Human Fatigue Due to Automobile Steering Wheel Vibration

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Abstract

This study investigated the human fatigue caused by automobile steering wheel vibration. Discomfort data was collected from 15 subjects using a steering wheel vibration bench. A rigid wheel was used to apply sinusoidal rotational excitation of 0.08 m/s and 0.1 m/s amplitude at test frequencies of 4, 8, 16 and 32 Hz. Human discomfort was quantified after periods of 1, 5 and 10 minutes by means of a body part discomfort form. Significance testing showed that the discomfort ratings were dependent on vibration frequency, but not on vibration amplitude at a 5 % confidence level. Perceived discomfort was found to increase approximately linearly with increasing length of exposure, but the rate of increase was found to vary depending on the body region. Female subjects were found to perceive greater discomfort in the arm regions from 4 to 8 Hz than males, but no significant differences were found for the other body regions at $p<0.05$. On average, lighter subjects experienced greater discomfort than heavier subjects. Elbow angle was found to have no significant effect on perceived discomfort at $p<0.05$. The results suggest the importance of identifying the location of the discomfort when evaluating steering wheel vibration.

1 The Perception of Vibration in Automobiles

The sensations produced by the vibrational stimuli which reach the vehicle driver can provide important information regarding the dynamic state of the vehicle, but can also provide annoyance and discomfort. Figure 1 illustrates the three main interfaces across which a vehicle transmits tactile information to the driver, namely the foot interface (floor and pedals), the body interface (seat cushion and backrest) and the hand-arm interface (steering wheel and gearshift). Of these, the hand contact at the steering wheel plays an important role in transmitting both information and discomfort.

The area of research which investigates the vibrational and torque stimuli which inform the driver about the dynamic state of the vehicle can be termed that of *Perception Enhancement Systems*. The term Perception Enhancement System can be used to describe a device which optimises the feedback of vehicle movements and tyre-road dynamics to the driver. Such systems treat the vibrational stimuli from an information theoretic point of view, and thus are concerned with the optimisation of the man-machine interface so as to make the vehicle feel more like an extension of the driver's body. Current research is attempting to define the vibrational frequency bands which contain the information regarding the vehicle dynamic state, so that steering components can be designed to better transmit the information to the driver.

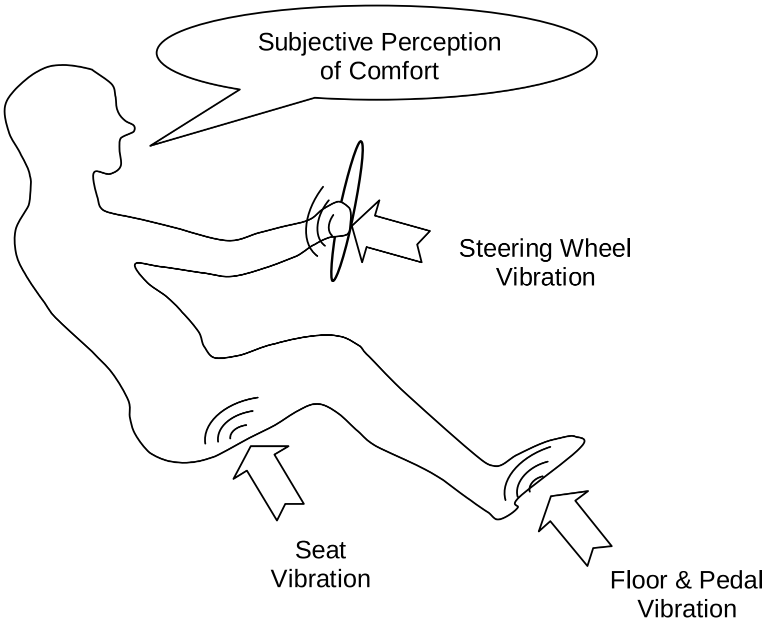


Figure 1) Vibration stimuli acting in the vehicle environment.

