Subjective response to seated fore-and-aft direction whole-body vibration

T.M. Hacaambwa and J. Giacomin*

*corresponding author
Head of Design, Brunel University,
Uxbridge, Middlesex, UB8 3PH, United Kingdom
Tel: 01895 265 340 Fax: 01895 269 763
E-mail: joseph.giacomin@brunel.ac.uk

Abstract

Subjective response to seated, fore-and-aft direction, whole-body vibration of the type experienced in automobiles was investigated. Fore-and-aft acceleration was measured at the seat guide of a small automobile when driving over two representative road surfaces, and was replicated in a laboratory setting using a whole-body vibration test rig and rigid seat. A single 15-second section of each of the two acceleration time histories was band-pass filtered to the frequency interval from 0.5 to 50.5 Hz, and was used as a base stimulus. Thirteen test stimuli were then constructed for each base stimulus by rescaling to BS 6841 W_d frequency-weighted r.m.s. amplitudes from 0.01 to 0.86 m/s^2. Two groups of 16 participants (8 male and 8 female in each case) rated the discomfort of the test stimuli. The first group was asked to use the psychophysical method of magnitude estimation while the second used a Borg CR-10 scale. The order of presentation of the test stimuli was fully randomised and each was repeated 3 times. For each group of participants, regression analysis was used to determine both the individual and the group mean Stevens' Power Law exponent describing the relationship between stimulus amplitude and subjective response. All mean power exponents were found to be less than unity, with the CR-10 scale having produced smaller exponents than magnitude estimation. The power exponents ranged from 0.66 to 0.91, corroborating the value of 0.84 obtainable from the guidelines of standard BS 6841.The results suggest that the numerical response scale provided in the BS 6841 guidelines is appropriate for use in the case of automobile fore-and-aft vibration, but that the semantic labels under-represent the actual human subjective response in this direction. Psychophysical test method, vibration stimulus range and test participant gender were all found to affect the Stevens' Power Law exponent achieved from subjective testing. Each factor may therefore require control when attempting to compare human responses to vibration originating from different automobiles.

Keywords: psychophysics, vibration, discomfort, automobile, seat, borg scale

NOTATION

$a_w(t)$	*frequency-weighted acceleration time history (m / s^2)*
a_o	*reference acceleration of 10^{-5} m/s^2*
c	*constant of proportionality in Stevens' Power Law*
L	*Stimulus range; the ratio of maximum to minimum stimulus magnitudes*
R	*Response range; the ratio of maximum to minimum subjective numerical responses*
r.m.s.	*Root Mean Square acceleration value [m/s^2]*
r.m.q.	*Root Mean Quad acceleration value [m/s^2]*
T	*duration in seconds over which r.m.s and VDV measures are calculated (s)*
VDV	*Vibration Dose Value [$m/s^{1.75}$]*
W_d	*frequency-weighting used for the horizontal axis in BS6841 and ISO 2631(dimensionless)*
X	*physical magnitude of a vibration stimulus*
N	*subjectively perceived discomfort*
b	*Stevens' Power Law exponent*

1. Introduction

The standards BS 6841 (1987) and ISO 2631-1 (1997) are widely used (Dupuis and Zerlett 1986; Griffin 1990) for the evaluation of discomfort caused by whole-body vibration. This discomfort depends on four main factors: the axis of vibration, the frequency of vibration, the magnitude of vibration and the exposure duration. Generally, the frequency of vibration is considered to have the greatest influence (Griffin, 1990), and both British Standards Institution BS 6841 and International Organization for Standardization ISO 2631-1 specify frequency-weightings that account for the way human perception changes as a function of frequency. These weightings are applied to convert the mechanical (objective) input acceleration into a perceived (subjective) human response. BS 6841 specifies three assessment methods. For crest factors less than 6, use of the root-mean-square (r.m.s) value is suggested :

$$r.m.s. \;=\; \left[\frac{1}{T}\int_0^T a_w^2(t)\,dt\right]^{\frac{1}{2}} \qquad (1)$$

where a_w (t) is the frequency-weighted acceleration and T is the time duration over which the r.m.s value is determined. For crest factors greater than 6, the use of a root-mean-quad (r.m.q) measure

$$r.m.q. \quad = \quad \left[\frac{1}{T} \int_0^T a_w^4(t)\, dt \right]^{\frac{1}{4}} \qquad (2)$$

or of a vibration dose value (VDV)

$$VDV \quad = \quad \left[\int_0^T a_w^4(t)\, dt \right]^{\frac{1}{4}} \qquad (3)$$

is recommended. These 4th power methods reflect an increased human sensitivity to high amplitude acceleration events. The VDV is the dose form of the r.m.q, thus the metric is a cumulative measure of the 4th power exposure over time. In addition to the metrics, BS 6841 also provides a table (see Figure 1) which lists the subjective discomfort response associated with various r.m.s. levels of frequency-weighted acceleration. The standard states that “the following values give very approximate indications of the likely reactions to various magnitudes of frequency-weighted r.m.s. acceleration”. Figure 1 also presents the human subjective response which can be defined using the numerical scale values provided. Since subjective response is not a linear function of the frequency-weighted acceleration, the accuracy of the assumed response function represents an important component of the overall accuracy of the complete evaluation procedure.

The transformation from mechanical (objective) acceleration to perceived (subjective) human discomfort response falls into the general category of psychophysical relationships (Gescheider 1997). In particular, Stevens (1957) established that for many sensory modalities the magnitude of the subjective response N is proportional to the stimulus intensity X raised to a power β. Stevens further proposed that ß should be considered to be a physiological characteristic of the perceptual modality. In logarithmic form, the Stevens' Power Law is expressed as:

$$\log_{10} N \quad = \quad \log_{10} c \quad + \quad b \, \log_{10} X \qquad (4)$$

where c is a constant which depends on various factors including the measurement units of the input stimuli.

