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Title:

DEPENDENCE OF VIBROTACTILE THRESHOLDS ON THE PSYCHOPHYSICAL MEASUREMENT METHOD

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Abstract

Objectives: To investigate the dependence of vibrotactile thresholds on the psychophysical method used in the diagnosis of neurological dysfunction caused by exposure to hand-transmitted vibration. To compare thresholds obtained with: a) ‘continuously variable’ versus intermittent, ‘staircase’, stimulation using ‘yes-no’ responses, and b) ‘yes-no’ and ‘forced-choice’ responses using intermittent staircase stimulation.

Methods: Vibrotactile thresholds were measured on 12 healthy males with three different psychophysical methods. All measurements were performed using the same vibrometer in which the vibratory stimulus was applied by a 6 mm diameter probe protruding through a 10 mm-diameter hole in a surround, controlling both the contact force and the push force. Four stimulus frequencies (16, 31.5, 63 and 125 Hz) were used to obtain responses from FA I and FA II mechanoreceptors.

Results: There was a 3 to 6 dB variation in threshold due to the psychophysical method: thresholds were lower with intermittent stimulation and thresholds obtained with the ‘forced-choice’ procedure were lower than those obtained with the ‘yes-no’ procedure. Alternative explanations of the findings were offered.

Conclusions: The dependence of psychophysical measurement method on vibrotactile thresholds was partly due to influencing responses via mechanoreceptor systems. It was suggested the psychophysical measurement method had a sufficiently large effect on vibrotactile thresholds for it to be taken into account when standardising methods for the diagnosis of neurological disorders.

Key words:

vibrotactile thresholds, psychophysical measurement method, mechanoreceptor

Introduction

Determination of vibrotactile perception thresholds at the fingertips are undertaken for two purposes: (i) fundamental research: the identification of mechanisms responsible for vibration perception (e.g. studies conducted by Verrillo and co-authors, e.g. Verrillo 1985, Gescheider *et al*., 1978); and (ii) the diagnosis of sensorineural disorders caused by hand-transmitted vibration: often referred as the 'hand-arm vibration syndrome', HAVS, (e.g. Bovenzi, 1990; Griffin, 1990).

The measurement of vibrotactile perception thresholds at the fingertips is often intended to obtain separate mediation by SA I, SA II, FA I and FA II mechanoreceptors (see definitions of these receptors by Johansson and Vallbo, 1979a,b). The currently known sensory mechanisms suggest some influence on the sensitivity of receptors due to: physical form of the apparatus [i.e. contactor size (e.g. Verrillo, 1963), probe-surround gap (e.g. Verrillo, 1979), see also summary by Gescheider, 1976]; skin-stimulus conditions [i.e. skin temperature (e.g. Verrillo and Bolanowski, 1968), contact force (e.g. Green and Craig, 1974); psychophysical algorithm (e.g. Maeda and Griffin, 1995). A draft International Standard (ISO/FDIS 13091-1, 2001) suggests requirements for measurement methods intended to obtain reproducible and comparable results using different apparatus for diagnostic applications. The draft does not specify one particular method, leaving limited options for the measurement conditions. Brammer and Piercy (2000) outlined the rationale for including two measurement methods (with and without surround around the vibrating contact probe). There has been little attention on how the measured thresholds are influenced by the different psychophysical measurement methods included in the standard.

International Standard (ISO/FDIS 13091-1, 2001) defines two psychophysical algorithms for determining vibrotactile perception thresholds at the fingertip: (i) the staircase algorithm, in which a sequence of short duration stimuli, with successively increasing (or decreasing) intensities, is applied to the skin until the stimuli are perceived (or no longer perceived), and (ii) the von Békésy algorithm, in which a continuous stimulus, with changing intensity, is used to determine, sequentially, ascending and descending thresholds. The main difference between the staircase algorithm and the von Békésy algorithm is the stimulation procedure and whether the stimuli are presented intermittently or continuously. According to the Standard, intermittent stimulation is preferred for all measurements so as to: (a) reduce the possibility of a supra-threshold stimulus causing a temporary threshold shift, and (b) introduce a quiescent interval which serves to contrast the sensations caused by the applied stimulation with the background sensations.

With intermittent stimulation, two procedures can be applied to obtain responses from subjects: (i) the 'yes-no' response procedure, in which subjects are presented with a single stimulus and asked to respond whether or not it is perceptible, and (ii) the 'forced-choice' response procedure, in which subjects are presented with a stimulus during one of two periods and then asked to choose which observation period contained the stimulus. Many psychophysical experiments choose forced-choice procedures, in which the signal detection criterion can be brought under the control of the experimenter. The forced-choice staircase procedure is the most frequently used with just two alternatives (i.e. the two-interval forced-choice, 2IFC, procedure; Rose *et al*., 1970).

Although a few studies have discussed the use of different psychophysical methods (e.g. Maeda, 1992; Maeda and Griffin, 1995), there appears to be no study investigating how the two different types of stimulation (i.e. intermittent or continuous) or the two different response procedures (i.e. 'yes-no' or 'forced-choice') influence measures of vibrotactile thresholds.

This study was designed to compare vibrotactile thresholds at the fingertip using two psychophysical algorithms (the staircase and the von Békésy algorithms), examining the difference in threshold between intermittent and continuous stimulations, and also between 'yes-no' and 'forced-choice' (2IFC) response procedures.