A second and more traditional area of research is that of vibrational discomfort. Numerous studies have been performed to investigate the interaction between vibrating surfaces and the hand-arm system [3,7]. Reynolds et al. [16-19] investigated hand-arm response to vibrating handles when held with either the palm or the fingers. Miwa [14] measured threshold and tolerance limits for subjects holding their palm flat against a vibrating surface. Reynolds and Soedel [18] investigated the dynamic response of the hand-arm system to translational sinusoidal vibrations in the frequency range from 20 to 500 Hz. They concluded that arm position had little effect on the impedance of the hand while grip tightness and hand pressure were found to influence vibration response at frequencies above 60 Hz. They also suggested that once a method of grip had been established, the hand-arm system could be treated as a linear system. Burstrom and Lundstrom [1] assessed the influence of vibration direction, grip force, vibration level, and hand-arm posture on the absorption of energy by the hand-arm system. They concluded that energy absorption was dependent mainly on the frequency and direction of vibration. Absorption increased with both higher energy levels and firmer handgrips. Burstrom and Lundstrom also stated that varying hand-arm postures produced only small changes in the absorption of the translational energy, while the size and mass of the subject's hand and arm greatly affected energy absorption.

More recently, Giacomin and Onesti [6] investigated the effect of frequency and grip force on the perception of steering wheel rotational vibration using 10 second exposures to sinusoidal test signals in the range from 4 to 125 Hz. Discomfort was highly dependent on frequency. Large amplitude movements of the hand-arm system were found at low frequencies, while higher frequencies tended to localise the vibration response to only those parts of the hand which were in the immediate vicinity of the steering wheel. 30 Hz was found to be roughly the frequency above which the response movements localised to the hand. Giacomin and Onesti produced iso-comfort curves for the frequency range from 8 to 125 Hz for the reference amplitudes of 1.86 and 5.58 m/s^2. They concluded that a linear iso-comfort weighting might be acceptable at 5-10 % accuracy for evaluating typical steering wheel vibration signals, and that grip tightness would not greatly effect the evaluation. Mechan and Versmold [13] performed an investigation using 30 subjects which produced iso-comfort curves for the frequency range from 4 to 32 Hz. Merchan and Versmold also analysed the effect of the length of the vibration exposure on the perceived discomfort. A summary table was presented which indicated the frequencies at which the individual body parts were most prone to suffer discomfort

The study described in this paper represents an extension of the previous research into the perception of steering wheel rotational vibration performed at Sheffield University. The objectives of the study were to investigate fully the effect of frequency in the range up to 32 Hz, and to analyse the importance of exposure duration.

2 Experimental Method

2.1 Test Equipment

The tests were performed using the bench shown in Figure 1, which consisted of a rigid steering wheel connected to a shaft supported by five precision bearings. The shaft incorporates a lever arm which is connected to an electrodynamic shaker unit by means of a stinger rod. All mechanical components were rigid to frequencies in excess of 80 Hz. The seat and guide-rail were taken from a Fiat Punto, and the bench geometric dimensions (see Table 1) were chosen based on data from European B-segment automobiles. Seat travel and seat height were adjustable as in the vehicle, and the bench incorporated a scale and pointer system to measure the distance of the H point from the steering wheel hub centre.

