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TITLE

Equivalent comfort contours for vertical vibration of steering wheels: effect of vibration magnitude, grip force, and hand position

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ABSTRACT

Vehicle drivers receive tactile feedback from steering wheel vibration that depends on the frequency and magnitude of the vibration. From an experiment with 12 subjects, equivalent comfort contours were determined for vertical vibration of the hands at two positions with three grip forces. The perceived intensity of the vibration was determined using the method of magnitude estimation over a range of frequencies (4 to 250 Hz) and magnitudes (0.1 to 1.58 ms^{-2} r.m.s). Absolute thresholds for vibration perception were also determined for the two hand positions over the same frequency range. The shapes of the comfort contours were strongly dependent on vibration magnitude and also influenced by grip force, indicating that the appropriate frequency weighting depends on vibration magnitude and grip force. There was only a small effect of hand position. The findings are explained by characteristics of the Pacinian and non-Pacinian tactile channels in the glabrous skin of the hand.

(151 words)

(Approximately 100-150 words)

Key words:

Absolute threshold, Equivalent comfort contour, Hand-transmitted vibration

MAIN TEXT

1. Introduction

Steering wheels provide vehicle drivers with vibration sensations at their hands that give tactile feedback of the state of the car and the road. The vibration from a steering wheel may affect driver judgements of ride comfort. The manner in which steering wheel vibration affects comfort is complex and may depend on the vibration magnitude, the vibration frequency, the direction of vibration, the location of contact with the hands, and the posture of the hands. The sources of steering wheel vibration include the engine, wheels and tyres, and the road surface that produce various patterns of vibration transmitted to the steering wheel through the steering shaft. Transfer functions between these individual sources of vibration and the steering wheel have been investigated by Kim et al. (1985) who found that vibration can be transmitted to the steering wheel at frequencies up to about 200 Hz, with greatest transmissibility around 20 to 30 Hz. Discomfort, annoyance, or interference with activities due to vibration is only expected if the vibration exceeds the threshold for the perception of vibration.

The current International Standard for the evaluation of hand-transmitted vibration (ISO 5349-1, 2001) defines a single frequency weighting, W_h, for the evaluation of human exposure to hand-transmitted vibration in any axis. The W_h frequency weighting indicates greatest sensitivity to acceleration at frequencies between 8 and 16 Hz with sensitivity to acceleration reducing in proportion to frequency at frequencies greater than 16 Hz. The W_h weighting was derived from equivalent comfort contours and perception threshold contours determined by Miwa (1967) over the frequency range 3 to 300 Hz with the hand pressing on a flat plate.

The perception of hand-transmitted vibration is highly dependent on the frequency of vibration. Absolute thresholds have U-shaped curves with the minimum vibration displacement required for perception between 150 and 250 Hz but with a sensitivity that varies between studies, due to differences in hand posture (e.g., a gripping posture or a flat palm), psychophysical measurement method, grip force and feed force (see Miwa, 1967; Reynolds *et al*., 1977; Brisben *et al*., 1999; Morioka and Griffin 2002; 2006). At supra-threshold levels, the frequency-dependence of equivalent comfort contours determined by Miwa (1967), Reynolds (1977), Mishoe and Suggs (1977), Giacomin *et al*. (2004) and Morioka and Griffin (2006) seem to differ from the frequency-dependence of absolute perception threshold contours, possibly due to the involvement of different receptors at different vibration magnitudes (Morioka and Griffin, 2005a).

Of four classes of mechanoreceptive afferent fibres in the glabrous skin of the hand, two are fast adapting (i.e. FA I and FA II) and two are slow adapting (SA I and SA II) (Johansson and Vallbo, 1979). The Pacinian (P) channel has distinctive characteristics: spatial and temporal summation and a dependence on skin temperature (Gescheider *et al*., 1978), and is associated with the FA II fibres (Bolanowski and Verrillo, 1982; Mountcastle *et al.* 1972). The non-Pacinian (NP) channels include the FA I, SA II and SA I fibres (i.e. NP I, NP II and NP III channels, respectively), some of which seem incapable of temporal or spatial summation and whose responses depend on stimulus gradients (Gescheider, 1976; Verrillo, 1985). Studies have demonstrated ‘tuning curves’ for thresholds of vibrotactile perception for each of the four tactile channels in the glabrous skin of the hand (Bolanowski *et al.*, 1988; Gescheider *et al*., 2001). It is reasonable to assume that the absolute threshold for the perception of steering wheel vibration is determined by the tactile channel that has the greatest sensitivity (i.e. the lowest threshold) among the four tactile channels, whereas sensations of steering wheel vibration at supra-threshold levels may be mediated by more than one tactile channel.

It is intuitively obvious that increasing the magnitude of vibration will increase the perceived intensity of vibration and some research has been dedicated to determining the rate of growth of sensation as a function of the intensity of vibrotactile stimuli (Verrillo *et al*., 1969; Verrillo and Capraro, 1975). However, little is known about how the frequency-dependence of sensitivity (i.e. the shapes of equivalent comfort contours) depends on hand position and grip force applied to a steering wheel.

The present study was conducted to assist the development of a method for predicting the perception and discomfort associated with steering wheel vibration, examining the effect of: (i) vibration frequency (over the range 4 to 250 Hz), (ii) vibration magnitude (from absolute thresholds to levels associated with discomfort), (iii) hand position, and (iv) grip force. Two experiments were performed so as to determine both absolute thresholds and equivalent comfort contours for vibration with a stimulus range and contact conditions representative of those experienced by drivers holding steering wheels.

2. General method

2.1 Apparatus

It was desired to study two commonly used positions of a hand on a steering wheel as illustrated in Fig. 1. For a 14-inch (356 mm) diameter steering wheel, a 30-mm diameter rim and 20 degrees of inclination to the vertical, an upper hand position (referred to as UPPER) was positioned 45 degrees above the centre of the steering wheel; a lower hand position (referred to as LOWER) was positioned 45 degrees below the centre of the steering wheel.

A test rig was built to provide vibration at the hands over the required frequency range with a body posture similar to that when holding a steering wheel. The rig consisted of a wooden base structure clamped between aluminium plate at the top (2 mm thick) and the bottom (15 mm thick), rigidly secured to a vibrator (Derritron VP30) by four bolts. The wooden base structure supported two cylindrical handles (100 mm length, 30 mm diameter) rigidly inserted and glued into holes on both sides, the handles being orientated at 45 degrees to the horizontal and 20 degrees to the vertical (see Fig. 1) so as to approximate the hand-grasping posture on a car steering wheel. The subjects were instructed to hold the cylindrical handles without contact with the ends of the handles, so as to ensure the contact pressures at the hands were not influenced by increased pressure over the ends of the handles. A second hand position was obtained by mounting the rig upside down on the vibrator table.

FIG. 1 ABOUT HERE

Sinusoidal vibration was generated and acquired using *HVLab* Data Acquisition and Analysis Software (version 3.81) on a personal computer fitted with anti-aliasing filters (TechFilter) and analogue-to-digital and digital-to-analogue converters (PCL-818). The signals were generated at 5000 samples per second and passed through 600 Hz low-pass filters. The stimulus parameters and the psychophysical measurement procedures were computer-controlled.

A piezoelectric accelerometer (type DJ Birchall) was attached to the wooden base so as to measure vibration in the vertical direction. The difference in vibration magnitude between the wooden base and the cylindrical handle was previously found to be generally within ±5% (within ±15% at frequencies greater than 125 Hz). The signal from the accelerometer was conditioned by a charge amplifier (Brüel and Kjær, type 2635) and acquired at 5000 samples per second. The cross-axis motion and distortion were not determined during this study, but have been measured previously for the same apparatus. For the same vibrator, Morioka and Griffin (2006) measured the cross-axis acceleration at less than 5% of the vertical acceleration over the frequency range 8 to 315 Hz. The waveform distortion varied with magnitude and frequency but was low and estimated at less than 10% for all stimuli. The handles used on the steering wheel rig were rigid so as to ensure a flat frequency response up to approximately 300 Hz.

Subjects sat in a car seat with adjustable backrest inclination. The height of the seat was adjusted to obtain the required hand position in a driving posture (see Fig. 2). A footrest (295 mm x 195 mm) inclined at 30 degrees was fixed to the floor. The distance between seat and the handles was adjustable, but the position of the footrest was fixed such that the heels were positioned vertically beneath the handles.