Methods

Subjects

Twelve healthy males participated in the study: aged 22 to 27 years (mean 24.4 years), height 175 to 185 cm (mean 180.7 cm) and weight 66 to 86.7 kg (mean 74.7 kg). All subjects were non-smokers, right handed, and free from vibration injuries or history of occupational exposure to hand-transmitted vibration and relevant illness.

Apparatus

Vibrotactile thresholds were determined using the *HVLab* Tactile Vibrometer. The vibrometer unit contains an electrodynamic mini-shaker (Ling V101) attached via an accelerometer (PC308 B14) to a 6 mm-diameter nylon probe. The probe is counter-balanced to produce a constant upward force and protrudes through a 10 mm-diameter hole in a flat plate. Strain gauges are mounted under the plate to indicate the downward push force. A meter was provided for visual feedback of the force applied by the finger. A schematic view of the vibrometer is shown in Figure 1, and the skin-stimulator contact conditions are summarised in Table 1.

FIGURE 1 AND TABLE 1 ABOUT HERE

Experimental conditions

Subjects attended one session lasting up to 45 minutes. They were asked not to consume coffee, tea or alcohol for at least two hours prior to the session. Finger skin temperature was measured before and after the tests. Tests only proceeded if the skin temperature was above 29 ° Celsius; the subjects were asked to warm up their hands if the temperature was below this value. The room temperature was kept constant at about 23° Celsius.

Three psychophysical measurement methods, Methods A, B and C, were defined in the study. These employed the possible combinations of continuous and intermittent stimulations with ‘yes-no’ and ‘forced-choice’ responses. The combination of continuous stimulation with ‘forced-choice’ responses is not possible.

Method A: von Békésy algorithm (continuous stimulation)

The intensity of vibration increased or decreased continuously at a constant rate (test magnitude increment = 3 dB/s, initial magnitude increment = 5 dB/s). The direction of change of stimulus intensity was reversed according to the response of the subject; the intensity decreased until the subject no longer perceived vibration and then increased until the subject began to perceive the vibration. The subject responded by pressing a button when perceiving vibration stimuli. A test was terminated after 30 seconds. Thresholds were calculated as the arithmetic mean of the mean peak and the mean trough (expressed in ms^{-2} r.m.s.), ignoring the first cycle of the measurement. A schematic time history of vibration stimuli during the test is shown in Figure 2.

FIGURE 2 ABOUT HERE

Methods B and C: Staircase algorithm (intermittent stimulation)

The three-down one-up rule was used for both Method B and Method C in conjunction with the staircase (i.e. up-and-down) algorithm. An example set of data for a threshold measurement is shown in Figure 3. The vibration stimulus intermittently increased in intensity by 2 dB (25.8% increment) after a negative (incorrect) response from the subject and decreased by 2 dB after three consecutive positive (correct) responses.

FIGURE 3 ABOUT HERE

The measurement was terminated after six reversals: a point where the stimulus level reversed direction at either a peak (= *p*) or a trough (= *t*) (see Figure 3). The threshold was calculated from the mean of the last two peaks and the last two troughs, omitting the first two reversals, as suggested by Levitt (1971):

$$\text{Absolute threshold} = \frac{\left(\sum_{i=2}^{i=3} p_i + \sum_{j=2}^{j=3} t_j\right)}{N}$$

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.

Absolute vibrotactile thresholds are normally estimated from the acceleration level corresponding to 50% probability of detecting the vibration stimulus. However, when using forced-choice, it is required to determine more than 50% of positive responses, as 50% of correct responses can be obtained by guessing, such as when subjects do not detect the stimulus. Zwislocki *et al.* (1958) introduced an efficient method of estimating thresholds for other than 50% of positive responses by modifying the rule for presenting stimulus intensities from the simple staircase method. A 'three-down one-up' rule gives thresholds corresponding to 79.4% correct responses: close to half-way between a chance response (i.e. 50 %) and certainty (i.e. 100 %).

Two different response procedures were used to obtaining thresholds with the staircase algorithm. With Method B, single vibration stimuli were presented, each 1.0-second in duration, followed by a no-stimulus interval (not less than 1.0 second duration). The subjects' task was to indicate whether they perceived the vibration stimulus or not: a 'yes-no' response. They responded saying, "yes" or "no". With Method C, subjects were presented with pairs of stimuli, each 1.0-second in duration, separated by a 1.0-second pause. The two observation periods were designated to the subjects by lights. The subjects' task was to judge whether the first or the second stimulus contained vibration: a 'forced-choice' response. They responded saying, "first" or "second". Figure 4 shows a schematic view of the stimuli used in Method B and Method C.

FIGURE 4 ABOUR HERE

The measurement conditions employed for the three psychophysical methods used in the study are summarised in Table 2. For each method, vibrotactile thresholds were determined at the four preferred octave centre frequencies from 16 to 125 Hz. The order of presenting the three methods was balanced and the order of presenting the four frequencies was randomised.

TABLE 2 ABOUT HERE

Statistical methods

Non-parametric tests (Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed for statistical analysis, as it was expected that the threshold data were not normally distributed. Correlation coefficients were obtained using Spearman's rank correlation, so as to investigate the associations between thresholds measured with two different psychophysical measurement methods.