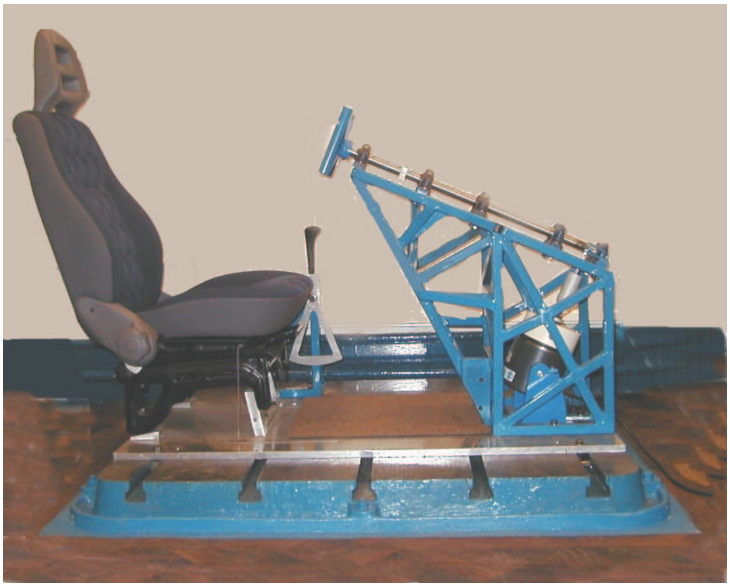


Figure 2) Steering wheel rotational vibration test bench

Geometric Parameter	Value
steering column angle with respect to floor	23°
steering wheel hub centre height above floor	700 mm
steering wheel diameter	325 mm
horizontal distance from h point to steering wheel hub centre	390–450 mm
Seat h point height from floor	275 mm

Table 1) Bench geometric dimensions which effect sitting posture

The bench incorporated a G&W V20 electrodynamc shaker driven by a PA 100 amplifier [5], with internal sine wave generator. The acceleration obtained at the steering wheel was measured using an Entran EGAS-FS-25 accelerometer located on the top left side of the steering wheel. The accelerometer signal was amplified by means of an Entran MSC6 signal-conditioning unit [4] and monitored by means of a Tektronix TDS210 digital oscilloscope [21]. The experimental layout is illustrated in Figure 3.

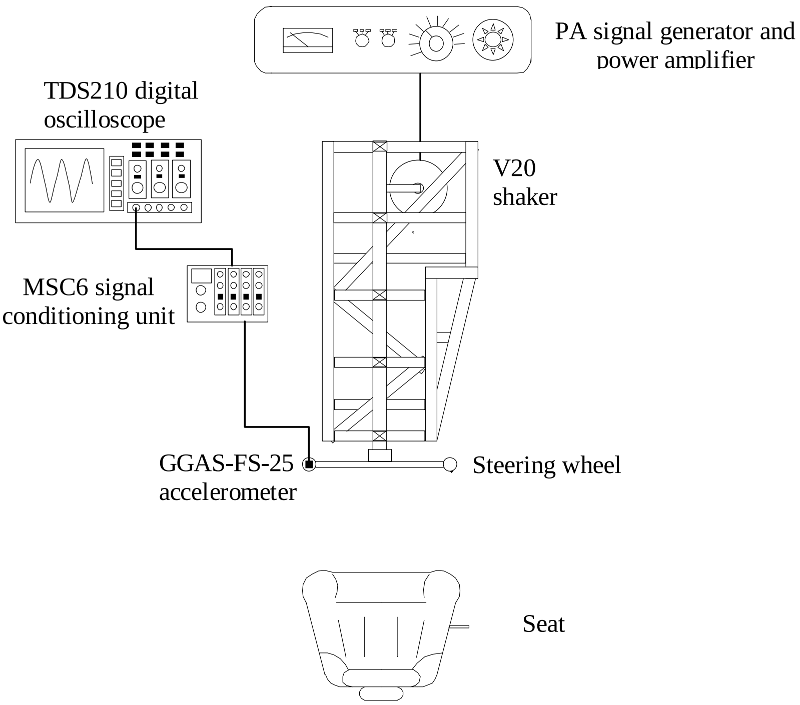


Figure 3) Experimental layout

2.2 Test Frequencies and Amplitudes

Previous research [6] showed that at frequencies below about 30Hz subjects perceived vibrational discomfort over wide areas, whereas at frequencies above that value the discomfort was localised to the vicinity of the hand. In order to investigate this further, four sinusoidal test signals were chosen with frequencies of 4, 8, 16 and 32 Hz. Two test amplitudes were chosen for the current study based on the analysis of steering wheel vibration signals from European automobiles. The lower amplitude was chosen to be similar in root-mean-square terms to vibration which would be considered just noticeably uncomfortable in road vehicles. The higher amplitude was chosen to produce significant discomfort after about 10 to 15 minutes of continuous exposure. The constant peak velocity chosen for the low amplitude signals was 0.08 m/s, while that chosen for the high amplitude signals was 0.1 m/s. Table 2 presents the test frequencies, peak velocity amplitudes and the resulting peak acceleration amplitudes. For comparison purposes, a 0 Hz and 0 m/s signal (a static test) was included in the test programme so as to evaluate the level of background discomfort due to maintaining the static posture over the length of time of a test.