A sheet of cardboard (930 mm x 420 mm) was placed between subjects and the steering wheel so as to prevent visual clues that might influence their perception and judgement of the handle movement. Subjects inserted their arms through 150 mm diameter holes to grasp the handles.

FIG. 2 ABOUT HERE

2.2 Subjects

Twelve healthy male subjects aged between 21 and 28 years (mean 24.6 years, standard deviation 2.7) with a mean stature of 178.9 cm and a mean weight of 77.0 kg, participated in the two experiments. They were staff or students of the University of Southampton and attended both experiments.

A questionnaire was completed by all subjects so as to collect personal information: nationality, dominant hand, occupation, health (smoking, alcohol, medication, hand injuries, previous vibration exposure and relevant diseases) and car driving experience. All subjects were right handed and eight had driving experience. Subject stature, weight, sitting height, upper limb length, hand length, handbreadth, and hand thickness were measured according to methods defined by Pheasant (1990).

The experiments were approved by the Human Experimentation Safety and Ethics Committee of the ISVR, University of Southampton. Informed consent to participate in the experiment was given by all subjects.

The subjects were given written instructions at the beginning of each session. The skin temperature of the distal phalanx of the middle finger was measured by means of thermocouples at the beginning and end of each session using an *HVLab* Tactile Aesthesiometer. The tests only proceeded if the skin temperature was greater than 29 °C; the subjects were asked to warm their hands if the temperature was below this criterion. The room temperature was 20 ±2 °C. During the tests, the subjects were exposed to white noise at 65 dB(A) via a pair of headphones in order to prevent them from hearing the vibration.

3. Experiment 1: Absolute Thresholds

Absolute thresholds for the perception of hand-transmitted vibration in the two hand positions (i.e. UPPER and LOWER) were determined using sinusoidal vibration at the seven preferred octave centre frequencies from 4 to 250 Hz. It was hypothesised that thresholds would depend on vibration frequency and hand position.

3.1 Method

An up-down (staircase) algorithm was employed to determine thresholds in conjunction with a ‘three-down one-up’ rule. Sinusoidal vertical vibration stimuli, 2 seconds in duration, with rise and fall times of 0.2 seconds were created as test stimuli. The task for the subjects was to indicate whether they perceived a vibration stimulus or not. They responded saying, ‘yes’ or ‘no’. The vibration stimulus increased by 2 dB (25.8 % increment) after a negative (‘no’) response from a subject and decreased by 2 dB after three consecutive positive (‘yes’) responses. A measurement was terminated after six reversals: a point where the stimulus level reversed direction at either a peak or a trough. 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). Absolute thresholds were measured at the seven frequencies (i.e. 4, 8, 16, 31.5, 63, 125, and 250 Hz) in random order. Six subjects commenced with their hands in the UPPER position and 6 subjects commenced with their hands in the LOWER position.

During the threshold determinations, subjects were instructed to grasp the handles with both hands using a force that they felt ‘most comfortable’. Much of the glabrous skin of their hands was in contact with the handle.

3.2 Results and Discussion

3.2.1 Effect of frequency

Fig. 3 shows the median absolute thresholds determined with both hand positions. Within the UPPER and the LOWER hand positions, the acceleration thresholds showed a statistically significant dependence on stimulus frequency (Friedman, $p<0.001$).

The frequency-dependence of the threshold contours for the UPPER and the LOWER hand positions is similar to the frequency-dependence reported previously by Miwa (1967), Reynolds et al. (1977) and Morioka and Griffin (2005b). .

One approach to identifying the tactile channels responsible for perception is to determine correlations between thresholds at different frequencies: a subject having high thresholds at one frequency would be expected to have high thresholds at another frequency mediated by the same tactile channel. Generally, high correlations were obtained between thresholds at frequencies less than 16 Hz and between thresholds at frequencies greater than 16 Hz. With the UPPER position, the thresholds were significantly correlated between 8 and 16 Hz, between

31.5 and 125 Hz and between 63 and 125 Hz (Spearman $r^2>0.6$, $p<0.05$). With the LOWER position, the thresholds were significantly correlated between 4 and 8 Hz, between 16 and 63 Hz, between 16 and 125 Hz and between all possible pairs of frequencies between 31.5 and 250 Hz (Spearman $r^2>0.6$, $p<0.06$) except between 125 and 250 Hz (Spearman $r^2=0.71$, $p=0.54$). There were no consistent significant correlations between thresholds and age, skin temperature, anthropometric measurements or gripping force.

Another approach to identifying tactile channels responsible for perception thresholds is to determine a slope that represents the frequency-dependence of the perception threshold expressed in terms of the vibration displacement. The slope of the displacement threshold of the Pacinian receptors between 15 and 200 Hz has been suggested to be approximately -12 dB per octave (e.g., Verrillo, 1963; Gescheider, 1976; Verrillo and Gescheider, 1977; Bolanowski *et al*., 1988; Gescheider *et al*., 2001). When the present thresholds are expressed in terms of displacement (see Fig. 3), two slopes are evident for both the UPPER and the LOWER hand positions: similar to -12 dB per doubling of frequency at frequencies between 16 and 250 Hz and -5 dB per doubling of frequency between 4 and 16 Hz. It therefore seems likely that thresholds at frequencies greater than 16 Hz were mediated by the Pacinian system. The Meissner's corpuscles (NP I) respond with a slope of about -5.0 dB per octave between about 3 and 35 Hz (Bolanowski *et al*. 1988; Gescheider *et al*., 2001; 2002), while the Ruffini endings (NP II) respond with a slope of -5.0 to -6.0 dB per octave between about 15 and 250 Hz (Capraro *et al*., 1979; Gescheider *et al*., 1985; Bolanowski *et al*., 1988). For both the UPPER and the LOWER hand positions in the current study, the slope of the thresholds at frequencies less than 16 Hz were about half the slope expected for the Pacinian channel but typical of the slope of the NP I and NP II channels.

FIG. 3 ABOUT HERE

3.2.2 Effect of hand position

There was a significant effect of hand position on thresholds only at 4 Hz and 250 Hz: thresholds with the UPPER position were significantly higher than those with the LOWER position at 4 Hz (Wilcoxon, $p=0.006$), whereas thresholds with the UPPER position were significantly lower than those with the LOWER position at 250 Hz (Wilcoxon, $p=0.028$). High correlation coefficients were obtained between thresholds at the UPPER and LOWER positions at 4, 31.5, 63, and 125 Hz (Spearman, $r^2>0.6$, $p<0.03$), suggesting the same tactile channel mediated thresholds at both hand position.

In the UPPER position, the steering wheel was mainly in contact with the palm of the hand, whereas in the LOWER position the steering wheel made more contact with the fingers. At 4 Hz, thresholds with the LOWER hand position may have been lower than in the UPPER hand position because the FA I and SA I fibres (NP I and NP III channels, respectively) are densely innervated towards distal parts of the fingers. The ratios between fibres densities at the distal fingers, proximal fingers and palm are approximately 7:2:1 for FA I fibres and 9:4:1 for SA I fibres, whereas the FA II fibres are more evenly distributed over the glabrous area of the hand, with a ratio of 2:1:1 (Johansson and Vallbo, 1979). At 250 Hz, thresholds were lower with the UPPER hand position than the LOWER hand position, possibly due to a greater number of Pacinian receptors activated by contact with the palm increasing transmission of vibration to other areas, such as the wrist and forearm. Alternatively, perhaps a greater pressure was applied on the steering wheel with the UPPER position by the weight of the hand and arm than in the LOWER position, resulting in lower thresholds at 250 Hz. The sensitivity of the Pacinian channel (FA II) is increased by increased contact area (Verrillo, 1963; Gescheider, *et al*., 1978) and by increased contact force (Lamoré and Keemink, 1988; Verrillo, 1962).

4. Experiment 2: Equivalent comfort contours

The rates of growth in vibration sensation with increasing vibration magnitude were determined at the 19 preferred one-third octave centre frequencies from 4 Hz to 250 Hz so as to produce equivalent comfort contours for vibration at each of the two hand positions (i.e. UPPER and LOWER). The effect of grip force on the equivalent comfort contours was also investigated. It was hypothesised that the frequency-dependence of the equivalent comfort contours would depend on vibration magnitude, grip force, and the hand position on the steering wheel.

