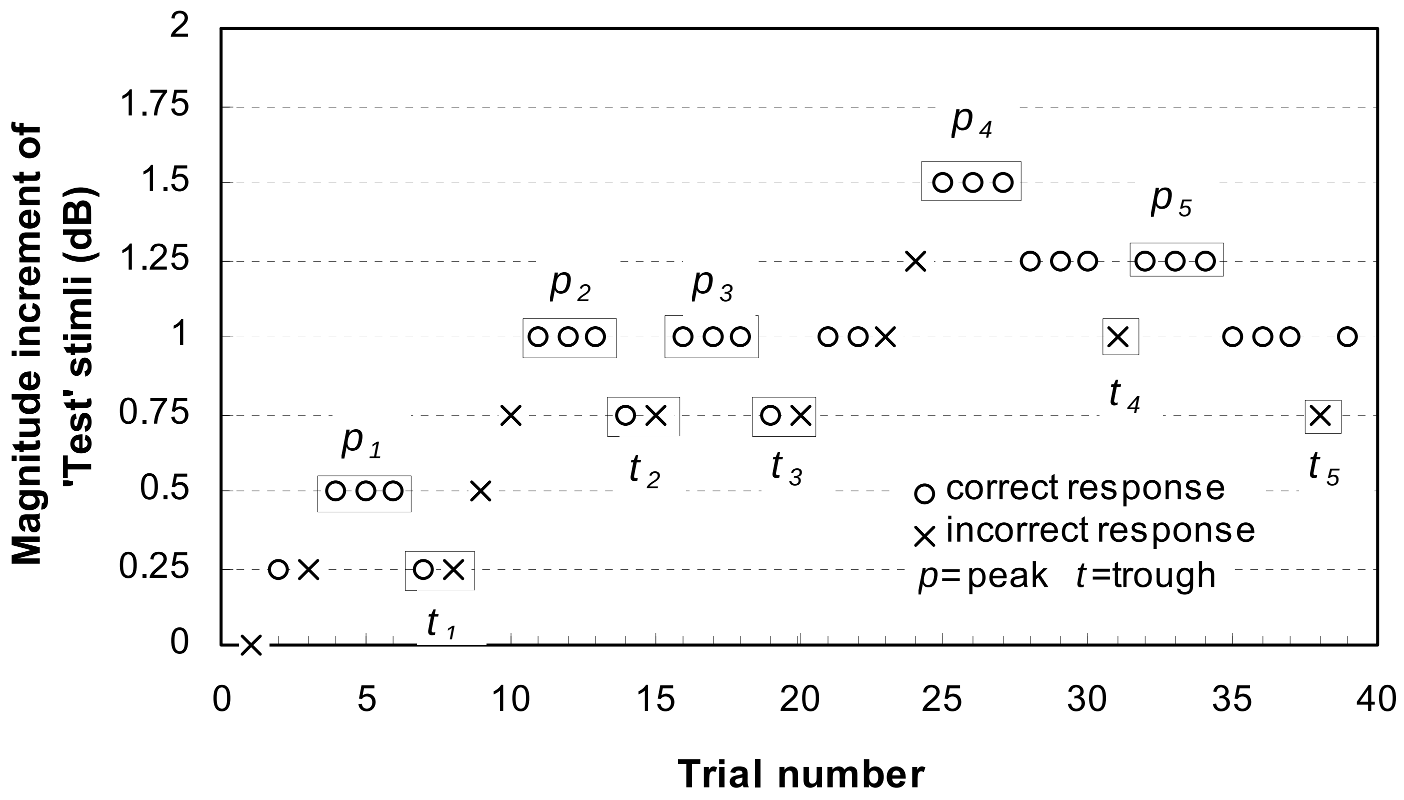
FIGURE CAPTIONS

FIG. 1. Typical data for the difference threshold measurement using the UDTR procedure (three-down and one-up rule).

FIG. 2. Absolute difference thresholds for twelve subjects measured with four vibration stimulus conditions.