Results

Median vibrotactile thresholds obtained by the three psychophysical methods are shown in Figure 5. The thresholds are re-plotted in Figure 6 to present threshold differences in dB caused by different psychophysical methods. Median vibrotactile thresholds varied between the three psychophysical methods, with a 3 to 6 dB difference over the frequency range. The results differed between the three measurement methods (Friedman, $p<0.05$), except at 31.5 Hz (Friedman, $p=0.17$). Lowest thresholds were obtained with Method C: there were significant differences in threshold compared to Method A (Wilcoxon, $p<0.006$) and compared to Method B (Wilcoxon, $p<0.03$, except at 16 Hz, $p=0.21$). There were generally no significant differences in threshold between Methods A and B (Wilcoxon, $p>0.07$), except at 125 Hz (Wilcoxon, $p=0.008$).

FIGURES 5 AND 6 ABOUT HERE

Thresholds obtained by two different psychophysical methods were generally correlated each other (see Figure 7). Spearman's correlation coefficient was significant at high frequencies (i.e. 125 Hz, 63 Hz) for all combinations of methods ($p<0.05$) also at low frequency (i.e. 16 Hz) between Method A and Method B ($p=0.015$). Within the group of 12 subjects, a person who had higher (or lower) thresholds relative to other subjects when measured by one psychophysical method tended to have higher (or lower) thresholds when measured by another psychophysical method. Lower correlations were obtained at low frequencies (i.e. 16 Hz and 31.5 Hz), partly because thresholds were distributed within a narrow range within the 12 normal subjects. The variability between subjects (expressed as the ratio of the inter-quartile range to the median threshold) was least at low frequencies and greatest at high frequencies for all methods (see Table 3). It is seen in Figure 7 that most of the regression lines do not fall at the corners of the graph, suggesting different thresholds with different methods. Between Methods B and C (middle graph of Figure 7), a constant difference in threshold was found, indicating no frequency dependence in threshold differences.

FIGURE 7 ABOUT HERE

TABLE 3 ABOUT HERE

Discussion

Comparison of continuous versus intermittent stimulation (Method A versus Method B)

With intermittent stimulation (Method B) the thresholds tended to be lower than with continuous stimulation (Method A), but the effect of stimulus presentation was statistically significant only at 125 Hz.

A choice of different detection probabilities could be a factor affecting thresholds, because a higher probability of detection would result in a higher threshold. However, the present results showed the opposite tendency: Method B gave lower thresholds than Method A, even though Method B provided a threshold for 79.4% probability whereas Method A estimated thresholds for 50% probability (both over the range 0 to 100%). Maeda (1992) compared thresholds at 125 Hz determined by the most orthodox up-down algorithm (using intermittent stimulation) and the von Békésy algorithm (using continuous stimulation), both estimating a 50% threshold, and found higher thresholds with the von Békésy method. Maeda and Griffin (1995) measured 125 Hz vibrotactile thresholds using the staircase algorithm with seven different rules allowing the estimation of 50% thresholds. The results were compared with those obtained in a previous study using the von Békésy algorithm (the same as Method A) and again found higher thresholds with continuous stimulation than with intermittent stimulation.

Stimuli at 125 Hz in the present study were likely to be mediated by FA II (Pacinian corpuscles). It is known that the Pacinian system is capable of 'temporal summation' in which thresholds decrease as the stimulus duration increases, up to about 0.6 seconds (Gescheider *et al*., 1978). Therefore, when vibration intensity increases during the integration period, the intensity at the moment of perception via the Pacinian system may need to be higher than when the stimulus is of constant intensity. When vibration intensity decreases during the integration period, the intensity at the moment of loosing perception via the Pacinian system may be lower than when the stimulus is of constant intensity. However, if there is exponential integration over the previous 0.6 seconds, the bias introduced by increasing intensities may differ from that introduced by decreasing intensities. This implies that the higher the rate of change of stimulus amplitude the greater the change in thresholds. Löfenberg and Johansson (1984) and Lundström (1984) employed 2.5 or 7.5 dB/s and 10.0 dB/s, respectively for vibrotactile measurements using the von Békésy algorithm. Their results tended to give higher thresholds, notably Lundström's results gave thresholds approximately a factor of 3 to 5 greater than the current results using Method A, although the large difference may not be entirely due to the different rate of change of stimulus magnitude.

Thresholds for detecting the vibration stimuli may have been influenced by previous stimulation causing a shift in mechanoreceptor sensitivity (e.g. by masking, or as a result of a temporary threshold shift). If this occurred, continuous stimulation would be expected to raise the threshold more than intermittent stimulation (as in this study). Gescheider *et al*., (1989) investigated stimulus onset asynchrony (SOA) functions using a masker 20 dB above the threshold level. It was found that the greatest elevation of threshold occurred when the test stimulus was presented close to the time of onset or cessation of the masking stimulus, and then gradually disappeared as the interval between the test and the masking stimulus increased up to about 0.6 seconds. Harada and Griffin (1991) measured vibrotactile thresholds at the fingertip after exposure to hand-transmitted vibration at 20 ms^{-2} r.m.s. for five minutes. The results showed that exposure to vibration at higher frequencies (more than 63 Hz) induced significant TTS (temporary threshold shift) for FA II (Pacinian corpuscles), but there was a lower TTS for FA I (Meissner's corpuscles) when exposed to lower frequency vibration (less than 63 Hz). Thresholds shifts have not been reported at vibration levels associated with the measurement of thresholds; however, such an effect would be consistent with higher thresholds obtained when using continuous stimulation and they cannot be ruled out without further study.