Stevens' Power Law exponents ß for the perception of whole-body vibration by subjects seated on a rigid seat have been reported by several researchers. Miwa (1968) investigated the subjective response to sinusoidal vibration at frequencies of 5, 20 and 60 Hz and r.m.s. amplitudes from 0.02 to 2.2 m/s^2 in the fore-and-aft direction, and from 0.007 to 0.71 m/s^2 in the vertical direction. Using a psychophysical test protocol based on combined equisection and fractionation methods, he obtained exponent values of 0.46 below 1 m/s^2 r.m.s. and 0.6 above 1 m/s^2 r.m.s.. Using the method of magnitude estimation, Shoenberger and Harris (1971) obtained a mean exponent of 0.94 from experiments performed using vertical sinusoidal vibration at frequencies from 3.5 to 20 Hz and r.m.s. amplitudes from 0.8 to 5.6 m/s^2. Using a “relative intensity estimation procedure”, Jones and Saunders (1974) obtained an overall exponent of 0.93 for vertical sinusoidal vibration at frequencies in the range from 5 to 40 Hz. Using the method of magnitude estimation, Shoenberger (1975) obtained a mean exponent of 1.43 for short duration (30-60 seconds) vertical sinusoidal vibration at frequencies from 0.25 to 4.0 Hz and r.m.s. amplitudes from 0.71 to 5.6 m/s^2. Hempstock and Saunders (1976) investigated the subjective response to whole-body, vertical, sinusoidal vibration in the frequency range 5-80 Hz. The method of Cross-Modality was used with sound stimuli at pressure levels from 60 to 100 dB and vibration stimuli at amplitudes from 0.5 to 6.0 m/s^2. Reported exponent values ranged from 1.2 to 1.43, and from 0.49 to 0.87, respectively. The exponents at each frequency obtained from the pooled data of the two experiments when the sound and vibration were independent variables were reported as ranging from 0.85 to 0.99, with a mean value of 0.95. Using both magnitude estimation and magnitude production, Fothergill and Griffin (1977) reported an exponent of 1.13 for 10 Hz vertical sinusoidal vibration ranging from 0.175 to 2.8 m/s^2 r.m.s. in amplitude, and 1.75 for the same frequency at amplitudes from 0.33 to 1.88 m/s^2 r.m.s.. Using the method of magnitude estimation, Hiramatsu and Griffin (1984) reported an exponent of 0.964 for vertical sinusoidal vibration of 8.0 Hz in frequency for amplitudes from 0.5 to 2.5 m/s^2. Using magnitude estimation, Howarth and Griffin (1988) obtained mean exponent values of 1.4 for sinusoidal fore-and-aft vibration, and 1.2 for sinusoidal vertical vibration, for stimuli having frequencies from 4 to 63 Hz and r.m.s amplitudes from 0.04 to 0.4 m/s^2.

Ruffel and Griffin (1995) investigated the discomfort caused by 1 and 2 Hz vertical sinusoidal transient vibration superimposed on background band-limited random vibration centred on 1 Hz. The transients were added at five magnitudes in the range 0.63 to 1.6 m/s^2, and seven durations in the range 1 to 60 seconds. Using the method of magnitude estimation the authors reported an exponent value of 1.14 based on mean percentage VDV values, the mean percentage VDV value being defined as the percentage ratio of the VDV of the test motion to the VDV of the reference motion. Yokota and Hirao (1998) used the method of magnitude estimation to obtain the subjective sensation caused by vertical road traffic vibration on subjects seated on a wooden seat in a wooden house. The vibration stimuli had weighted r.m.s. acceleration levels ranging from 0.02 to 0.25 m/s^2 for stimuli containing no shock events, and from 0.025 to 0.5 m/s^2 for stimuli with shock events. Exponent values of 0.68 and 0.61 were found for vibration stimuli without and with shock events, respectively. Jang and Griffin (1999) investigated the effect of relative phase between vibration at the seat and feet on the discomfort of seated subjects exposed to vertical 4 Hz sinusoidal vibration. The vibration stimuli had seven phases between 0 and 180 degrees and five acceleration amplitudes from 0.25 to 1.6 m/s^2

r.m.s.. Using a relative judgment method, they reported an exponent value of 1.35 for in-phase motion with thigh contact and 1.24 for in-phase motion without thigh contact. The exponents varied between 0.97 and 1.48 for out-of-phase motion with thigh contact and between 0.98 and 1.19 for out-of-phase motion without thigh contact.

Using magnitude estimation, Ebe and Griffin (2000) obtained a mean exponent of 0.929 for subjects who were seated on either a flat wooden seat or a square-shaped polyurethane foam block. Vertical direction random vibration was used with contained energy from 0.8 to 20 Hz and which was scaled to frequency-weighted r.m.s. acceleration amplitudes from 0.125 to 2.0 m/s^2. Jang and Griffin (2000) investigated the effect of the interaction between the frequency and the relative phase between vibration at the seat and feet on the discomfort of seated subjects exposed to vertical sinusoidal vibration. The vibration stimuli were presented at five frequencies between 2.5 and 6.3 Hz, two phases at 0 and 180 degrees and five acceleration amplitudes from 0.25 to 1.6 m/s^2 r.m.s.. Using a relative judgement method they reported exponent values for in-phase motion ranging between 0.7 and 1.37 with a mean value of 1.06 when subjects maintained thigh contact with the seat, and exponent values ranging between 0.9 and 1.25 with a mean value of 1.05 when subjects maintained no thigh contact. The exponents for out-of-phase motion ranged between 0.7 and 1.2 with a mean value of 0.92 with thigh contact and between 0.62 and 0.98 with a mean value of 0.85 without thigh contact. A summary of the power law exponents reported by the various researchers is provided as Table 1.

The BS 6841 and ISO 2631-1 standards are widely used in the automotive industry for assessing driving discomfort. For the automotive engineer, however, the applicability of the guidelines is not fully obvious. A first question is whether the subjective response scale provided by BS 6841 is appropriate when evaluating road-induced vibration, which is random in nature and broadband, as opposed to the sinusoidal stimuli favoured in research settings. Further, the majority of studies have involved vertical vibration, with only two reporting the response to fore-and-aft vibration, and none reporting the response to lateral vibration. Previous whole-body research has most probably focused on the vertical direction because vibration levels along this axis in automobiles have been shown in the past to be as much as four times greater than those measured in the fore-and-aft direction (Griffin, 1990). Recent evidence (Bellman 2002) suggests, however, that the suspension systems adopted by today's automobiles can lead to many situations in which the vibration level is comparable in the two directions. The question of how to best evaluate fore-and-aft vibration is therefore of great importance in many current applications.