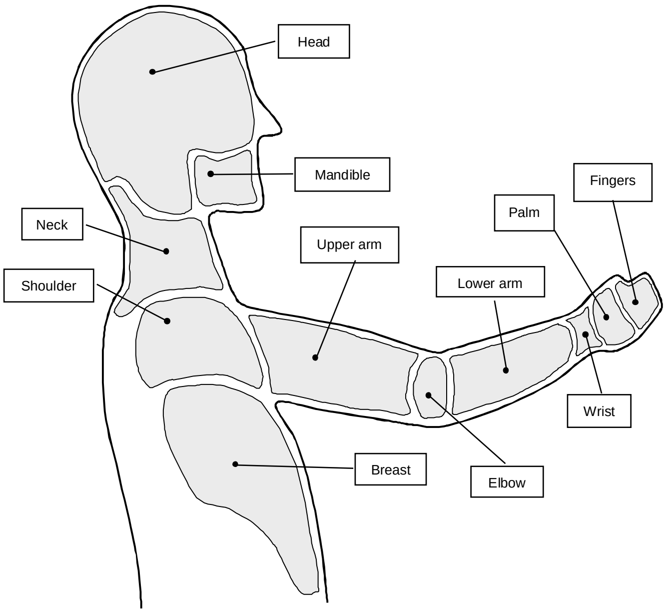
	Constant Velocity (0.08 m/s)				**Constant Velocity (0.10 m/s)**			
Frequency (Hz)	4	8	16	32	4	8	16	32
Acceleration (m/s^2)	2.0	4.0	8.0	16.0	2.5	5.0	10.1	20.1
Amplitude (mV)	37.5	75.0	149.9	299.9	46.9	93.7	187.4	374.9

Table 2) Frequencies and amplitude of the test signals

2.3 Test Subjects

8 men and 7 women were tested. Their ages ranged from 20 to 24 years, with an average of 21.73 years and standard deviation of 0.9978. Their weights ranged from 51 kg to 84 kg, with an average of 66.53 kg. All were in good health, and none used vibration-producing tools as a regular part of their work or pastimes. Each declared that they drove automobiles regularly.

2.4 Body-Part Discomfort Form



Not at all		A little		Slightly		Strongly		Very strongly	
1	2	3	4	5	6	7	8	9	10

Figure 4) Body-part discomfort form with Likert format discomfort scale

Discomfort was evaluated by means of the body-part discomfort form presented in Figure 4. The upper body was divided into 11 regions, covering the major skeletal joints and the areas containing the largest muscle groups. A two-stage Likert-type response format [8,20] was used for numerically quantifying the discomfort of each body region. Preliminary tests were performed with five subjects in order to try to establish semantic scale-anchors for the two extremes of the discomfort scale which would be specific to the steering wheel vibration application. This was thought useful given that Reynolds, Standlee and Angevine [19] highlighted the problems associated with subjective questioning without absolute criteria by which to make a judgement. Unfortunately, the preliminary testing was only partially successful, and definitive scale-anchors were not achieved. As a compromise solution, each subject was given the instruction that a rating of 10 did not mean pain, but rather, a level of discomfort which would lead to not wish to hold the wheel for more than a period of about 15 minutes.

2.5 Test Protocol

Each individual vibration test lasted about 10 minutes and consisted of a set of fixed activities as outlined in Table 3. Prior to their first test, information was gathered from each subject regarding their anthropometry, health and previous vibration exposure. During all tests the subjects were asked to wear ear protectors and to keep their eyes closed so as to avoid audio and visual cues from the movement of the test bench.