4.1 Method

4.1.1 Procedure

Judgements of discomfort caused by sinusoidal vibration were determined using the method of magnitude estimation. A set of two motions, reference motion and test motion, were created; each motion lasted 2.0 seconds with an interval of 1.0 second between the motions. The motions had 0.2-second cosine-tapered ends. The reference motion was 0.4 ms^{-2} r.m.s. at 31.5 Hz. The test motions had frequencies from 4 to 250 Hz (in one-third octave steps) and magnitudes from 0.1 to 1.58 ms^{-2} r.m.s. (in 3 dB steps), and were presented in a random order. The task of the subjects was to assign a number that represented the discomfort caused by the test motion relative to the discomfort caused by the reference motion, assuming the discomfort caused by the reference motion was ‘100’.

The test was repeated with five conditions: UPPER, LOWER, MINIMUM, LIGHT, and TIGHT. For the UPPER and LOWER conditions (as shown in Figure 1), the subjects were instructed to grasp the steering wheel with forces they felt ‘most comfortable’. The gripping force that each subject subjectively assessed as that they used during the experiment was measured at the end of the session using a Jamar Hand Dynamometer, with the grip position setting at 35 mm. The mean grip force applied by the twelve subjects was 85 N (standard deviation: 24 N).

For the MINIMUM, LIGHT, and TIGHT conditions, the subjects were instructed to grasp the test rig handles with both hands in the UPPER position at a required gripping force: at minimum grip force (only just in contact with the handle surface), at 50 N, and at 100 N, respectively. The subjects familiarised themselves with the required force prior to the tests using the Jamar Hand Dynamometer. They were asked to maintain the required gripping force throughout each test. The test conditions are summarised in Table 1.

Prior to the magnitude estimation tests, two types of practice judgement were obtained from each subject in order to familiarise them with the procedure and the vibration stimuli: (i) the magnitude estimation of the lengths of lines; (ii) magnitude estimation of a few selected vibration test stimuli, as suggested by Hiramatsu and Griffin (1984).

TABLE 1 ABOUT HERE

4.1.2 Analysis

The relationship between sensation magnitude, ψ, and vibration magnitude, φ, was determined for each frequency using Stevens' Power law with an additive constant representing the threshold (Ekman, 1961), assuming no sensation below the perception threshold:

$$\psi = k(\varphi - \varphi_0)^n \qquad (1)$$

where k is a constant, φ_0 is the perception threshold, the exponent n describes the rate of growth of sensation with vibration magnitude, φ. The median perception threshold for each subject as determined in Experiment 1 was used in the calculations. Perception thresholds at the preferred 1/3 octave frequencies were estimated by interpolation between the thresholds plotted with logarithmic scales of frequency and vibration magnitude. The growth of sensation, n, and the constant, k, were determined by performing a linear regression at each frequency (see Fig. 4 for examples) by transforming Equation 1 to:

$$\log_{10}\psi = n \log_{10}(\varphi-\varphi_0) + \log_{10}k \qquad (2)$$

FIG. 4 ABOUT HERE

4.2 Results and discussion

4.2.1 Growth of sensation

The median rate of growth of sensation with vibration magnitude, n, the median constant, k, and the median perception thresholds (determined or estimated from the results of Experiment 1), φ_0, for each frequency determined from the five conditions are listed in Table 2. Figure 5 shows the effect of hand position and grip force on the rate of growth of sensation. It is seen that the growth of sensation depended on vibration frequency, with generally the highest exponent at 31.5 Hz for all five contact conditions (an average exponent of 1.04) with a systematic decrease in exponent with increasing frequency from 31.5 to 125 Hz. The trend is consistent with results from a study by Morioka and Griffin (2006) who found a systematic decrease in the rate of growth of sensation as the frequency increased above 16 Hz with vertical and lateral vibration and increased above 50 Hz with fore-and-aft vibration of a hand grasping a 30 mm-diameter cylindrical handle.

There were no significant differences in the rates of growth of sensation between the two hand positions (i.e. UPPER and LOWER) except at 8, 10, and 12.5 Hz (Wilcoxon, $p<0.05$) where the UPPER position showed a reduced rate of growth of sensation. There were also no significant differences in the rate of growth of sensation between the three grip forces (i.e. MINIMUM, LIGHT and TIGHT) except at 125 and 250 Hz (Friedman, $p<0.05$) where the rate of growth of sensation decreased with increasing grip force. Increased grip force applied to the handle would be expected to produce increased transmission of vibration around the area in contact with the vibrating surface particularly at high frequencies and increase the number of active fibres. This is consistent with the theory by Verrillo and Capraro (1975) in which the greater the number of activated fibres the lower the slope.

TABLE 2 ABOUT HERE

FIGURE 5 ABOUT HERE

4.2.2. Equivalent comfort contours

Equivalent comfort contours were determined by expressing acceleration magnitudes, φ , as a function of vibration frequency for each subjective magnitude, ψ , (from 25 to 300 in steps of 25), and are shown for the UPPER and LOWER hand positions in Fig. 6 and for the MINIMUM, LIGHT and TIGHT grip conditions in Fig. 7. The equivalent comfort contours illustrate the vibration magnitudes required to produce the same sensations across the frequency range. They provide information on which frequencies produce greatest discomfort (a lower vibration magnitude at a particular frequency indicates greater discomfort at that frequency). Any absolute differences in discomfort between the two hand positions and between the three grip conditions were not investigated in this study.

Within each of the five conditions, there is a frequency-dependence in the equivalent comfort contours but the frequency-dependence varies with vibration magnitude. At low vibration magnitudes (below about 0.5 ms^{-2} r.m.s.), there is increased sensitivity to vibration acceleration with increasing frequency from 20 to 125 Hz. At high vibration magnitudes (greater than about 1.0 ms^{-2} r.m.s.), there is decreased sensitivity to vibration acceleration with increasing frequency from 20 to 125 Hz. For example, 1.0 ms^{-2} r.m.s. of steering wheel vibration produced stronger sensations at 16 Hz than at 125 Hz, whereas 0.2 ms^{-2} r.m.s. of steering wheel vibration produced stronger sensations at 125 Hz than at 16 Hz. At vibration magnitudes between about 0.6 and 0.8 ms^{-2} r.m.s., sensitivity to steering-wheel vibration acceleration is almost independent of frequency.

The magnitude-dependence of the comfort contours may be evidence of different psychophysical channels being responsible for magnitude estimates at different frequencies and different magnitudes. At magnitudes close to perception thresholds (less than about 0.5 ms^{-2} r.m.s.), the sensation of steering wheel vibration was probably determined by the Pacinian channel at frequencies greater than about 16 or 20 Hz and by a non-Pacinian (NP) channel (most likely NP I channel) at frequencies less than about 16 or 20 Hz. At high vibration magnitudes, greater than about 1.0 ms^{-2} r.m.s., the change in the shape of comfort contours (diminished U-shaped portion of the comfort contours at high frequencies) as seen in Figs 6 and 7 may reflect the involvement of other psychophysical channels. This speculation is consistent with a study of masked thresholds determined with vibration of the whole hand on a rigid flat vibrating plate where individual thresholds for P, NP and NP II channels were found to be less than 30 dB above the absolute thresholds (Morioka and Griffin 2005a). With vertical vibration at 125 Hz, the threshold of the NP I channel (FA I) was found at approximately 1.0 ms^{-2} r.m.s., with the Pacinian channel (FA II) mediating the perception of vibration below this magnitude. Although this is consistent with the involvement of several tactile channels over the range of vibration magnitudes and frequencies in the present experiment, it does not identify whether the sensations at any the higher magnitudes are produced by the mediation of a single channel or the combined mediation of two or more channels.