The objective of this research study was to estimate the Stevens' Power Law exponent ß for seated, fore-and-aft direction, whole-body vibration of the type which occurs in automobiles. To achieve this, vibration stimuli from a small European automobile were used, as measured when driving over two representative road surfaces. As a secondary objective, the sensitivity of the exponent to the psychophysical test method was evaluated. The psychophysical method of magnitude estimation (Stevens 1957) was chosen since it has been used in most previous research. Magnitude estimation has, however, come under some criticism (Poulton, 1968; Gregory and Colman, 1995) due to the tendency on the part of test participants to logarithmically distribute their numerical responses. For this reason, an alternative method was also used which yielded a subjective discomfort scale with ratio properties. The Borg CR-10 scale (Borg 1998) was used for comparison because it combines the ease-of-use of a category scale with the analytical flexibility inherent in numbers reported using a ratio scale.

2. Test stimuli

The vibration stimuli used in this study were fore-and-aft direction accelerations measured at the rear outer mounting bolt of the driver's seat of a Fiat Punto automobile. The Punto was considered to be representative of many small to medium sized European automobiles in terms of its vibrational characteristics. The two signals were measured while the automobile traversed a cobblestone test track at 60 km/h and a motorway test segment at 100 km/h. The cobblestone was of the type found in many European cities, while the motorway segment was a smooth, well kept, asphalt surface. The surfaces were chosen because they provided representative (Giacomin and Bracco, 1998) driving conditions. The signal measured on the cobblestone track provided a mildly-nonstationary stimuli (Abdullah et. al., 2004), characterised by Gaussian behaviour with the addition of occasional shock events, while the signal measured on the motorway segment was more strongly harmonic due to the presence of dominant resonant frequencies of the suspension units and chassis. The complete test and data acquisition protocol has been described by Giuliano and Buco (1995).

Each acceleration was sampled at 250 Hz during the road measurement for a total of 131.10 seconds, then was band-pass filtered to the frequency range 0.5 to 50.5 Hz for use in the laboratory. The unweighted r.m.s. amplitude of the cobblestone stimuli was 1.05 m/s^2 while that of the motorway stimuli was 0.20 m/s^2. The autopower spectral densities of the two stimuli are presented in figures 3 and 4. For the laboratory tests, a 15 second section was extracted from each time history, which had the same r.m.s. and crest factor values as the complete 131.10 second measurement. A 15 second section of signal was used so as to provide a stimuli which remained within human short term memory, thus one which could be judged without reliance upon the storage of stimuli information by the test subject. Thirteen copies of each of the two acceleration segments were then constructed by rescaling the data such that the BS 6841 W_d frequency-weighted r.m.s. amplitudes were exactly 0.01, 0.02, 0.03, 0.05, 0.08, 0.11, 0.17, 0.25, 0.38, 0.48, 0.57, 0.71 and 0.86 m/s^2. Based on data known to the authors (Giuliano and Buco, 1995), the range of frequency-weighted r.m.s. amplitudes from 0.01 to 0.86 m/s^2 was considered to cover the full range of acceleration values achieved over the two road surfaces by European automobiles of different size. Since the crest factors of the two original time histories, and thus of all the scaled copies, was less than 6.0, the BS 6841 recommended assessment method is the root mean square (r.m.s) acceleration.

3. Test Facility

The fore-and-aft direction whole-body vibration test rig is shown in figure 2. The bench is driven by a Zonic 1100 series electro-hydraulic shaker unit which consists of a hydraulic supply, servo valve, shaker piston (+/- 1 inch stroke), LVDT displacement transducer and PD controller. The first resonance frequency of the bench structure (bearings, aluminium frame and seat) is approximately 90 Hz.

Control and data acquisition was performed by means of a Dell PC running LMS CADA-X version 3.5.E software and using a 16-channel SCADAS III unit. All bench voltage drive signals were obtained by means of the Time Waveform Replication (TWR) software whereas all tests were run using the LMS Endurance Monitor software. Acceleration measurements were performed during each test so as to monitor the accuracy of the actuated vibration stimuli. An ENTRAN EGAS3–CM–25 accelerometer (indicated as point 'A' in figure 2) was used, which was mounted at a point on the seat frame directly below the support surface. An ENTRAN MSC-12 signal-conditioning unit was used to amplify the acceleration signals before return to the data acquisition system.

A rigid seat frame and a rigid seat surface were used to eliminate any possible effects due to seating system compliance. In order to fit UK nationals from a 5^{th} percentile female to a 95^{th} percentile male, the seat surface height needed to be adjustable over the range from 351.8 to 439.2 mm (Peebles and Norris, 1998). The rigid seat was therefore designed to have a height of 575 mm above the platform surface, and wooden footrest plates (labelled FR in figure 2) were used to accommodate smaller participants to a minimum seat surface height of 340 mm. For each participant, the sitting posture was adjusted prior to testing so as to achieve an included angle of the knee of approximately 90 degrees and a vertical alignment of the back. Participants were instructed to be careful to maintain their initial posture during the full duration of their test. The amplitude of the reproduced signals varied between 0.7% and 15% with respect to their target values, with a mean amplitude error of 8%. The 8% error was less than the just noticeable difference value of approximately 13% reported by Mansfield and Griffin (2000) for seated, vertical direction, whole-body automobile road vibration.

The rig incorporates several hardware safety features including a rubber end-of-travel snubber to limit maximum bench travel, emergency soft-stop leak capacitors on the SCADAS III unit and an emergency manual stop button (labelled ESB in figure 2) within reach of the test participant. Software safety features include the limiting of the test acceleration in EMON, which was set to abort platen motion if the actuated peak acceleration exceeded 1 g acceleration. The safety features and the test acceleration levels used conform to the health and safety recommendations outlined by British Standard BS7085 (1989). During all tests the temperature in the room was from 20 to 25° C. The facility and protocol were externally reviewed and found to meet the University of Sheffield guidelines for good research practice.