During the 10-15 minute period of vibration exposure, the subjects were asked to state their levels of body part discomfort after 1, 5, and 10 minutes of time had elapsed. The evaluation was performed using a poster-sized copy of the body-part discomfort form, and was solicited verbally by the experimenter who recorded the discomfort values. Intervals of at least 3 hours were introduced between each vibration exposure so as to avoid fatigue or learning effects. No more than two tests were performed for a given subject on a single day.

Phase	Tasks Performed and Information Obtained
Participation form and questionnaire (~3 minutes)	**Only at beginning of first test.** Each subject was asked to read the instructions and intended purpose of the experiments and to sign a consent agreement to participate. Each subject also completed a questionnaire concerning age, height, weight, health and previous exposure to vibration.
Adjustment of driving posture (~1 minute)	The subject was asked to remove heavy clothing, watches and jewellery. They were asked to adjust the sitting posture to a comfortable position, simulating the driving task as realistically as possible.
Measurement of posture angles (~1 minute)	The seat position was measured using the bench pointer and the elbow and wrist angles were measured using a full circle goniometer.
Introduction to frequency and amplitude range (~3 minutes)	**Only at beginning of first test.** The subject was given a verbal introduction to the experiment and to the use of the body-part discomfort diagram. The range of experimental frequencies and amplitudes were run through so as to familiarise the subject with them.
Preparation for test (~1 minute)	Each subject was asked to wear ear protectors and to close their eyes before gripping the steering wheel. The grip strength was suggested to be that required to drive an automobile over a country road. Once they were comfortable with their grip, they were asked to keep it constant during all tests.
Fatigue testing (~10 to 15 minutes)	Each of the following nine frequency-amplitude combinations was used tested: 0 Hz and 0 m/s^2, 4 Hz and 2.0 m/s^2, 4 Hz and 2.5 m/s^2, 8 Hz and 4.0 m/s^2, 8 Hz and 5.0 m/s^2, 16 Hz and 8.0 m/s^2, 16 Hz and 10.0 m/s^2, 32 Hz and 16.0 m/s^2, 32 Hz and 20.0 m/s^2. The tests were performed in random order, and no more than two tests were performed on a single day.

Table 3) Test procedure

3 Results

3.1 Normalisation of the Subjective Data

The minimum and maximum discomfort responses given by each subject were used to normalise their data set. This was done to minimise inter-subject variability caused by difference in use of the 10-point scale. The data normalisation performed was

$$x_{norm} = \frac{x - x_{\min}}{x_{\max} - x_{\min}}$$

where x_{min} and x_{max} were the minimum and maximum numerical values (on the scale from 1 to 10) found over the complete set of responses for the test subject in question. Figure 5 presents the average normalised subjective responses obtained from all tests with all subjects. A combination of t-tests, ANOVA tests and post hoc Tukey tests [9, 11] were performed on the normalised results to check for significant differences due to the effects of vibration frequency, vibration amplitude, elapsed time and test subject gender.

