Frequency dependence of perceived intensity of steering wheel vibration: effect of grip force

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Abstract

Vehicle drivers receive haptic feedback in response to their movement of the steering wheel and tactile feedback from various sources of vibration of the steering wheel, with the sensations varying depending on the frequency and the magnitude of the movements. From an experiment with 12 subjects, equivalent comfort contours were determined for vertical vibration of the hands with three grip forces. The perceived intensity of vibration on a rigid steering wheel was determined using the method of magnitude estimation at seven frequencies (4 to 250 Hz) over a range of vibration magnitudes (0.1 to 1.58 ms⁻² r.m.s). The comfort contours strongly depended on vibration magnitude, indicating that a frequency weighting for predicting sensation should be dependent on vibration magnitude. At low magnitudes, increased grip force increased sensitivity at high frequencies and enhanced the frequency-dependence of the equivalent comfort contours. The results may be explained by the characteristics of the Pacinian and non-Pacinian tactile channels in the glabrous skin of the hand.

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 may also influence driver perception of ride comfort. The sources of steering wheel vibration include the engine, the wheels and the tires, as well as the road surface. These result in various patterns of vibration transmitted to the steering wheel through the steering shaft. The perceived intensity of hand-transmitted vibration is dependent on the frequency of vibration [1-3] and the frequency-dependence of subjective judgments of vibration (e.g., equivalent comfort contours) may depend on the magnitude of vibration [4].

Of four classes of mechanoreceptive afferent fibers in the glabrous skin of the hand, two are fast adapting (i.e. FA I and FA II fibers) and two are slow adapting (SA I and SA II fibers) [5]. The Pacinian (P) channel has distinctive characteristics: spatial and temporal summation and a dependence on skin temperature [6], and is associated with the FA II fibers [7-8]. The non-Pacinian (NP) channels are considered to include the FA I, SA II and SA I fibers (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 [9-10]. Studies have demonstrated tuning curves for thresholds of vibrotactile perception for each of the four tactile channels in the glabrous skin of the hand [11-12]. 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.

The hand-arm system has a complex dynamic response that varies between individuals and is dependent on the direction of vibration excitation, the grip force, muscle tension, and the position of the arm. Of these factors, grip force has been found to be one of the most influential variables [13].

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 growth of sensation as a function of intensity of vibrotactile stimuli [14-15]. However, little is known about how the frequency-dependence of sensitivity (i.e. the shapes of equivalent comfort contours) depends on grip force.

This study was conducted to assist the development of a method for predicting the perception of steering wheel vibration, taking into account the effect of grip force on the frequency-dependence of the perception of vibration applied to the hands.

2. Method
2.2. Apparatus

A test rig was designed and constructed to simulate steering wheel vibration over the required frequency range. The rig had a wooden base clamped between two aluminum plates 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, with the handles orientated at 45 degrees to the horizontal in the coronal plane and 20 degrees to the vertical in the sagittal plane (see Figure 1).

Vibration was measured using two piezoelectric accelerometers (orientated in the vertical and fore-aft directions) attached to the wooden base and were monitored and controlled by a computer during the experiment. Vibration on the cylindrical handles was measured in advance: differences in magnitude between the wooden base and the cylindrical handles (while grasped by the hands) were less than 5% (less than 10% at frequencies greater than 125 Hz). The direction of excitation and the measured vibration was defined with reference to gravity (i.e. vertical).

Subjects sat in a car seat with an adjustable backrest inclination. Wooden footrests (295 mm x 195 mm) were fixed to the floor beside the vibrator base with an angle of 30 degrees to the floor. The distance between the seat and the cylindrical handles was adjustable.

![Hand position](image)

**Fig. 1.** Hand position (marked as ▲) and the test rig simulating a hand grip on a circular steering wheel.

2.3. Stimuli and procedure

The perceived intensity of vibration was 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 were randomly presented from a range of frequencies from 4 to 250 Hz (in one octave steps) over the magnitude range from 0.1 to 1.58 ms\(^{-2}\) r.m.s. in 3 dB steps. The task of the subjects was to assign a number that represented the perceived intensity of the test motion relative to the reference motion, assuming the intensity caused by the reference motion corresponded to '100'.