4. Psychophysical Experiments

4.1 Procedure of the magnitude estimation experiment

In its most common form, the method of magnitude estimation consists of presenting a reference stimulus followed by a set of test stimuli. The test participant is asked to assign numbers to the test stimuli such that the stimulus attribute of interest bears a ratio relationship with that of the reference. In magnitude estimation, it is known (Poulton, 1968) that the choice of the reference stimulus plays a role in determining the value of the power exponents that are obtained. For the set of 13 acceleration stimuli ranging from 0.01 to 0.86 m/s^2 in the current experiment, the median stimuli, which had an r.m.s. level of 0.17 m/s^2, was used as the reference and was assigned a discomfort value of 100.

Before commencing vibration testing, and following the example of Stevens (1971), each participant was asked to estimate the length of various lines drawn on paper in order to become acquainted with the method. Next, the reference vibration was presented, followed by four practice stimuli, and the participant was asked to rate each in order to practice the experimental method. The experiment itself consisted of two 20 minute test sessions, separated by a 5 minute rest period. One test session consisted of stimuli obtained by scaling the cobblestone road surface time history, while the other consisted of the data obtained by scaling the motorway time history. In order to reduce learning and fatigue effects, the order of the two sessions was randomised for each test participant, as was the order of the individual stimuli within each session. Each session was further subdivided into 3 runs, with each run consisting of the 13 cobblestone or motorway stimuli. In every run the reference stimulus was presented 3 times, each presentation followed by four test stimuli. In each session, therefore, 3 magnitude estimates were obtained for each test stimulus. The order of presentation of the three runs was randomised for each participant as was the order of presentation of the test stimuli in each run.

A total of 16 Sheffield University staff and students (8 males and 8 females) performed magnitude estimation. Participant age ranged from 21 to 40 years with a mean value of 26.1 years. Participant height ranged from 1.55 m to 1.80 m with a mean value of 1.69 m. Participant mass ranged from 54 kg to 95 kg with a mean value of 72 kg.

4.2 Results of the magnitude estimation experiment

Figure 5 presents the geometric mean discomfort response obtained from the data of all 16 participants, as a function of both the unweighted and the BS 6841 W_d frequency-weighted r.m.s. acceleration level of the test stimuli. Both the acceleration axis and the subjective response axis have been chosen logarithmic as in expression (4), and the responses obtained from both the cobblestone and the motorway stimuli are presented. Also presented are the results of linear regression performed on the data, indicated by a continuous line, by the power exponent ß and by the associated coefficient of determination (r^2). The Stevens' Power Law exponents were found to range from 0.78 to 0.91. The similarity between the power exponents obtained for the cobblestone and the motorway stimuli was greater in the case of the frequency-weighted representation than in the unweighted case. A possible reason is that the W_d frequency-weighting exhibits low pass filter characteristics, attenuating most of the vibrational energy at frequencies greater than 10 Hz, where the two stimuli differed most. For both road stimuli, the power exponents were found to be lower when determined using unweighted acceleration data, whose range of r.m.s. values is greater from minimum to maximum (Laming, 1997).

4.3 Procedure of the Borg CR-10 scale experiment

The CR-10 scale (Borg 1998) approximates the ease-of-use of a category scale while achieving the analytical flexibility inherent in numbers reported using a ratio scale. By assuming that people use semantic labels such as “weak” and “very strong” to signify similar quantities across different stimuli modalities, and by assuming that the range of perceived sensation varies from a minimum value to a maximum value which are similar for most people, Borg combined the characteristics of the two systems. Table 2 presents the CR-10 scale, which consists of 17 level points (9 labelled and 8 unlabeled). The scale is used by first finding the verbal label which best fits the stimulus attribute of interest, and then using the number scale to make adjustments to the rating. The value of 10 represents the maximum suggested intensity, but greater values can be chosen if the test participant so wishes. From their study of the human perception of hand-arm vibration, Wos et. al (1988a and 1988b) found reliability coefficients ranging from 0.841 to 0.986 for the CR-10 scale. Neely et. al. (1992) have reported coefficients of determination (r^2) of 0.79 between CR-10 results and subjective data obtained by means of a visual analogue scale, and have also reported retest coefficients of determination of 0.98. Due to its ease of use and reliability, the CR-10 scale has been applied in the fields of physiology, psychology and ergonomics to rate sensations of pain, fatigue, physical exertion and discomfort.

Before commencing testing, each participant was asked to rate the discomfort of each of four practice stimuli in order to become acquainted with the CR-10 scale. The experiment then consisted of two 18 minute test sessions, separated by a 5 minute rest period. One test session consisted of stimuli obtained by scaling the cobblestone road surface time history, while the other session consisted of the data obtained using the motorway time history. In order to reduce learning and fatigue effects, the order of the two sessions was randomised for each participant, as was the order of the individual stimuli within each session. Each session was further subdivided into 3 runs, with each run consisting of the 13 cobblestone or motorway stimuli. The order of presentation of the three runs was randomised for each participant as was the order of presentation of the test stimuli in each run. In each session the participant was exposed 3 times to each of the 13 test stimuli resulting in a total of 3 Borg scale values for each stimulus. All tests were conducted in accordance with the recommendations provided by Borg (1998).

A total of 16 Sheffield University staff and students (8 males and 8 females) performed CR-10 tests. The participants in CR-10 experiment were different from those in the magnitude estimation experiment. Participant age ranged from 19 years to 30 years with a mean value of 26.9 years. Participant height ranged from 1.55 m to 1.80 m with a mean value of 1.69 m. Participant mass ranged from 56 kg to 100 kg with a mean value of 69.2 kg.

4.4 Results of the Borg CR-10 scale experiment

Figure 6 presents the geometric mean discomfort response obtained from the data of all 16 participants, as a function of both the unweighted and the BS 6841 W_d frequency-weighted r.m.s. acceleration level of the stimuli. The mean results covered the suggested evaluation range of the CR-10 scale from 0 to 10. The results obtained from linear regression are indicated by a continuous line, by the power exponent ß and by the associated coefficient of determination (r^2). Being distributed across a 10 point scale, the CR-10 results provided Stevens' Power Law exponents ranging from 0.66 to 0.76. As with the results from magnitude estimation, the CR-10 results provided power exponents for the cobblestone and the motorway stimuli which were more closely similar in the frequency-weighted representation than in the unweighted case. Again the possible explanation may lie with the low pass filter characteristics of the W_d frequency-weighting. For the cobblestone road stimuli, the power exponent was found to be lower when determined using unweighted acceleration data, whose range of r.m.s. values is greater from minimum to maximum.