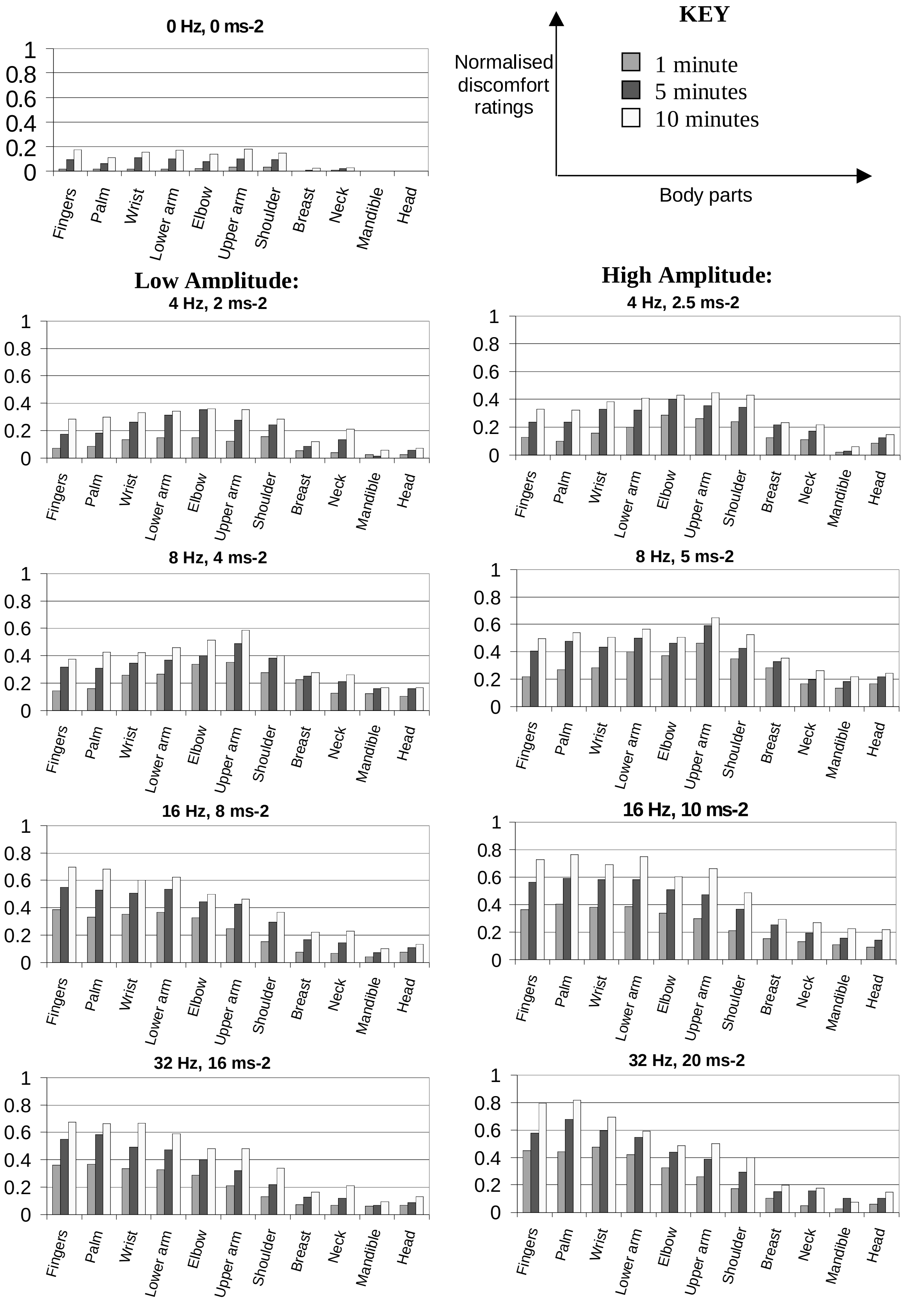


Figure 5) Average normalised discomfort responses after 15 minutes for all tests.

3.2 Effect of Time

From Figure 5 it can be seen that the average normalised discomfort ratings increased as a function of time. To test significance, a single factor ANOVA was performed at a 5% confidence level (p<0.05) for the time durations of 1, 5 and 10 minutes. The outcome was mixed, only about half of the ratings showing a significant difference. A one-tailed t-test was also performed at a 5% significance level between the average scores obtained for the 1 and the 10 minute exposures. In this case, the discomfort ratings for all body regions were found to be significantly greater after 10 minutes than at 1 minute. The increase in discomfort over time was approximately linear for all body regions evaluated.

3.3 Effect of Vibration Frequency

A single factor ANOVA was performed at a 5% significance level on both the low and the high amplitude results for the four test frequencies of 4, 8, 16 and 32 Hz and for all three time durations. The results were similar for both vibration amplitudes, so only the higher amplitude results are presented here. Table 4 presents the results obtained from both ANOVA and the post hoc Tukey tests performed at a 5% confidence level for the 10 minute exposure data. An ‘X’ in the ANOVA column denotes that there was a significant difference between the sample means. An ‘X’ in the Tukey test columns denotes that the frequency produced discomfort ratings which were different from the average for that body region taken over all frequencies.