The magnitude estimation test was repeated with three grip conditions (i.e., MINIMUM, LIGHT, and TIGHT conditions) presented in randomized order, in which the subjects were instructed to grasp the test rig handle at a required gripping force: no grip force (only just in contact with the handle surface), at 50 N, and 100 N, respectively. The subjects familiarized themselves with the required force prior to the tests using the Jamar Hand Dynamometer that has an accuracy of 5 N, with the handle dimensions (ellipse in shape) of 34 mm x 25 mm. The subjects were asked to maintain the required gripping force throughout each test. The test conditions are summarized in Table 1.

Twelve healthy male subjects aged between 21 and 28 years (mean 24.6 years, standard deviation 2.7) with a mean stature of 1.79 m and a mean weight of 77.0 kg, participated in the experiment.

The skin temperature of the hand was measured at the beginning and end of each session using an HVLab Tactile Aesthesiometer (by means of thermocouples). The tests only proceeded if the skin temperature of the subject was greater than 29°C; the subjects were asked to warm their hands if the temperature was less than this criterion. The subjects were exposed to white noise at 65 dB(A) via a pair of headphones so as to prevent them hearing the vibration, although most of the stimuli were inaudible.

![Table 1](image)

**Table 1. Summary of experimental conditions.**

<table>
<thead>
<tr>
<th>Grip force</th>
<th>MINIMUM</th>
<th>LIGHT</th>
<th>TIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Frequency</td>
<td>31.5 Hz</td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>0.4 ms(^{-2}) r.m.s.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test frequency</td>
<td>4-250 Hz (1 octave steps)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test magnitude</td>
<td>0.1-1.58 ms(^{-2}) r.m.s. (3 dB steps)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Results

3.1. Rate of growth of sensation

The relationship between perceived intensity, $\psi$, and the vibration magnitude, $\varphi$, was established for each frequency using Stevens’ Power law with an additive constant [16] assuming no sensation below the perception threshold:

$$\psi = k(\varphi - \varphi_0)^n$$  \hspace{1cm} (1)

where $k$ is a constant, $\varphi_0$ is the perception threshold, the exponent $n$ describes the rate of growth of sensation with vibration magnitude, $\varphi$. The absolute perception thresholds determined previously [17] were used for calculation. The growth of sensation, $n$, and constant, $k$, were determined by performing a linear regression at each frequency by transforming Equation 1 to:

$$\log_{10} \psi = n \log_{10}(\varphi - \varphi_0) + \log_{10}k$$  \hspace{1cm} (2)

This relationship was a reasonable representation of the rate of growth of sensation ($r^2>0.83$).

Figure 2 shows the effect of 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 three grip conditions (an average exponent of 1.14) with a systematic decrease in exponent with increasing frequency from 31.5 to 125 Hz. This trend is consistent with results from a similar study that found a systematic decrease in the rate of growth of sensation as the frequency increased above 16 Hz in the vertical and lateral axes and as the frequency increased above 50 Hz in the fore-and-aft axis for hand-transmitted vibration with the hand grasping a 30 mm-diameter cylindrical handle [4]. There were no significant differences in the rate of growth of sensation between the three grip conditions (i.e. MINIMUM, LIGHT and TIGHT), except at 125 and 250 Hz (Friedman, $p<0.05$) with a tendency for the rate of growth of sensation to decrease with increasing grip force.

3.2. Equivalent comfort contours

Equivalent comfort contours were determined by expressing vibration magnitudes, $\varphi$ (in acceleration) as a function of vibration frequency for each subjective magnitude, $\psi$ (varying from 25 to 300 in steps of 25) for each of the three grip conditions and are shown in Figure 3. Dotted lines in Figure 3 indicate the range of stimuli investigated in this study (equivalent comfort contours beyond these lines were determined by extrapolation of the regression lines).

Fig. 2. Effect of frequency and grip force on median rate of growth of sensation.

Fig. 3. Equivalent comfort contours for perceived intensities from 25 to 300 (relative to reference of 0.4 ms$^2$ r.m.s. at 31.5 Hz) for the three grip conditions calculated from Equation 1. Median absolute perception thresholds from [17] are overlaid.
The equivalent comfort contours illustrate the vibration magnitudes required to produce the same sensations across the frequency range. A lower value at a particular frequency indicates greater perception of vibration intensity at that frequency.