While there are no obvious differences in the shapes of the equivalent comfort contours obtained with the UPPER and LOWER hand positions, the equivalent comfort contours show some dependence on grip force. Increased sensitivity with increased contact force at high frequencies (greater than 63 Hz) was observed only at low vibration magnitudes (e.g. at perceived intensities less than 100). This might be related to spatial summation in the Pacinian channel, resulting in an increased number of active fibres when there is increased transmission of vibration in the vicinity of the skin in contact with the vibrating surface. It is reported by Harada and Griffin (1990) that Pacinian thresholds at the fingertip (determined with a 7-mm diameter circular probe within a 10-mm diameter surround) reduced with increasing contact force from 1 N to 2 N, but not from 2 N to 3 N. Their results are consistent with those of Lamoré and Keemink (1988) who found maximum sensitivity with 0.7 N static force (using a 13.8-mm diameter probe within a 15.8-mm diameter surround), corresponding to a contact pressure of 0.47 N/cm^2. Brisben *et al.* (1999) found no effects of variations in force from 0.05 to 1.0 N on absolute thresholds at the palm or the fingertip when using vibration stimuli perpendicular to the skin surface presented via a 32-mm diameter circular cylinder (i.e. without a surround). They speculated that thresholds would be lower if the force was increased from 1 N to 2 N – because vibration may be transmitted via bones and tendons to more distant Pacinian corpuscles and spatial summation would lower thresholds. The absence of an effect of grip force at high magnitudes in the present results may reflect the dominance of tactile channels other than the Pacinian channel in the perception of high magnitudes.

FIG. 6 ABOUT HERE

FIG. 7 ABOUT HERE

5. General discussion

With each of the hand conditions investigated, the perception threshold contours and the equivalent comfort contours indicate that sensitivity to steering wheel vibration is greatly dependent on vibration frequency. The frequency-dependence is consistent with mediation by the Pacinian (FA II) channel for low magnitudes at frequencies greater than about 16 or 20 Hz and mediation by non-Pacinian channels for frequencies less than about 16 or 20 Hz and for high magnitudes at higher frequencies. Although at some magnitudes the sensitivity to acceleration was approximately independent of frequency, it should be generally assumed that the frequency-dependence of perception must be taken into account and that the prediction of human perception of steering wheel vibration will require the application of a frequency weighting.

International Standard (ISO 5349-1, 2001) defines a single frequency weighting, W_h, for the evaluation of human exposure to hand-transmitted vibration in any axis. The W_h frequency weighting indicates greatest sensitivity to acceleration at frequencies between 8 and 16 Hz, with sensitivity to acceleration reducing in proportion to frequency at frequencies greater than 16 Hz. The $W_{h,}$ weighting was influenced by equivalent comfort contours determined by Miwa (1967) over the frequency range 3 to 300 Hz with the hand pressing on a flat plate.

The equivalent comfort contours determined in the present study were inverted, normalised to the same vibration acceleration at 8 Hz, and overlaid with frequency weighting W_h for the two hand positions (Fig. 8) and for the three grip forces (Fig. 9). The comparisons are shown for a range of vibration magnitudes (equivalent to subjective magnitudes of 50, 100, 200 and 300 where 100 corresponds to the strength of sensation produced by 0.4 ms^{-2} r.m.s. at 31.5 Hz). Between 4 Hz and 16 Hz, the weightings from the present results is somewhat similar to the flat weighting from 8 to 16 Hz in the W_h weighting, although the W_h weighting slightly overestimates sensitivity to steering wheel vibration between 8 and 16 Hz for some conditions. Between 16 and 250 Hz, the W_h frequency weighting generally underestimates sensitivity to vibration (or, conversely, the weighting W_h overestimates the sensations caused by lower frequencies). This inconsistency between the W_h weighting and the frequency weightings implied by the present results is greatest at the lowest sensation magnitudes. The variation in the shape of the equivalent comfort contours with vibration magnitude means that no one weighting will be suitable at all magnitudes. Nevertheless, frequency weighting W_h does not appear to be optimum for predicting sensitivity to hand-transmitted vibration for any of the conditions studied here.

FIG. 8 ABOUT HERE

FIG. 9 ABOUT HERE

With a real steering wheel, the direction of vibration relative to the hand depends on the position of the hands on the wheel. In the present study, the direction of the vibration on the cylindrical handles was vertical (with reference to gravity), which means the vibration was partly perpendicular and partly parallel to the hand-handle interface. Some sensations may have arisen from shear movement of the skin. Absolute thresholds for perception and equivalent comfort contours for hand-transmitted vibration in each of three axes (fore-and-aft, lateral, and vertical) over the frequency range 8 to 400 Hz have been determined by Morioka and Griffin (2006). Frequency weightings derived from the comfort contours did not differ greatly between the three axes, but absolute perception thresholds differed between the axes, implying the involvment of different tactile channels in the different axes at vibration magnitudes close to perception thresholds. Westling and Johansson (1987) recorded impulses in single tactile units innervating the human glabrous skin while an object was lifted, positioned in space and replaced using a precision grip between the fingers and thumb. It was found that most SA II fibres (NP II channel) were excited by skin deformation or stretch caused by grip forces and load forces while grasping the object, suggesting that the SA II fibres may play a role in regulating force coordination. Although the present study does not allow identification of tactile channels at supra-threshold levels, the SA II fibres may be involved in the perception of steering wheel vibration by mediating lateral vibration as well as grasping and registering manipulative forces.

6. Conclusions

Absolute threshold for vertical vibration determined over the frequency range 4 to 250 Hz with two hand positions on a steering wheel (UPPER and LOWER) showed frequency-dependent vibration thresholds. The thresholds were likely to have been mediated by the Pacinian channel at frequencies greater than 16 or 20 Hz and by non-Pacinian channels at frequencies less than 16 or 20 Hz. At 4 Hz, thresholds with the UPPER hand position were higher than those with the LOWER hand position, whereas at 250 Hz, thresholds with the UPPER hand position were lower than those with the LOWER hand position. The differences in threshold between the two positions may be due to different areas of contact between the hand and the steering wheel in the two positions.

Equivalent comfort contours for steering wheel vibration determined over a range of frequencies (4 to 250 Hz) and magnitudes (0.1 to 1.58 ms^{-2} r.m.s) were strongly dependent on vibration magnitude and, to a lesser extent, on grip force, but showed little dependence on hand position. At magnitudes greater than about 1.0 ms^{-2} r.m.s., the sensitivity to acceleration decreased as the vibration frequency increased above 20 Hz. At magnitudes less than about 0.5 ms^{-2} r.m.s., the sensitivity to acceleration increased with increasing frequency. The changes in the shapes of the equivalent comfort contours with vibration magnitude might be due to multiple channels being responsible for the mediation of perception at supra-threshold levels. The results indicate that no single frequency weighting will provide a good prediction of the discomfort caused by vertical steering wheel vibration. The currently standardised frequency weighting, W_h, does not provide a good prediction of the perception of steering wheel vibration at magnitudes less than about 1.5 ms^{-2} r.m.s., .

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FIGURE CAPTIONS

FIG. 1 The two hand positions (UPPER and LOWER) and a steering wheel rig employed in the study.

FIG. 2 The sitting postures with the test rig for the two hand positions (UPPER and LOWER).

FIG. 3 Median absolute perception thresholds determined for each of the three axes between 4 and 250 Hz, shown in acceleration (top graph) and in displacement (bottom graph). The error bars represent inter-quartile range. The same vibration frequency (4, 8, 16, 31.5, 63, 125, and 250 Hz) was applied for both conditions (UPPER and LOWER).

FIG. 4 Examples of linear regression for 5 Hz and 125 Hz data (UPPER) using Equation 1 (top graphs). The data are then converted into sensation magnitudes, ψ, as a function of vibration magnitudes, φ (bottom graphs) in the vertical axis. φ_0 = 0.08 ms^{-2} r.m.s (5 Hz), 0.023 ms^{-2} r.m.s. (125 Hz).

FIG. 5 Effect of hand position (top graph) and grip force (bottom graph) on growth of sensation (median exponent, *n*).

FIG. 6 Equivalent comfort contours for sensation magnitudes from 25 to 300 (relative to reference of 0.4 ms^{-2} r.m.s. at 31.5 Hz) for each of the two hand positions calculated from Equation 1. Median absolute perception threshold contour for each axis determined in Experiment 1 are also overlaid. Dotted lines indicate the range of stimuli investigated in this study (equivalent comfort contours beyond these lines were determined by extrapolation of the regression lines).