5. Discussion

All mean Stevens' Power Law exponents were found to be less than unity. This suggests that the human discomfort sensation caused by whole-body vibration in the fore-and aft direction is a negatively accelerating function of the r.m.s. acceleration level, when expressed over commonly used numerical intervals (from zero to a few hundred in the case of magnitude estimation, and from zero to ten in the case of the CR-10 scale). This finding contrasts with the results of several previous whole-body vibration studies, including the fore-and-aft direction study of Howarth and Griffin (1988), which reported exponents greater than unity. Further, the exponents obtained using the CR-10 scale were found to be smaller than those obtained using magnitude estimation, a fact which may be attributable to the category properties of the CR-10 scale since research (Baird, 1996) has shown that smaller exponents are usually obtained from category methods than from ratio estimation methods. This hypothesis is supported by the test data obtained using the CR-10 scale in the current study because few individuals exceeded a rating of 10 (extremely strong). This “ceiling effect” may have been caused by the reluctance of the test participant to define his or her own values above 10, as opposed to the possibility of choosing from among convenient existing values below this scale point.

As shown in Figures 5 and 6, the power exponents determined in the current study for fore-and-aft direction automobile vibration were found to range from 0.66 to 0.91, which corroborates the value of 0.84 obtainable from the numerical scale provided in BS 6841 (see figure 1 and table 1). It can be stated that the numerical scale of subjective response provided in BS 6841 is appropriate for the assessment of fore-and-aft direction automotive whole-body vibration. Based on the current study, however, it is also suggested that the semantic labels “not uncomfortable”, “a little uncomfortable”, etc., used in BS 6841 under-represent the actual subjective response. As an example, with a W_d frequency-weighted r.m.s. amplitude of 0.86 m/s^2, the maximum test stimuli used in the current study was considered “extremely uncomfortable” by all test subjects, while application of the BS 6841 guideline in the fore-and-aft direction would suggest, instead, vibration which was only “uncomfortable”.

Figure 7 presents a comparison of the mean discomfort responses obtained for each psychophysical test method by averaging the data across all participants for the cobblestone stimuli. Both methods produce a similar response curve, but the different numerical ranges for the subjective response leads to different Stevens’ Power Law exponents. Magnitude estimation produced a mean power exponent of 0.90 while the CR-10 scale produced a mean power exponent of 0.75. Determined over the same stimulus range (approximately 0 to 1.0 m/s^2), the power exponent was, of mathematical necessity (Laming, 1997), greater in the case of magnitude estimation since the subjective response values ranged from approximately 4 to 400, as opposed to the span of 0 to 10 for the CR-10.

Poulton (1968) has suggested six factors that may influence the psychological processes involved in judging sensory magnitude. Of these, he suggested that the magnitude range of the stimulus accounted for up to 33% of the total variation in the power exponents. Teghtsoonian (1971) later showed that up to 87% of the variation in the power exponents, found in a set of published studies, could be accounted for by the change in the stimulus range. Teghtsoonian further suggested that for a fixed psychophysical test protocol and fixed numerical value of the reference response, power law exponents vary with the inverse of stimulus range. Following the same reasoning, Laming (1997) has recommended that the widest possible stimulus range be used when accurate power law exponents are required. From a reanalysis of the data from 24 experiments involving several sensory modalities, Laming also determined that the range of the human numerical response was not a fixed value, but rather, grew with approximately the one-eight power of the stimulus range (Laming, 1997).

Following Laming (1997), the stimulus range L of the magnitude estimation data from the current experiment and from the previous studies of subjective response to whole-body vibration (see table 2) was defined to be the ratio of the maximum and the minimum stimuli, while the human response range R was defined to be the ratio of the maximum and the minimum numerical responses. A regression line describing the relationship between the two was then determined, and the result is presented in figure 8 together with Laming's results for 24 psychophysical studies involving several sensory modalities. As a sensory modality characterised by a smaller stimulus range than modalities such as sound and light, the results for whole-body vibration are characterised by a more pronounced rise in response range as a function of stimulus range (slope of 0.510 as opposed to 0.124). Both the current results and the previous work of Laming are characterised by low coefficients of determination (0.22 for the vibration data and 0.18 for Laming's analysis), nevertheless the expression for whole-body vibration presented here may prove a useful first approximation which can be used to correct for the effect of stimulus range when comparing the subjective responses obtained under different vibration conditions.

As a final point, Tables 3 and 4 present the mean power exponents and standard deviations obtained for each of the 16 participants using each psychophysical test method to assess the discomfort produced by the cobblestone stimuli. Magnitude estimation produced a greater inter-participant variability, with power exponents ranging from 0.65 to 1.34 with a mean value of 0.88 as opposed to values of 0.61 to 0.88 with a mean value of 0.74 for the CR-10 scale. The gender of each test participant is also indicated in Tables 3 and 4. For the sample size considered, a two-tailed t-test performed at a 5% confidence level for the magnitude estimation data suggested no significant differences between the power exponents of males and females. Instead, a two tailed t-test performed at a 5% confidence level for the CR-10 data suggested that the responses of the male and female participants were significantly different. Gender may therefore be a factor which requires control in psychophysical tests of human response to whole-body vibration. The current data, particularly the CR-10 results, suggests a power exponent closer to unity in the case of female participants.