The shapes of the equivalent comfort contours depend on the perceived intensity of vibration. With high perceived intensities (more than about 150), the equivalent comfort contours show decreased sensitivity to vibration acceleration with increasing frequency from 20 to 125 Hz. With low perceived intensities (less than about 100), the contours show increased sensitivity with increasing frequency from 20 to 125 Hz; similar in shape to the absolute perception threshold. It is expected that the equivalent comfort contours for low sensation magnitudes will be similar to the threshold contours, due to the employment of the linear regression method (Equation 2). The magnitude-dependence of the comfort contours implies that the relative perceived intensity of steering wheel vibration at different frequencies depends on the vibration magnitude. For example, at a magnitude of 1.0 ms\(^{-2}\) r.m.s., 16 Hz vibration produced a stronger sensation than 125 Hz, whereas at a magnitude of 0.2 ms\(^{-2}\) r.m.s., 125 Hz vibration produced a stronger sensation than 16 Hz.

In the frequency range 63 to 250 Hz the equivalent comfort contours are lower with increased grip force at low vibration magnitudes - those with magnitude estimates less than about 100 (i.e. those producing sensations no greater than that produced by 0.4 ms\(^{-2}\) r.m.s. at 31.5 Hz).

4. Discussion

The magnitude-dependence of the equivalent comfort contours may be evidence of different psychophysical channels being responsible for the subjective intensity of vibration at different magnitudes as well as at different frequencies. At magnitudes close to perception thresholds (e.g. less than about 0.5 ms\(^{-2}\) r.m.s.), the sensation of steering wheel vibration was probably mediated by the Pacinian system (FA II) at frequencies greater than about 20 Hz and by a non-Pacinian system (FA I and possibly SA II) at frequencies less than about 20 Hz. For vibration magnitudes greater than about 0.5 ms\(^{-2}\) r.m.s., the change in shape of the equivalent comfort contours at high frequencies suggests mediation by different receptors, such as NP II receptors (or possibly SA II receptors). This 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 FA II, SA II, and FA I receptors were found to be less than 30 dB above the absolute thresholds [18].

Increased sensitivity with increased contact force at high frequencies (greater than about 63 Hz) was observed only at low vibration magnitudes (e.g. less than perceived intensities of 100). This finding might be related to spatial summation in the Pacinian channel, resulting in an increased number of active fibers 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 [19] that Pacinian thresholds at the fingertip (determined with a 7-mm diameter circular probe with 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 [20] who found maximum sensitivity with 0.7 N static force (using 13.8-mm diameter probe with 15.8-mm diameter surround), corresponding to a contact pressure of 0.47 N/cm\(^2\). Brisben et al. [21] found no effects of variations in force from 0.05 to 1.0 N on absolute thresholds at the palm and 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 to 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 mediation of tactile channels other than the Pacinian channel.

The current International Standard for the evaluation of hand-transmitted vibration, ISO 5349-1 [22], and the former British Standard, BS 6842 [23], define 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 [1] 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, normalized to the same vibration acceleration at 8 Hz, and overlaid with frequency weighting \(W_h\) for the three grip conditions (Figure 4). 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). The differences between the \(W_h\)
weighting and the frequency weightings derived from the present results are 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. The frequency weighting \( W_h \) does not appear to be optimum for predicting the perception of steering wheel vibration with any of the grip forces investigated.

5. Conclusions

Contours representing the equivalent strength of sensation of steering wheel vibration depend strongly on vibration magnitude. At magnitudes greater than about 1.0 ms\(^2\) r.m.s., the sensitivity to acceleration decreases as the vibration frequency increases above 20 Hz. At magnitudes less than about 0.5 ms\(^2\) r.m.s., the sensitivity to acceleration increases with increasing vibration frequency. At frequencies greater than about 20 Hz, steering wheel vibration may be mediated by the Pacinian system (FA II). At frequencies less than about 20 Hz, perception may be mediated by a non-Pacinian system (FA I and possibly SA II) at magnitudes close to the vibration perception thresholds (less than about 0.5 ms\(^2\) r.m.s.). The change in the shape of the equivalent comfort contours with vibration magnitude might be due to mediation by different receptors being responsible for perception at different vibration magnitudes. The results indicate that the appropriate frequency weighting is dependent on vibration magnitude, and depends on the grip force applied to the steering wheel.

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References