FIG. 7 Equivalent comfort contours for sensation magnitudes from 25 to 300 (relative to reference of 0.4 ms^{-2} r.m.s. at 31.5 Hz) for each of the three grip conditions calculated from Equation 1. Dotted lines indicate the range of stimuli investigated in this study (equivalent comfort contours beyond these lines were determined by extrapolation of the regression lines).

FIG. 8 Frequency weightings (inversed form of comfort contours normalised at 8 Hz) for sensation magnitudes of 50, 100, 200 and 300, determined from UPPER and LOWER positions. The results are compared with the W_h frequency weighting from ISO 5349-1 (2001).

FIG. 9 Comparison of frequency weightings (inversed form of comfort contours normalised at 8 Hz) between the tree grip conditions for sensation magnitudes of 50, 100, 200 and 300 relative to vibration magnitude at 0.4 ms^{-2} r.m.s. of 31.5 Hz. The results are compared with the W_h frequency weighting from ISO 5349-1 (2001).

TABLES

Table 1.

Summary of experimental conditions for Experiment 2.

	Effect of hand position		**Effect of grip force**		
	UPPER	**LOWER**	**MINIMUM**	**LIGHT**	**TIGHT**
Hand position	Upper position	Lower position	Upper position		
Grip force	Normal grip (mean, 86 N)		Minimum grip	50 N	100 N
Test frequency	4-250 Hz (1/3 octave step)		4-250 Hz (1 octave step)		
Reference frequency	31.5 Hz				
Reference magnitude	0.4 ms^{-2} r.m.s.				
Test magnitude	0.1-1.58 ms^{-2} r.m.s. (3 dB steps)				
Auditory white noise masking	65 dB(A)				

Table 2.

Median exponent (*n*), constant (*k*) and additive constant (= threshold, φ_0) for the five conditions determined from the Eq. (1).

Frequency	**Exponent (*n*)**					**Constant (*k*)**					**Threshold (φ_0)**	
	UPPER	**LOWER**	**MINIMUM**	**LIGHT**	**TIGHT**	**UPPER**	**LOWER**	**MINIMUM**	**LIGHT**	**TIGHT**	**UPPER**	**LOWER**
4	0.649	0.691	0.938	0.865	0.778	223.7	270.3	238.3	222.0	225.2	0.080	0.053
5	0.779	0.668				260.4	234.5				0.080	0.063
6.3	0.786	0.661				234.4	188.8				0.079	0.073
8	0.710	0.954	0.700	0.777	0.720	255.4	230.1	204.4	220.0	215.9	0.081	0.086
10	0.573	0.881				219.8	211.6				0.091	0.102
12.5	0.595	1.154				179.6	204.8				0.102	0.120
16	0.653	0.698	0.766	0.777	0.727	188.5	162.0	183.7	183.0	170.6	0.115	0.142
20	0.873	1.045				186.3	173.2				0.101	0.124
25	1.020	1.198				211.2	197.4				0.089	0.108
31.5	0.895	0.879	1.035	1.230	1.162	185.6	166.8	194.4	198.1	195.5	0.079	0.094
40	0.770	0.850				162.3	181.7				0.062	0.070
50	0.623	0.718				163.9	162.8				0.048	0.052
63	0.544	0.503	0.513	0.527	0.550	177.9	155.1	148.3	164.6	161.3	0.038	0.039
80	0.366	0.488				158.1	166.2				0.032	0.035
100	0.371	0.371				161.3	161.3				0.027	0.031
125	0.283	0.467	0.608	0.439	0.279	157.0	156.9	147.5	158.9	154.1	0.023	0.027
160	0.326	0.401				163.8	160.7				0.028	0.033
200	0.433	0.461				165.3	162.5				0.034	0.040
250	0.419	0.572	0.674	0.435	0.453	143.4	157.6	122.1	140.3	157.0	0.041	0.049