The reaction time of subjects when responding to stimuli of increasing or decreasing intensity may have an effect on reported thresholds, irrespective of any temporal integration, masking or TTS effects. In this study, the stimulus in Method A increased at a rate of 3dB/s, so a 3 to 6 dB shift in thresholds would require a reaction time of 1 to 2 seconds, far greater than reaction times to supra-threshold stimuli. Reaction times tend to be longer with stimuli close to threshold but this might be considered to be a matter of temporal integration rather than reaction time. The task in Method A was somewhat predictable and subjects may be able to anticipate the stimulus, so shortening reaction times. A reaction time effect would tend to raise the average thresholds of a subject with Method A if it applied equally to the pressing and release of the button indicating the detection of a stimulus.

With Method A (von Békésy algorithm) the stimulus was present at all times and so there was not a clear 'contrast' between moments when the stimulus was present and moments when it was absent. With Method B (intermittent stimulation) observers may have noticed the difference in sensation at the start or end of stimulation, even though at all times there may have been a sensation similar to that caused by the vibration. This opportunity to distinguish 'signal' from 'noise' may have made it easer to detect the stimulus with Method B and resulted in lower thresholds with this method.

Comparison of ‘yes-no’ versus ‘forced-choice’ response procedures (Method B versus Method C)

Employing different response procedures also seemed to shift thresholds. The ‘forced-choice’ procedure (Method C) significantly lowered thresholds compared with the ‘yes-no’ procedure (Method B). This was evident from the middle graph of Figure 7 in which all regression lines overlap, indicating that the thresholds obtained by Method B were all elevated by about 2.2 dB (22%) relative to the thresholds obtained by Method C, irrespective of the stimulus frequency. There may be a criterion difference between the two response procedures. With the ‘yes-no’ procedure, subjects can wait for sufficient stimulus intensity to give a correct response: subjects may tend to give negative answers until they detect the stimulus with certainty so as to avoid being wrong. With the ‘forced-choice’ procedure, subjects were forced to give an answer following each pair of intervals and could not avoid errors. They may have detected a faint stimulus and given correct responses at a level where they had insufficient confidence to respond with ‘yes’ when using the ‘yes-no’ procedure.

Conclusions

The psychophysical measurement method had a significant influence on vibrotactile thresholds: intermittent stimulation lowered thresholds compared with continuous stimulation at 125 Hz, and the ‘forced-choice’ procedure lowered thresholds compared with the ‘yes-no’ response procedure at all frequencies except for 16 Hz. Possible explanations for the findings include: (i) the response characteristics of the mechanoreceptive system (the sensitivity of the Pacinian system changes as a function of stimulus duration), (ii) masking, or TTS, effects whereby stimulus detection is reduced by previous stimulation, (iii) easier detection of ‘signal’ from ‘noise’ when a clear contrast between stimulation and no stimulation occurs, and (iv) criterion shifts in detection by observers. It is concluded that the psychophysical method has a sufficiently large effect on thresholds for it to be taken into account when standardising procedures for the diagnosis of neurological disorders.

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Table legends

Table 1 Skin-stimulator contact conditions of *HVLab* Tactile Vibrometer.

Table 2 Summary of the conditions of three psychophysical methods.

Table 3 Summary of thresholds of 12 subjects determined by three psychophysical methods (median, inter-quartile-range = IQR, and the ratio of the IQR and the median value).

Figure Legends

Figure 1 Schematic view of the *HVLab* Tactile Vibrometer unit.

Figure 2 An example of threshold recording by the von Békésy algorithm (employed for Method A). The vibrogram shows the period after the subject made the first positive response to the stimulus (after first press of the response button).

Figure 3 Typical data by the staircase algorithm (employed for Method B and Method C). Three-down one-up rule was used. The thresholds were determined by mean of peaks and troughs omitting the first peak and trough values.

Figure 4 Schematic presentation of stimulus design used for Method B (‘yes-no’ response) and Method C (‘forced-choice’ response).

Figure 5 Median vibrotactile thresholds for 12 subjects obtained by three psychophysical methods.

Figure 6 Dependence of median thresholds on the three different psychophysical methods.

Figure 7 Correlation between vibrotactile thresholds for 12 subjects between pairs of psychophysical methods. The slopes represent regression lines for each stimulus frequency.

Table 1 Skin-stimulator contact conditions of *HVLab* Tactile Vibrometer.

Probe diameter	6 mm
Probe-surround gap	2 mm
Contact force	1 N
Push force	2 N
Skin indentation	2.78 mm *

* data from Lindsell (1997)

Table 2 Summary of the conditions of three psychophysical methods.