6. Conclusions

Vibration stimuli measured at the seat guide of a small European automobile when driving over two representative road surfaces were used to investigate the human subjective response to seated, fore-and-aft direction, whole-body vibration. The method of magnitude estimation and the Borg CR-10 scale were used to determine the subjective responses of each of 16 test participants to both road vibration types in a laboratory setting. All mean Stevens' Power Law exponents were found to be less than unity, with the CR-10 scale having produced smaller exponents than magnitude estimation. The power exponents were found to range from 0.66 to 0.91, which corroborates the value of 0.84 obtainable from the numerical scale provided in BS 6841, which therefore appears appropriate for the assessment of fore-and-aft direction automobile vibration. While the numerical scale of BS 6841 was found to be accurate, the semantic labels "not uncomfortable", "a little uncomfortable", etc., were found to under-represent the actual human subjective response. From the results of the current investigation, the psychophysical test method, the vibration stimulus range and the gender of the test participant have all been found to be factors influencing the Stevens' Power Law exponents achieved from subjective testing. Each factor may therefore require control when attempting to compare human responses to vibration originating from different automobiles.

References

Abdullah, S., Giacomin, J.A. and Yates, J.R., 2004. A mission synthesis algorithm for fatigue damage analysis. Proceedings of the IMechE, Part D - Journal of Automobile Engineering 218, 243-258.

Baird, J.C., 1996. Sensation and Judgment – Complementary theory of psychophysics. Lawrence Erlbaum Associates Publishers, Mahwah, New Jersey.

Bellman, M.A., 2002. Perception of whole-body vibrations: from basic experiments to effect of seat and steering-wheel vibrations on passenger's comfort inside vehicles. PhD Thesis. The University of Oldenburg, Oldenburg.

Borg, G., 1998. Borg's perceived exertion and pain scales. Human Kinetics Publishers, Champaign, Illinois.

British Standards Institution, 1989. BS 7085: Safety aspects of experiments in which people are exposed to mechanical vibration and shock. British Standards Institution, London.

British Standards Institution, 1987. BS 6841: Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. British Standards Institution, London.

Dupuis, H. and Zerlett, G., 1986. The effects of whole-body vibration. Springer Verlag, Berlin.

Ebe, K. and Griffin, M.J., 2000. Quantitative prediction of overall seat discomfort. Ergonomics 43 (6), 791-806.

Fothergill, L.C. and Griffin, M.J., 1977. The subjective magnitude of whole-body vibration. Ergonomics 20, 521-533.

Gescheider, G.A., 1997. Psychophysics: the fundamentals. Lawrence Erlbaum Associates Publishers, London.

Giacomin J. and Bracco R., 1995. An experimental approach for the vibration optimisation of automotive seats. ATA 3rd International Conference on Vehicle Comfort and Ergonomics, Bologna, Italy, March 29-31.

Giuliano, F. and buco, A., 1995. A road test procedure for the definition of the vibrational mission of automobile seats, ATA 3rd International Conference on Vehicle Comfort and Ergonomics, Bologna, Italy, March 29-31.

Gregory, L.R. and Colman, M.A., 1995. Sensation and Perception. Longman, London.

Griffin, M.J., 1990. Handbook of Human Vibration. Academic Press, London.

Hempstock, T. I., and Saunders, D. J., 1976. Cross Modality determination of the subjective growth function for whole-body vertical, sinusoidal vibration. Journal of Sound and Vibration, 46(2), 279-284

Hiramatsu, K. and Griffin, M.J., 1984. Predicting the subjective response to nonsteady vibration based on the summation of subjective magnitude. Journal of Acoustical Society of America, 74 (4), 1080-1089.

Howarth, H.V.C. and Griffin M.J., 1988. The frequency dependence of subjective reaction to vertical and horizontal whole-body vibration at low magnitudes. Journal of American Society of Acoustics 83, 1406-1413.

International Organisation for Standardisation, 1997. ISO 2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration. International Organisation for Standardisation, Geneva.

Jang, H. –K., and Griffin, M. J., 1999. The Effect of Phase of Differential Vertical Vibration at the Seat and Feet on Discomfort. Journal of Sound and Vibration, 223(5), 785-794

Jang, H. –K., and Griffin, M. J., 2000. Effect of Phase, Frequency, Magnitude and Posture on Discomfort Associated with Differential Vertical Vibration at the Seat and Feet. Journal of Sound and Vibration, 229(2), 273-286.

Jones, A.J., and Saunders, D.J., 1974. A scale of human reaction to whole-body, vertical, sinusoidal vibration. Journal of Sound And Vibration, 35, 503-520.

Laming, D., 1997. The measurement of Sensation. Oxford University Press, Oxford.

Mansfield, N.J. and Griffin, M.J., 2000. Difference thresholds for automobile seat vibration. Applied Ergonomics, 31, 255-261.

Miwa, T., 1968. Evaluation methods for vibration effect, Part 4: Measurements of vibration greatness for whole body and hand in vertical and horizontal vibrations. Industrial Health 6, 1-10.

Neely, G., Ljunggren, G., Sylven, C. and Borg, G., 1992. Comparison between the Visual Analogue Scale (VAS) and the Category Ratio Scale (CR-10) for the evaluation of leg exertion. International Journal of Sports Medicine, 13 (2), 133-136.

Peebles, L. and Norris, B., 1998. AdultData: The Handbook of Adult Anthropometric and Strength Measurements. Department of Trade and Industry (DTI) Publication, London.

Poulton E.C., 1968. The new psychophysics: Six models for magnitude estimation. Psychological bulletin 69, 1-19.

Ruffel, C. M., and Griffin, M. J., 1995. Effects of 1-Hz and 2-Hz transient vertical vibration on discomfort. Journal of the Acoustical Society of America, Vol. 98, No. 4, pp 2157-2164.

Shoenberger, R.W., 1975. Subjective response to very low-frequency vibration. Aviation, Space and Environmental Medicine 46, 785-790.

Shoenberger, R.W. and Harris, C.S., 1971. Psychophysical assessment of whole-body vibration. Human Factors 13, 41-50.

Stevens, S.S., 1957. On the Psychophysical Law. Psychological Review 64, 153-181.

Stevens, S.S., 1971. Issues in psychophysical measurement. Psychological Review 78, 426-50.

Wos, H., Marek, T., Noworol, C. and Borg, G., 1988a. Perceptual rating of local vibration: A psychophysical study of hand-arm vibration of short duration (Part I). International Journal of Industrial Ergonomics 2, 143-150.