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Fig.1

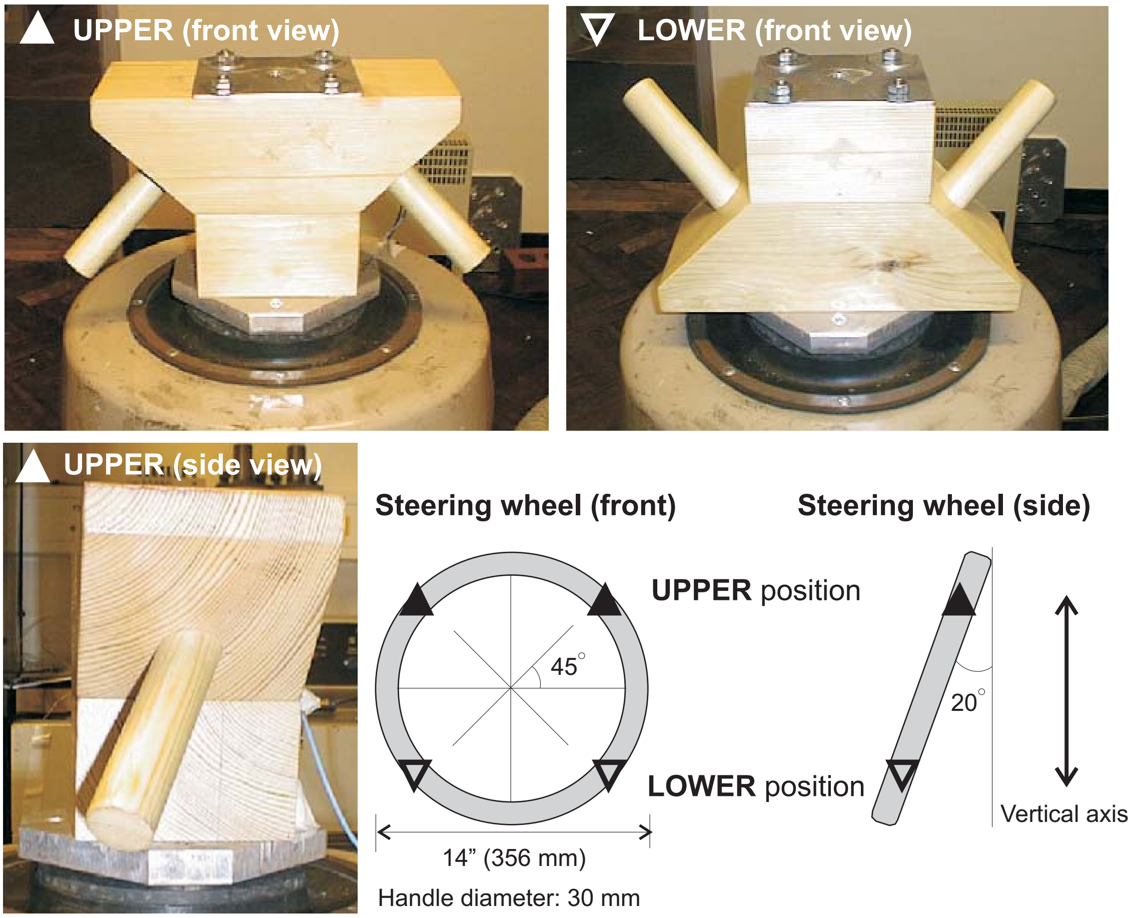

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Fig.2

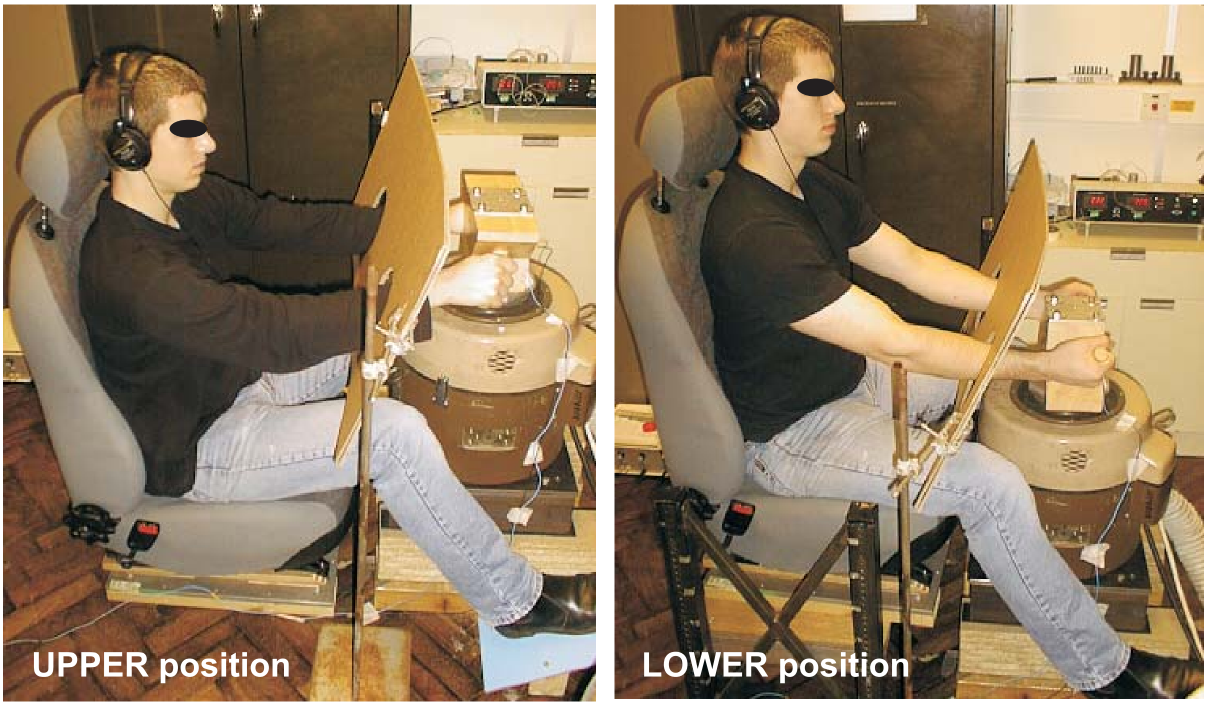

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Fig.3

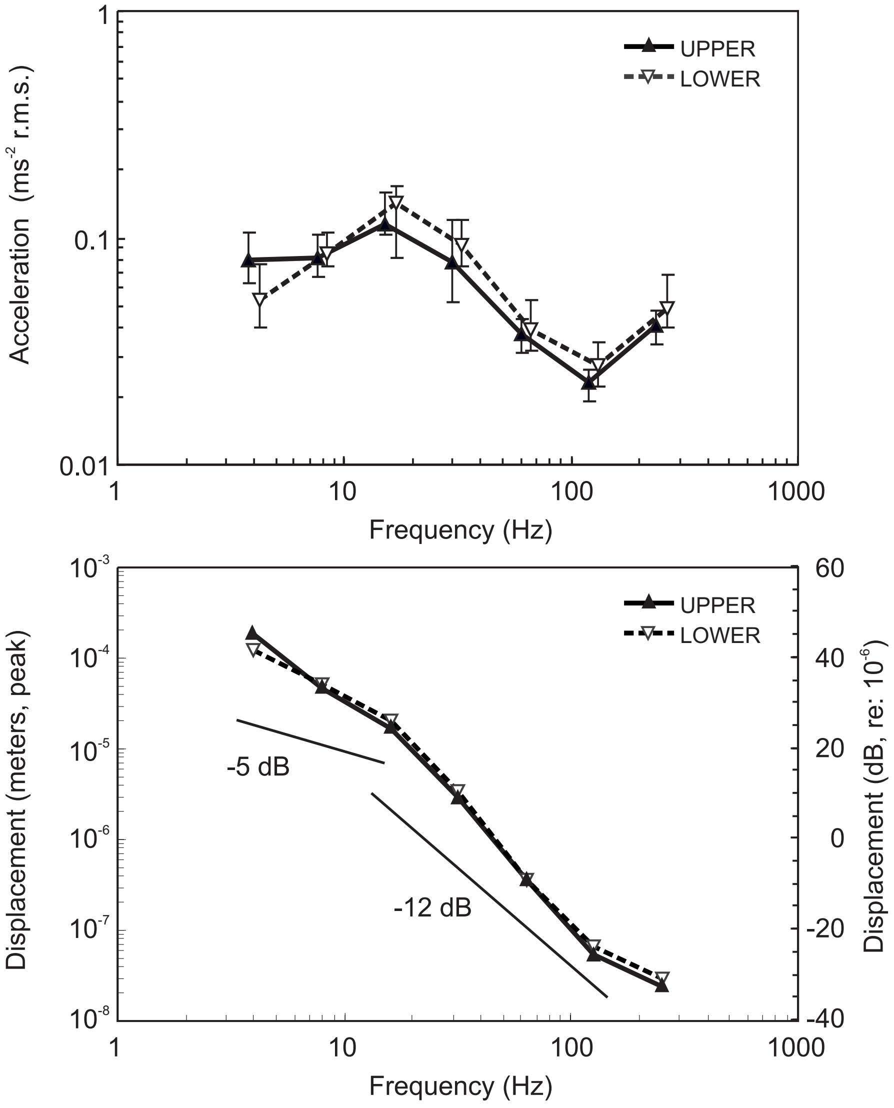