	Method A	**Method B**	**Method C**
Algorithm	Von Békésy	Staircase (3-down 1-up rule)	Staircase (3-down 1-up rule)
Stimulation	Continuous	Intermittent	Intermittent
Response procedure	Yes-no	Yes-no	Two-interval forced-choice (2IFC)
Intermittent stimulation	-	Yes	Yes
-burst duration		1.0 s	1.0 s
-quiescent duration		> 1.0 s	1.0 s
Continuous stimulation	Yes	-	-
-maximum duration	30 seconds per test		
Step rate	3 dB/s	2 dB	2 dB
Trial number	-	20-25 trials	25-30 trials
Subject response	Stop button (press-yes, release-no)	Oral (yes or no)	Oral (1st or 2nd)
Calculation of thresholds	Mean of reversals (> 6 reversals)	Mean of last 4 reversals	Mean of last 4 reversals

Table 3 Summary of thresholds of 12 subjects determined by three psychophysical methods (median, inter-quartile-range = IQR, and the ratio of the IQR and the median value).

		Method A (von Békésy)	**Method B** (staircase, 'yes-no')	**Method C** (staircase, forced choice)
16 Hz	Median	0.065	0.034	0.030
	IQR	0.045	0.015	0.008
	IQR/Median	**0.692**	**0.441**	**0.267**
31.5 Hz	Median	0.107	0.104	0.076
	IQR	0.064	0.045	0.054
	IQR/Median	**0.598**	**0.433**	**0.711**
63 Hz	Median	0.221	0.169	0.118
	IQR	0.133	0.151	0.102
	IQR/Median	**0.602**	**0.893**	**0.864**
125 Hz	Median	0.168	0.098	0.080
	IQR	0.119	0.136	0.086
	IQR/Median	**0.708**	**1.388**	**1.075**

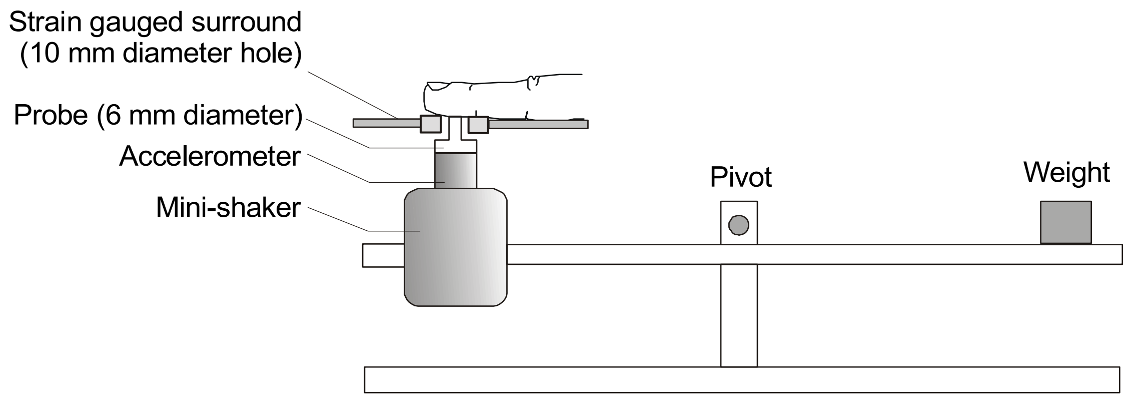
Strain gauged surround
(10 mm diameter hole)
Probe (6 mm diameter)
Accelerometer
Mini-shaker
Pivot
Weight

Figure 1

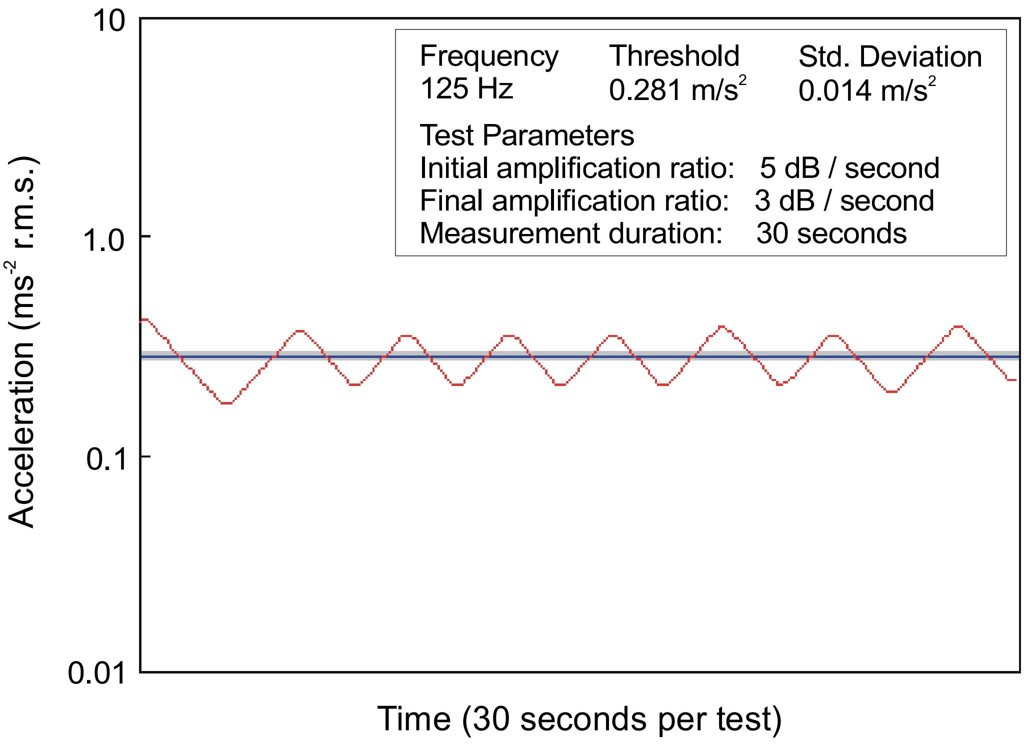
10
1.0
0.1
0.01
Acceleration (ms-2 r.m.s.)
Time (30 seconds per test)
Frequency
125 Hz
Threshold
0.281 m/s2
Std. Deviation
0.014 m/s2
Test Parameters
Initial amplification ratio: 5 dB / second
Final amplification ratio: 3 dB / second
Measurement duration: 30 seconds