Wos, H., Marek, T., Noworol, C. and Borg, G., 1988b. The reliability of self ratings based on Borg's scale for hand-arm vibrations of short duration (Part II). International Journal of Industrial Ergonomics 2, 151-156.

Yokota, A. and Hirao, Y., 1998. Evaluation of Whole-Body Road Traffic Vibration in Building. Industrial Health, 36, 120-126

Table 1) The Borg CR-10 scale.

Numerical Scale	**Verbal Scale**	**Perception "P"**
0	Nothing at all	No "P"
0.3		
0.5	Extremely Weak	Just Noticeable
1	Very Weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very Strong	
8		
9		
10	Extremely Strong	Max "P"
11		
?		
(a)	Absolute Maximum	Highest Possible

Table 2) Stevens' Power Law exponents reported for whole-body vibration. Studies involving fore-and-aft direction vibration are indicated by X while studies involving vertical direction vibration are indicated by Z.

Study	Semantic Descriptor	Stimulus Type	Frequency [Hz]	Stimulus range (m/s^2)	Response range	Exponent (ß)
Miwa_Z (1968)	Vibration Greatness	Sinusoidal (< 1.0 m/s^2)	5.0	0.22-1.0	0.19-0.8	0.6
			20.0	0.07-1.0	0.19-0.8	0.60
			60.0	0.07-1.0	0.19-0.8	0.60
		Sinusoidal (> 1.0 m/s^2)	5.0	1.0-7.07	1.0-2.2	0.46
			20.0	1.0-7.07	1.0-2.2	0.46
			60.0	1.0-2.5	1.0-1.3	0.46
Miwa_X (1968)	Vibration Greatness	Sinusoidal (< 1.0 m/s^2)	5.0	0.71-1.0	0.19-0.8	0.60
			20.0	0.22-1.0	0.19-0.8	0.60
			60.0	0.22-1.0	0.19-0.8	0.60
		Sinusoidal (> 1.0 m/s^2)	5.0	1.0-22.38	1.0-4.0	0.46
			20.0	1.0-22.38	1.0-4.0	0.46
			60.0	1.0-7.07	1.0-2.2	0.46
Shoenberger & Harris_Z (1971)	Intensity	Sinusoidal	3.5	0.56-3.96	2.20-17.0	0.95
			5.0		2.05-18.0	1.04
			7.0		3.00-19.0	0.86
			9.0		2.80-19.0	0.97
			11.0		2.40-19.0	0.98
			15.0		2.80-18.0	0.91
			20.0		2.90-17.0	0.87
Jones and Saunders_Z (1974)_Mean	Intensity	Sinusoidal	5.0-80.0	1.5-6.0	1.9-7.0	0.93
Shoenberger _Z (1975)	Intensity	Sinusoidal	0.25	0.11-0.28	3.9-13.0	1.34
			0.4	0.12-0.48	2.8-20.0	1.47
			0.63	0.18-0.54	3.9-20.0	1.47
			1.0	0.18-0.54	3.3-18.0	1.48
			1.6	0.16-0.51	3.0-19.0	1.47
			2.5	0.12-0.48	3.0-19.0	1.35
			4.0	0.07-0.42	1.5-20.0	1.43
Hempstock and Saunders_Z (1976) (Sound as independent variable)	Sensation	Sinusoidal	5	60-100 dB	0.045-0.31	0.49
			10		0.42-5.01	0.57
			20		0.07-0.5	0.62
			30		0.08-0.63	0.66
			40		0.06-0.63	0.87
			80		0.09-0.63	0.63
Hempstock and Saunders_Z (1976) (Vibration as independent variable)	Sensation	Sinusoidal	5	0.5-4.0	83.1-97.8	1.43
			10	0.5-6.0	76-96.8	1.11
			20		73.8-96.1	1.36
			30		72.3-96.2	1.30
			40		63.2-94.6	1.20
			80		68.7-91.2	1.43
Fothergill and Griffin_Z (1977) (Magnitude Estimation)	Discomfort	Sinusoidal	10.0	0.175-2.8	2.0-42.4	1.13
Fothergill and Griffin_Z (1977) (Magnitude Production)	Discomfort	Sinusoidal	10.0	0.33-1.88	2.5-40	1.75
Hiramatsu and Griffin_Z (1984)	Discomfort	Sinusoidal	8.0	0.5-2.5	0.48-2.4	0.96
BS 6841 (1987)	Magnitude	-	0.5-80	0.315-2.5	0-5.0	0.84
Howarth and Griffin_Z (1988)	Annoyance	Sinusoidal	4.0	0.04-0.4	5.0-200	1.21
			5.4		10-200	1.04
			8.0		10-200	1.09
			11.3		10-200	1.06
			16.0		10-200	1.14
			22.5		5.0-200	1.47
			31.5		10-200	1.35
			44.5		10-140	1.28
			63.0		10-180	1.29
Howarth and Griffin X (1988)	Annoyance	Sinusoidal	4.0	0.04-0.4	40-230	0.68
			5.4		30-300	0.85
			8.0		18-140	0.93
			11.3		3.5-100	1.41
			16.0		1-140	1.99
			22.5		1.0-80	1.75
			31.5		1.0-70	1.76
			44.5		1.7-70	1.57

			63.0		1.0-70	1.69
Ruffel and Griffin_Z (1995)	Discomfort	Sinusoidal	1-2	0.63-1.6	90-280	1.14
Yokota and Hirao_Z (1998)	Sensation	Road vibration (no shocks)	-	0.02-0.25	0.11-3	0.68
Yokota and Hirao_Z (1998)	Sensation	Road vibration (with shocks)	-	0.025-0.5	0.2-5	0.61
Jang and Griffin_Z (1999)*	Discomfort	Sinusoidal	4	0.25-1.6	20-400	1.35
Jang and Griffin_Z (2000)*	Discomfort	Sinusoidal	2.5	0.25-1.6	20-150	1.08
			3.15	0.25-1.6	40-400	1.22
			4	0.25-1.6	40-400	1.34
			5	0.25-1.6	80-400	0.95
			6.3	0.25-1.6	90-300	0.70
Ebe & Griffin_Z (2000)_Wood Seat	Discomfort	Random	0.8-20.0	0.10-1.61	50-360	0.72
Ebe & Griffin_Z (2000)_Foam A (Stiffness: 21.6N/mm)				0.04-0.88	21-300	0.94
Ebe & Griffin_Z (2000)_Foam B (Stiffness: 18.4N/mm)				0.04-0.82	23-330	0.92
Ebe & Griffin_Z (2000)_Foam C (Stiffness: 16.6N/mm)				0.04-0.76	20.5-300	0.94

* Only in-phase motion data with thigh contact is presented for ease of comparison with work by other authors

Table 3 Individual Stevens' Power Exponents β obtained by means of a magnitude estimation protocol for each of 16 test subjects.