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Fig.4

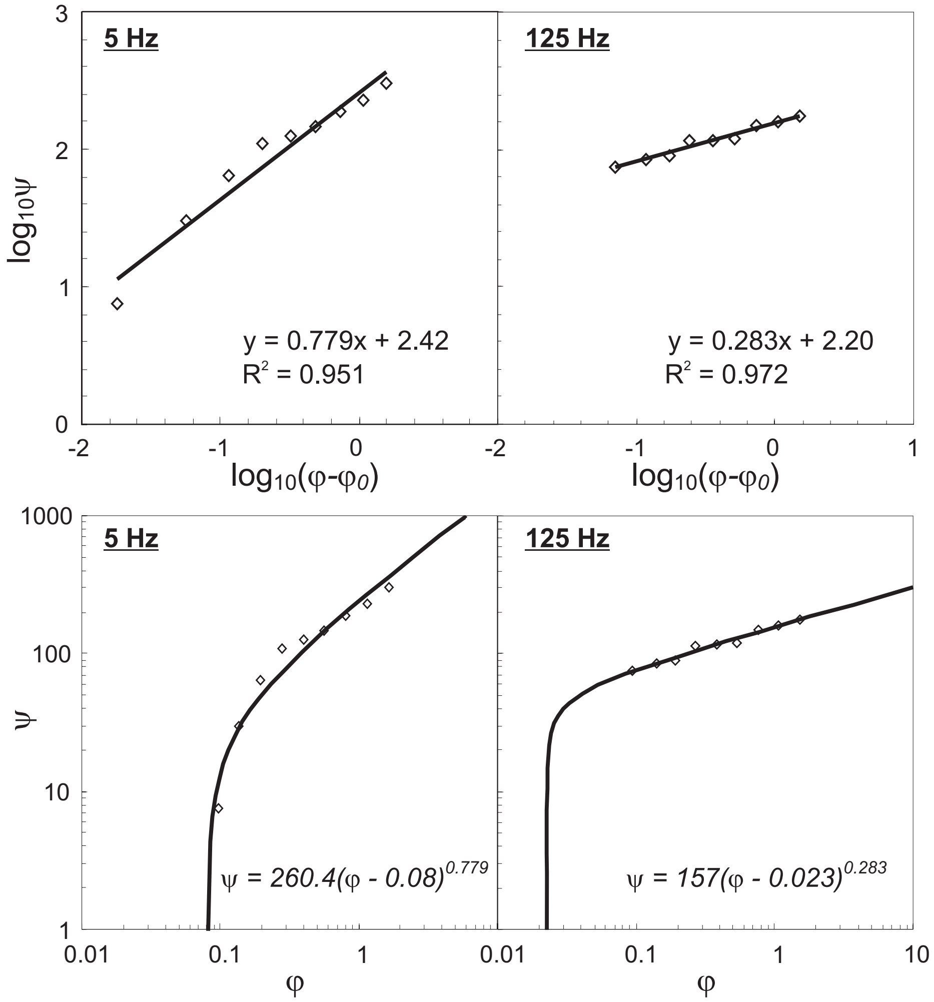

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Fig.5

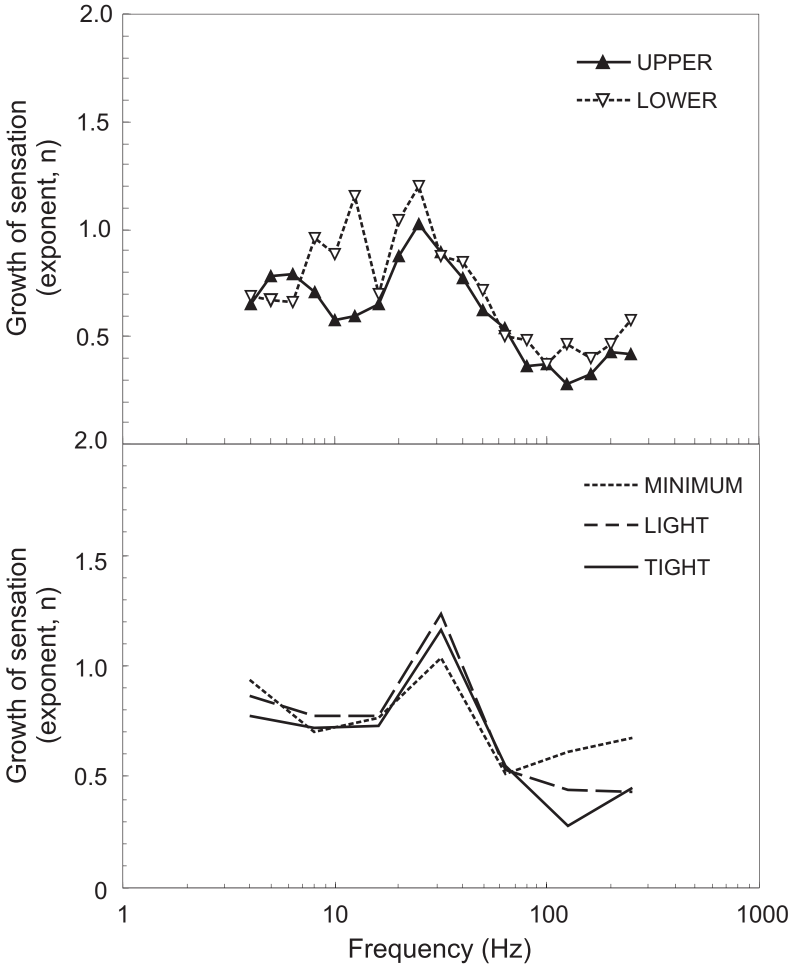

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Fig.6

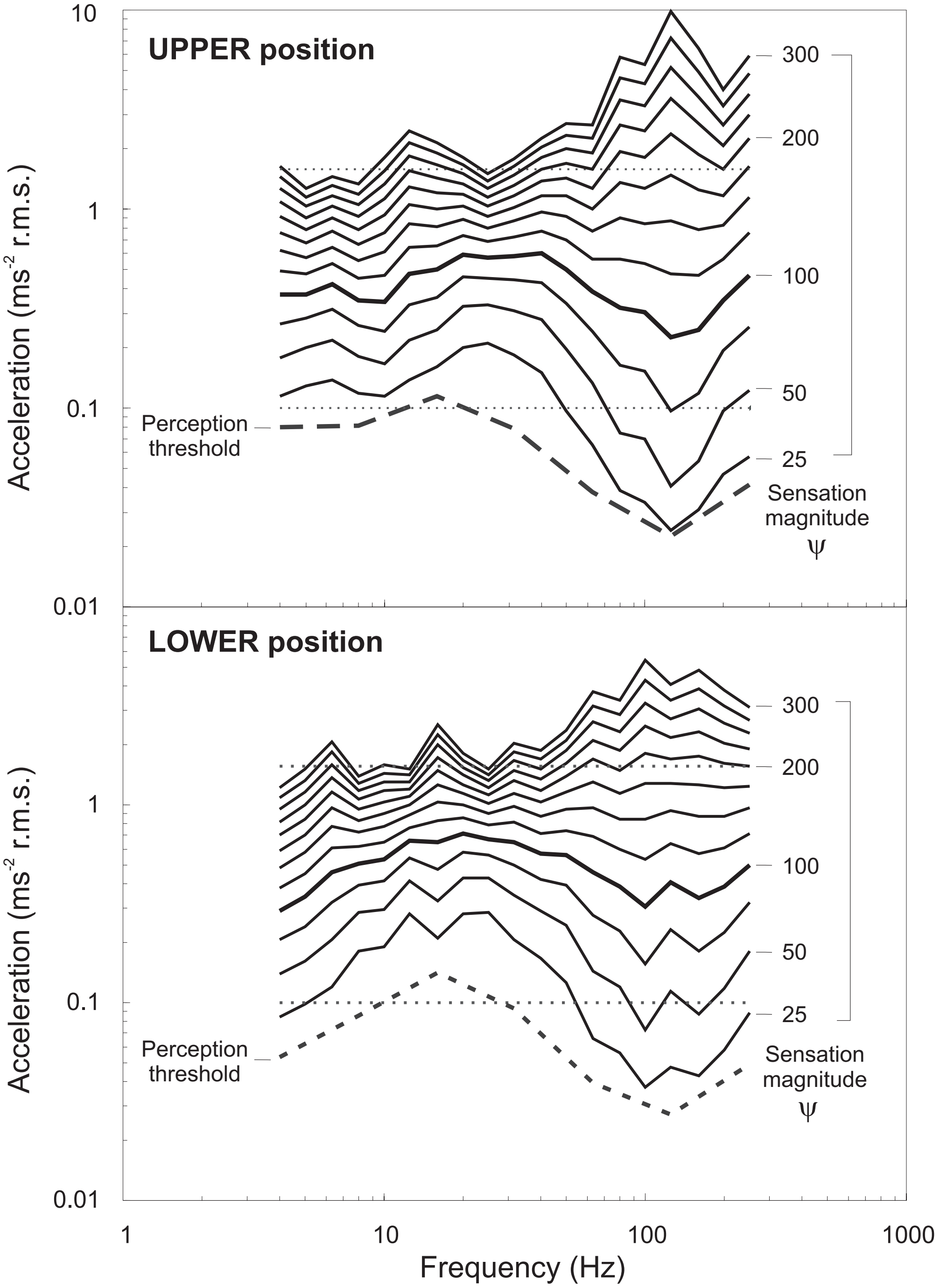

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Fig.7