Figure 2

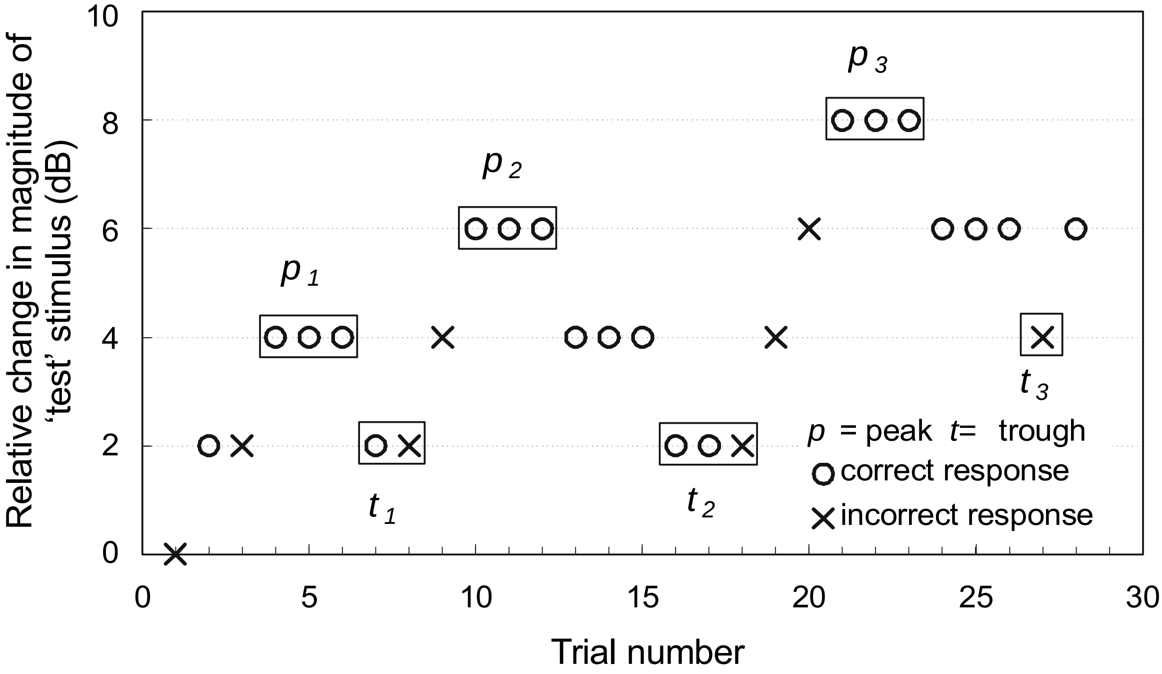
Relative change in magnitude of 'test' stimulus (dB)
Trial number
p 1
p 2
p 3
t 1
t 2
t 3
p = peak t= trough
correct response
incorrect response
0
2
4
6
8
10
0
5
10
15
20
25
30

Figure 3

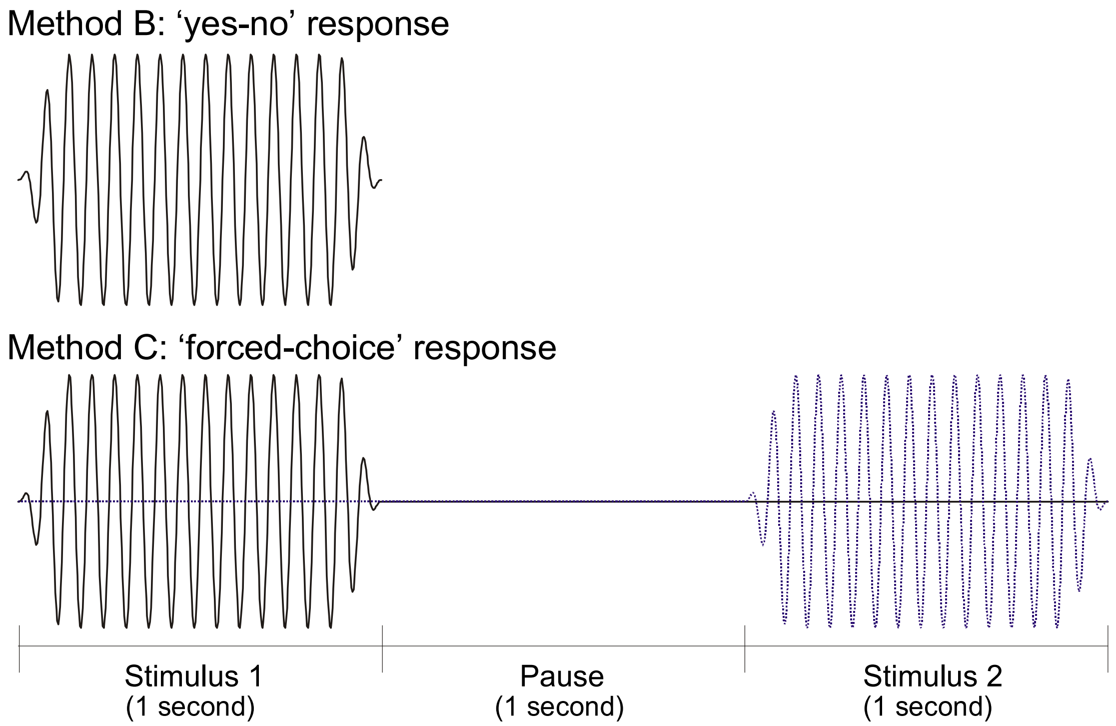
Method B: 'yes-no' response
Method C: 'forced-choice' response
Stimulus 1
(1 second)
Pause
(1 second)
Stimulus 2
(1 second)