Body region	ANOVA	Post Hoc Tukey Test			
		4 Hz	8 Hz	16 Hz	32 Hz
Fingers	X			X	X
Palm	X			X	X
Wrist	X			X	X
Lower arm	X			X	X
Elbow				X	
Upper Arm	X		X	X	
Shoulder					
Breast			X		
Neck					
Mandible	X		X	X	
Head					

Table 4) ANOVA and post hoc Tukey test results for the 10-minute discomfort ratings

Figure 6 presents the average normalised discomfort ratings for the group of 15 test subjects after 10 minutes of exposure to the high amplitude (0.10m/s) stimuli. The data is representative also of the results obtained for the 1 and 5 minute exposures. The data shows the decoupling of the upper body regions which occurs as the frequency of oscillation increases. At 32 Hz it can be seen that the discomfort is concentrated in the areas which are closest to the steering wheel (finger palm and wrist), while the discomfort is low for areas such as the head and mandible which are distant from the source of the vibrational energy.

Considering specific body regions, it can be seen from Figure 6 that significant levels of discomfort were perceived in the mandible region for frequencies in the neighbourhood of 8 Hz. This result supports previous research [3] which suggested a resonance frequency of about 8 Hz for the jaw. From Figure 6 it can also be seen that that the upper arm and shoulder perceived high levels of discomfort in the region around 6 Hz, supporting previous research [3] which suggested a resonance frequency of about 6 Hz for the shoulder complex.

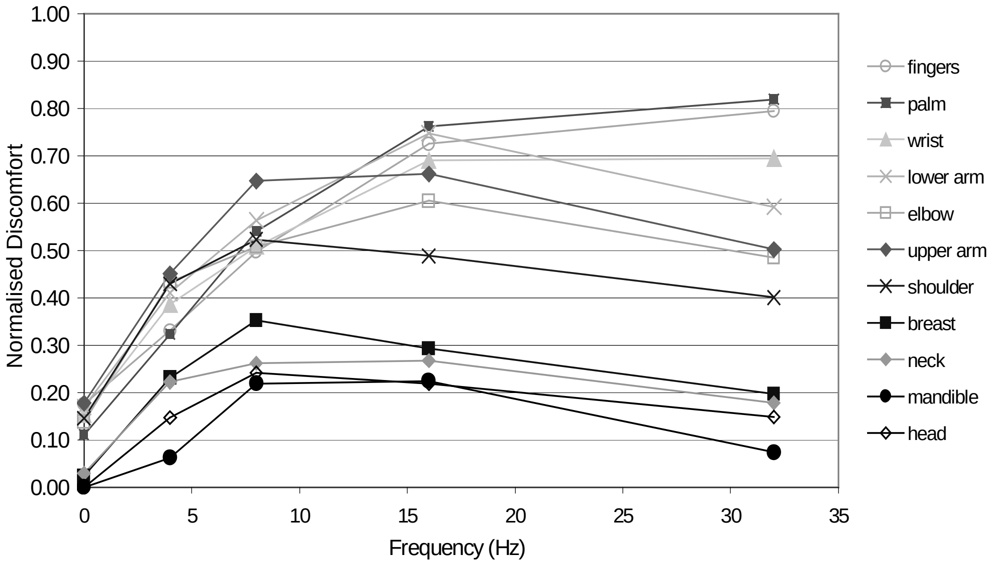


Figure 6) Effect of frequency on the average normalised discomfort ratings obtained after 10 minutes of vibration exposure at 0.10 m/s.