FIG. 3. Median relative difference thresholds for four vibration stimulus conditions.

FIGURES



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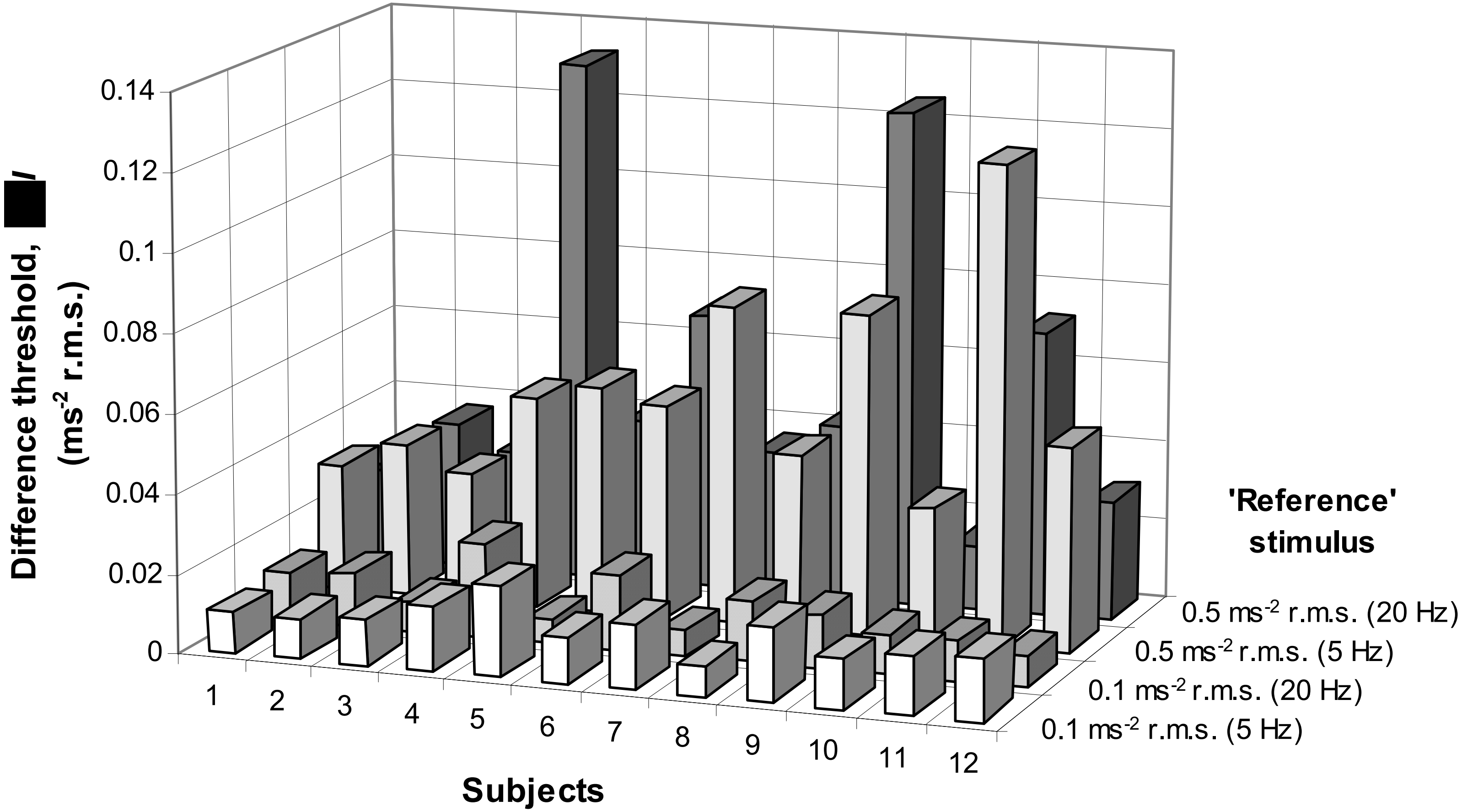