Figure 4

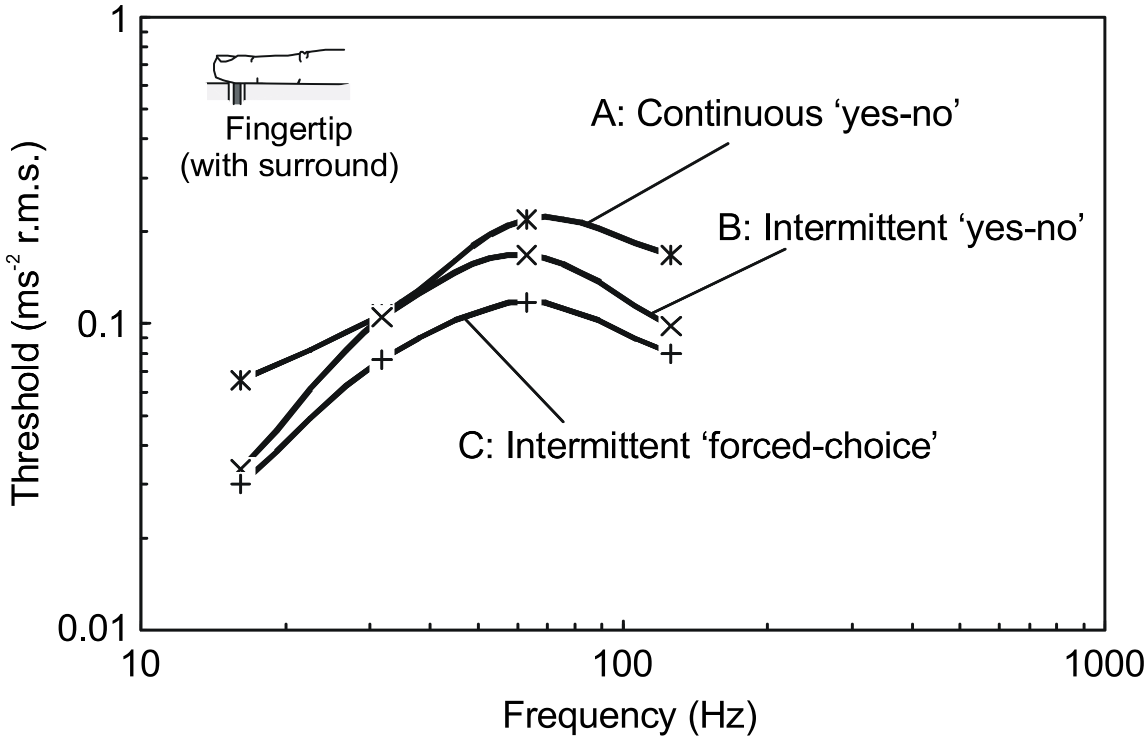
1
0.1
0.01
Threshold (ms-2 r.m.s.)
10
100
1000
Frequency (Hz)
Fingertip
(with surround)
A: Continuous ‘yes-no’
B: Intermittent ‘yes-no’
C: Intermittent ‘forced-choice’