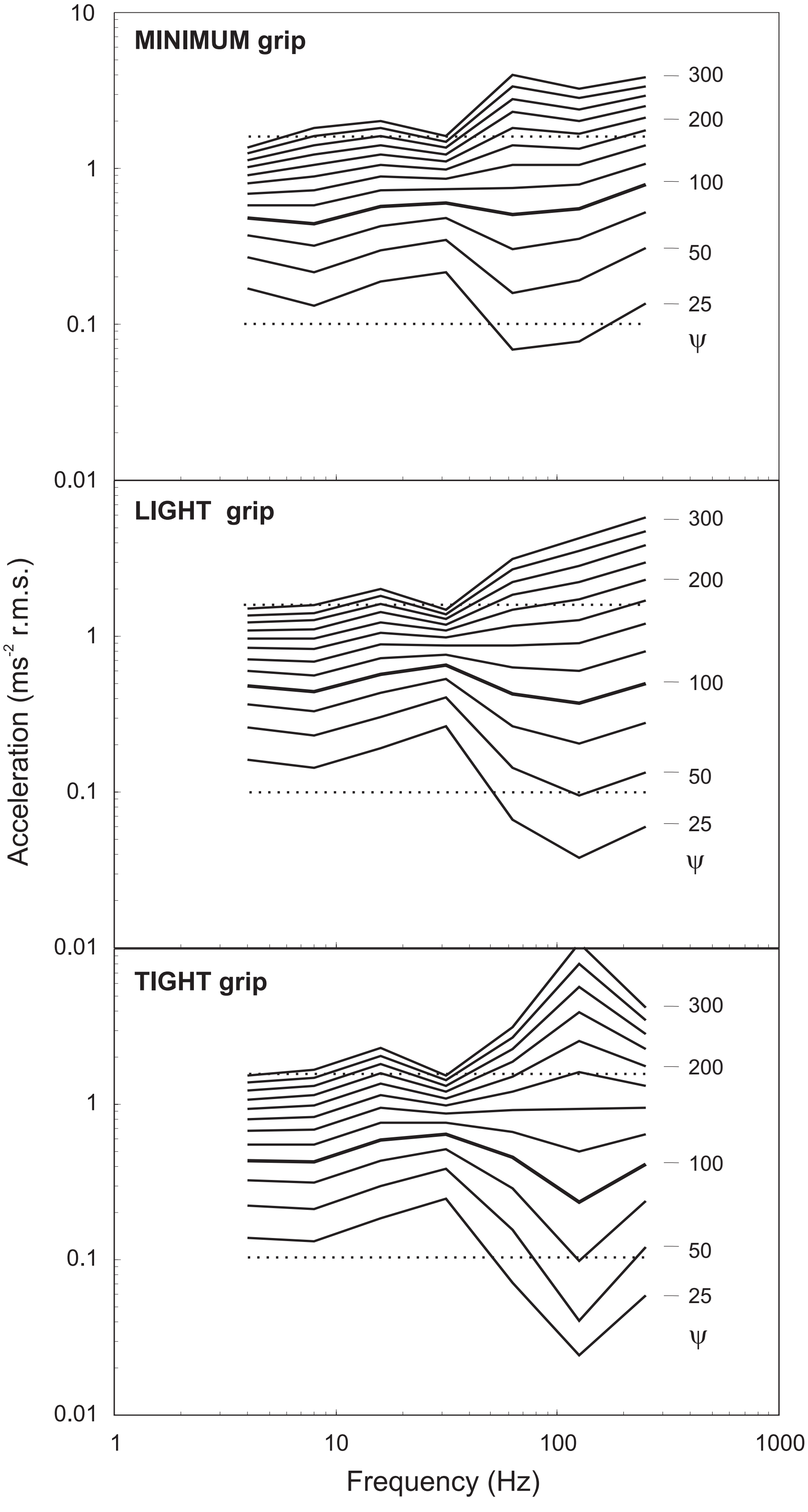

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Fig.8

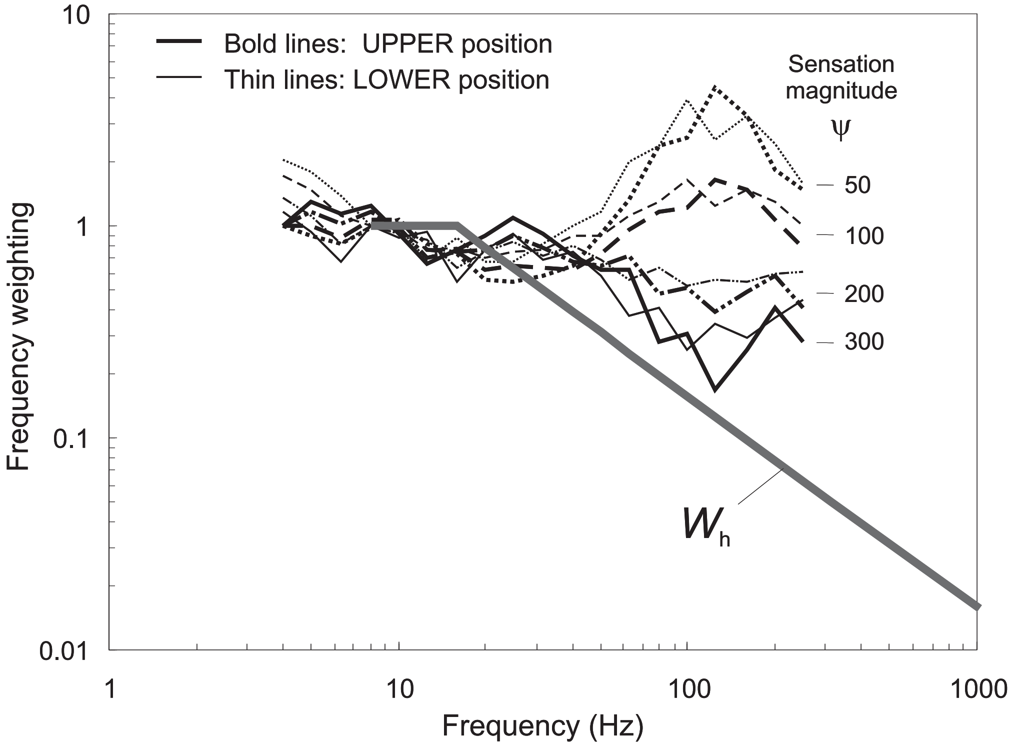

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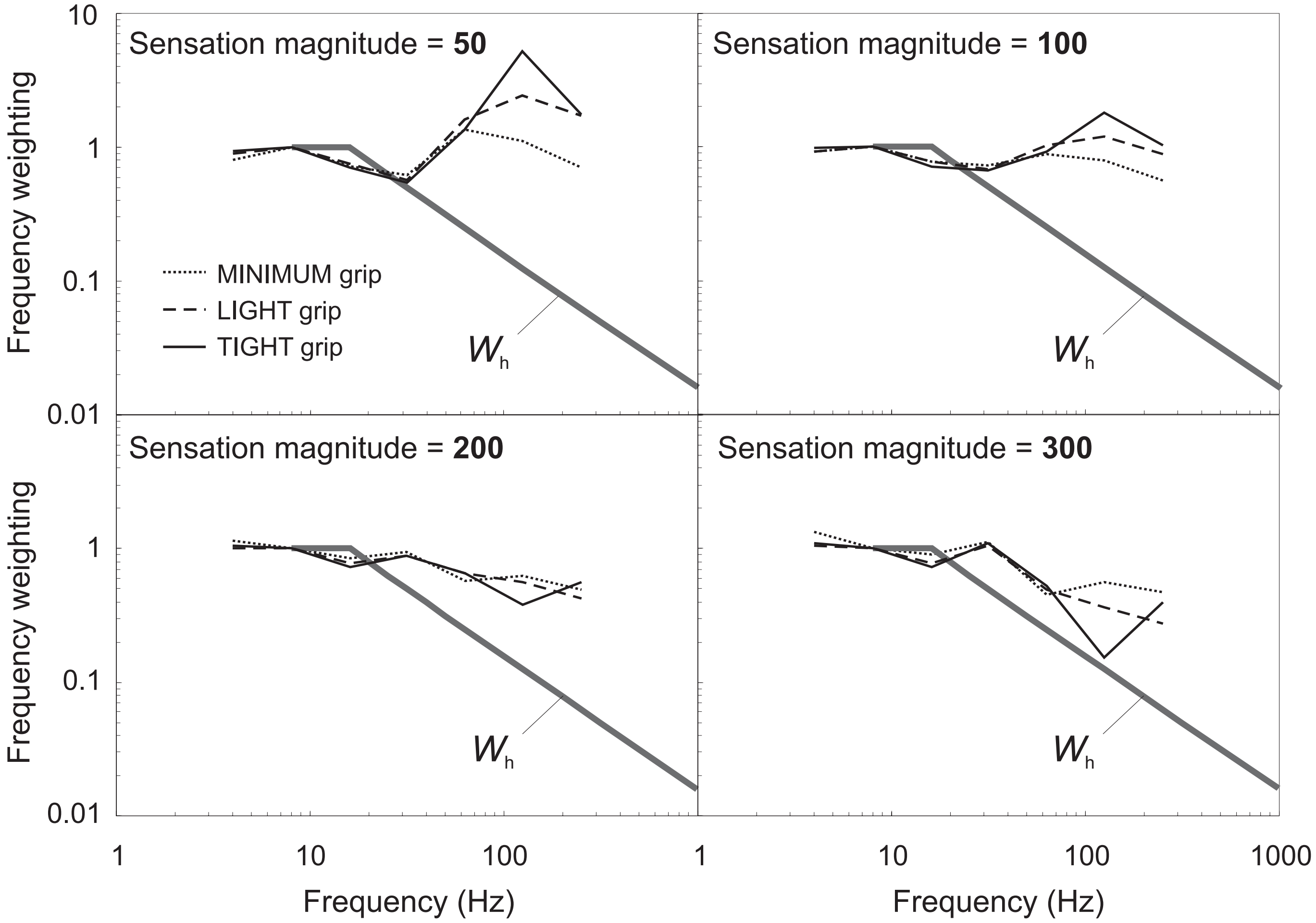
Fig.9



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