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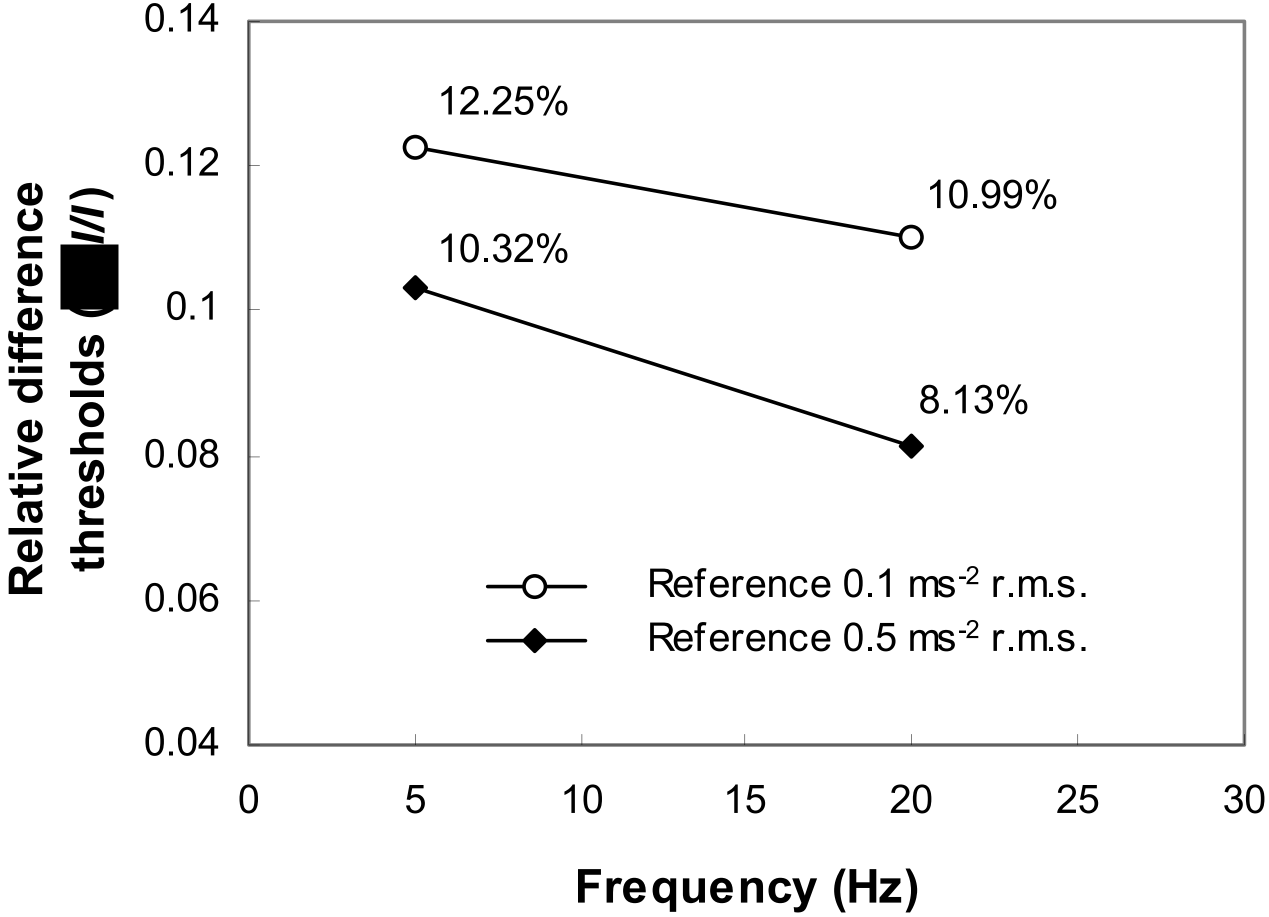

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