Figure 5

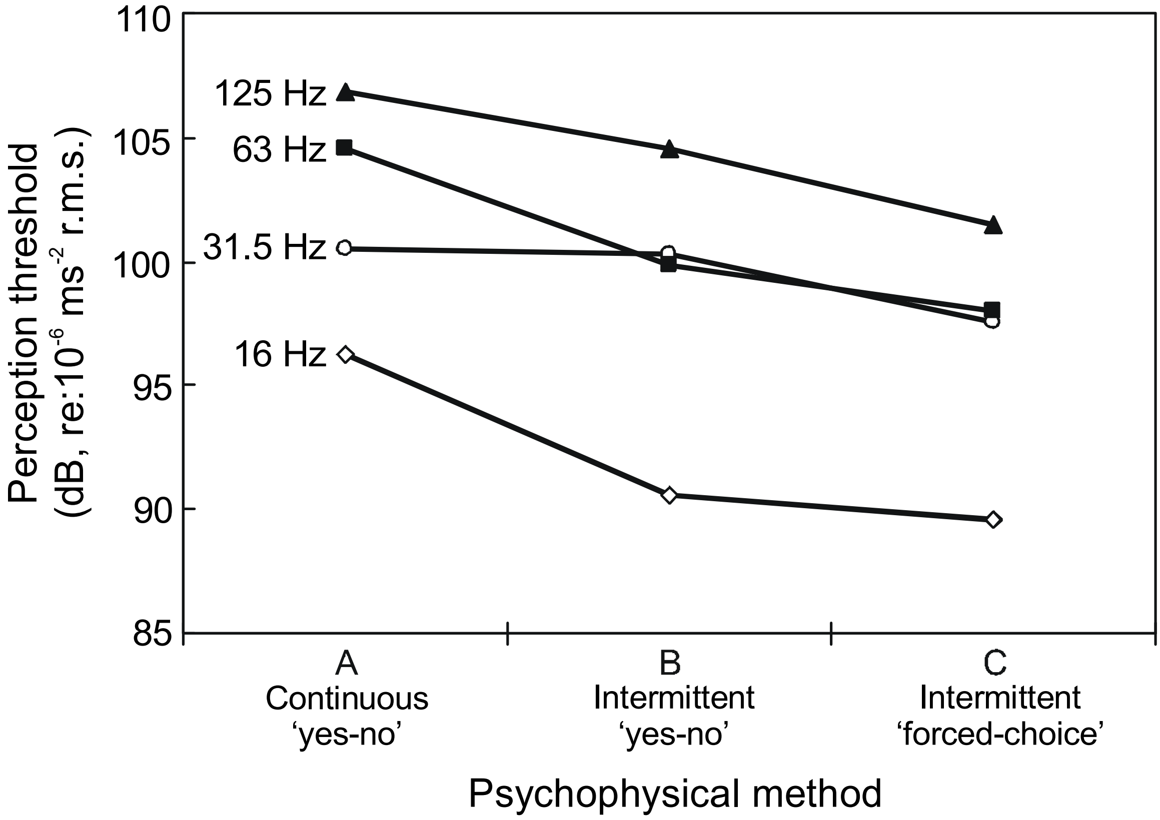
110
105
100
95
90
85
125 Hz
63 Hz
31.5 Hz
16 Hz
Perception threshold
(dB, re:10^{-6} ms^{-2} r.m.s.)
A
Continuous
'yes-no'
B
Intermittent
'yes-no'
C
Intermittent
'forced-choice'
Psychophysical method

Figure 6

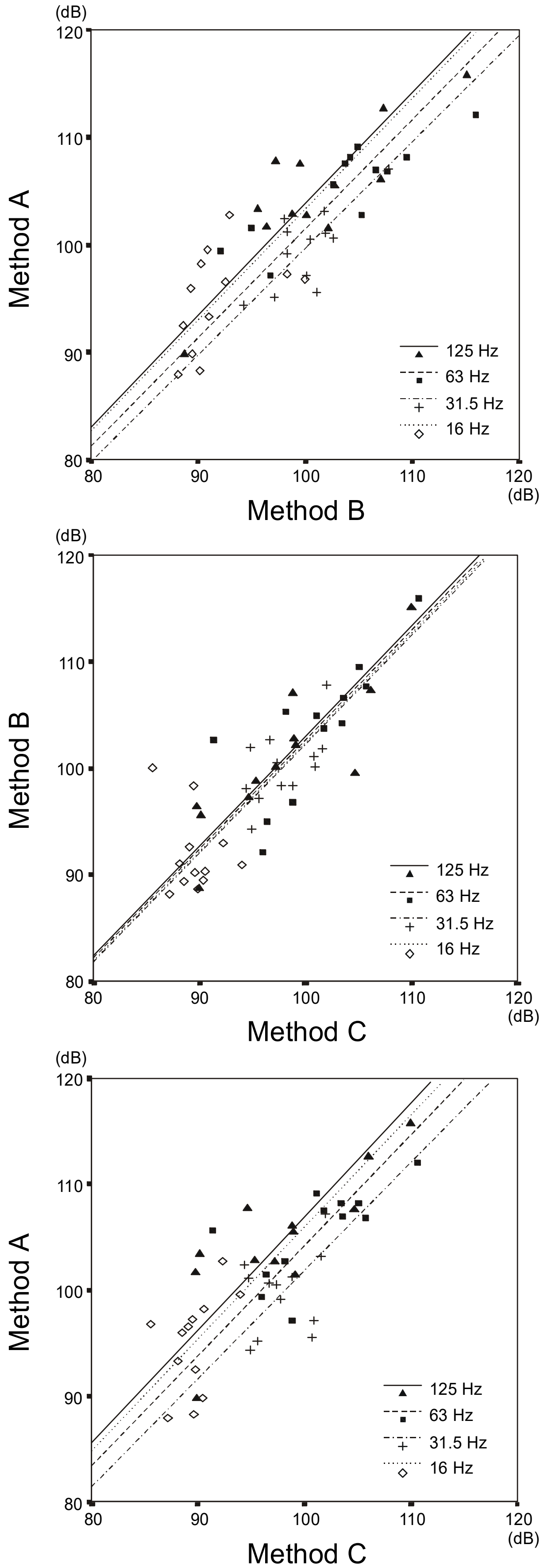
(dB)
Method A
Method B
Method C
125 Hz
63 Hz
31.5 Hz
16 Hz
80
90
100
110
120

Figure 7