3.4 Effect of Vibration Amplitude

A one-tailed t-test was performed between the low and the high amplitude discomfort ratings at a 5% significance level for each time exposure. The expected outcome was that the null hypothesis could be rejected, implying that higher amplitude vibration resulted in greater discomfort at all exposure durations; this did not prove to be the case. Table 5 presents the t-test results obtained at a 1% confidence level for the comparison between the low and high amplitude discomfort ratings. The number in each column indicates the exposure time (1, 5 or 10 minutes) for which a significant difference was found. Significant differences occurred systematically only for the lower arm at 8 Hz and the breast region at 4 Hz. The result is interesting because, from an automotive point of view [10,15], the velocity amplitudes used were of average and high intensity. The difference in peak velocity between the two stimuli was 20%, thus greater than the Weber Fraction of 13% recently reported by Mansfield and Griffin [12] for the perception of seated whole-body vibration, and far greater than the 3-5% values commonly reported in the literature for vibration perception. Presumably, the Weber Fraction [2] obtainable through self-reporting using Likert scales is larger than the values obtained by direct comparison methods. Future research is required to determine the precision limits of self-reporting of vibration exposures.

Body Region	**Frequency**			
	4 Hz	**8 Hz**	**16 Hz**	**32 Hz**
Fingers	1			10
Palm		1, 5		
Wrist				1
Lower arm		1, 5, 10		
Elbow				
Upper arm	1		10	
Shoulder	10	10		
Breast	5, 10			
Neck				
Mandible			10	
Head				

Table 5) T-test results for the comparison of average normalised discomfort ratings from the low and high amplitude tests at 1, 5 and 10 minute exposures.

3.5 Effects of Gender and Body Mass

A two-tailed t-test with unequal sample sizes was performed for all body regions to compare the differences between normalised discomfort ratings for male and female subjects. Significant differences were not found for the fingers, palm or upper body regions. Significant differences were, however, found at both 5% and 1% confidence levels from the wrist to the shoulder, with the females generally stating higher discomfort ratings than the males.

Since a lighter mass implies a higher acceleration response, it was thought that the increased discomfort ratings for female subjects could have been caused by their smaller body mass. To investigate this, a one-tailed unrelated t-test was performed at $p<0.05$. The discomfort scores for the lightest 1/3 (51-62 kg) of the subjects and for the heaviest 1/3 (73-84 kg) of the test subjects were used for the comparison. Differences between the discomfort ratings of the lightest and heaviest subjects were found to be significant for the 4 and 8 Hz test frequencies, with the lighter subjects giving the higher discomfort ratings.

Since, on average, the female subjects were also smaller than their male counterparts, they assumed a different sitting posture when adjusting the test bench. It was thought that the different elbow angle could have affected the transmission of vibration through the hand-arm system. A two-tailed unrelated t-test was therefore performed at $p<0.05$ between the upper and lower 1/3 of the test subjects. No significant differences were found between the two test groups (those with the more open and those with the more closed elbow angles).

4 Conclusions

The following conclusions can be drawn from the results:

- on average, the application of vibrational stimuli to the steering wheel caused discomfort to more than double with respect to the level caused by the maintenance of the static posture.

- the discomfort perceived in all body regions increased approximately linearly over time. The average normalised discomfort ratings increased by amounts varying from 0.16 to 0.26 over the 10 minute vibration exposure.

- human discomfort was found to be frequency dependent at a 5% confidence level. For frequencies up to 8 Hz the vibration was felt in all body regions, while for frequencies above 30 Hz it was felt to be localised in the hand and wrist.

- amplitude did not have a significant effect on discomfort for the levels (0.8 m/s and 1.0 m/s) chosen in this study.

- females were found to perceive greater discomfort than males in the wrist, lower arm, elbow, upper arm and shoulder regions (at $p<0.05$). Significant differences were not found for the other body regions considered.

- lighter subjects were found to perceive 10% greater discomfort in the arm regions than heavier subjects ($p<0.05$).

- elbow angle was not found to have a significant effect on discomfort ($p<0.05$).

- the accuracy obtainable through self-reporting using Likert scales appears to be lower than by direct comparison methods. Further investigation is required to determine the limits

- the results suggest that the localisation of the perceived discomfort in the human body will depend greatly on the frequency content of the vibratory signal acting at the steering wheel.

Since the discomfort sensations produced in the different body regions are physically different, it may be advisable to include a localisation procedure within steering wheel vibrational comfort evaluation procedures.

5 Acknowledgements

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