Subject's Gender	**Exponent (β)**	**Standard Deviation (σ)**
M1	1.34	0.07
M2	0.68	0.06
M3	0.98	0.02
M4	1.04	0.04
M5	0.66	0.06
M6	0.95	0.02
M7	0.89	0.05
M8	0.65	0.01
F1	0.82	0.03
F2	0.85	0.09
F3	0.81	0.04
F4	0.65	0.09
F5	0.89	0.02
F6	1.14	0.02
F7	0.80	0.04
F8	1.06	0.02

Table 4 Individual Stevens' Power Exponents β obtained by means of a Borg CR-10 scale protocol for each of 16 test subjects.

Subject's Gender	Exponent (b)	Standard Deviation (s)
M1	0.61	0.06
M2	0.62	0.08
M3	0.65	0.03
M4	0.65	0.02
M5	0.69	0.05
M6	0.66	0.06
M7	0.68	0.05
M8	0.66	0.03
F1	0.87	0.01
F2	0.84	0.04
F3	0.82	0.01
F4	0.79	0.03
F5	0.82	0.02
F6	0.86	0.02
F7	0.8	0.01
F8	0.83	0.04

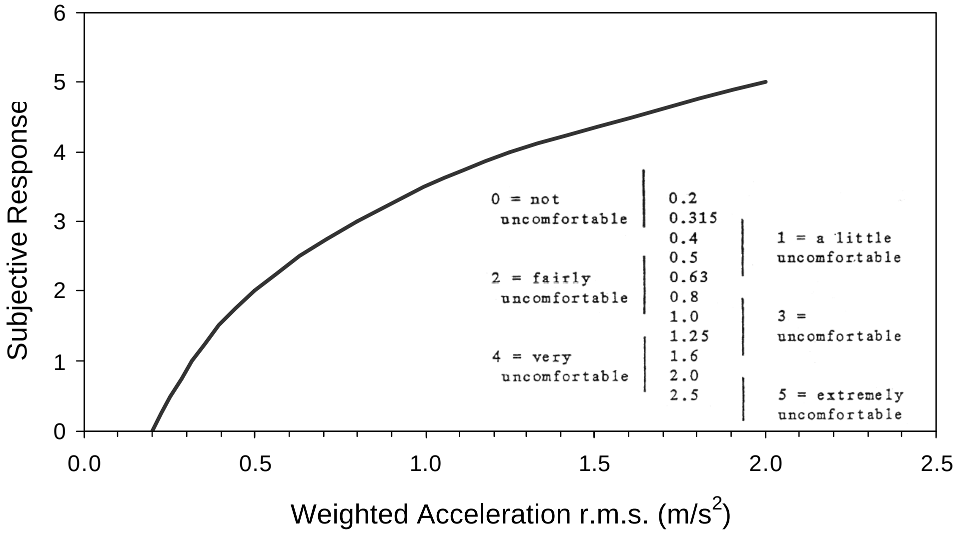

Figure 1) Human subjective discomfort as a function of the frequency-weighted r.m.s. acceleration level, as defined in BS 6841 (1987).

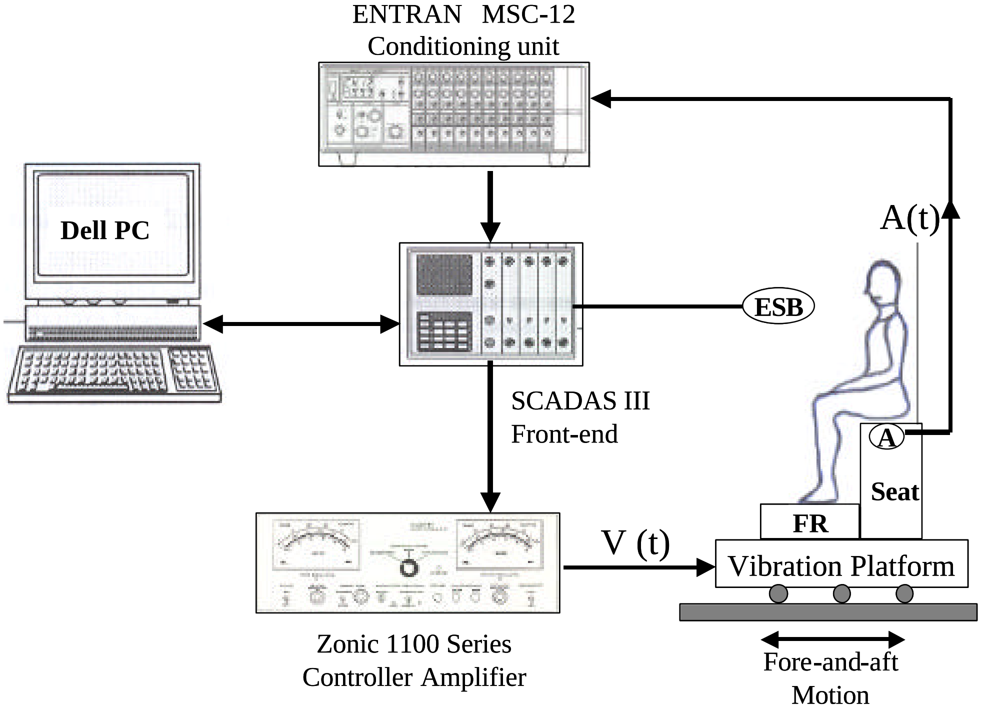

Figure 2) Fore-and-aft direction whole-body vibration test rig.

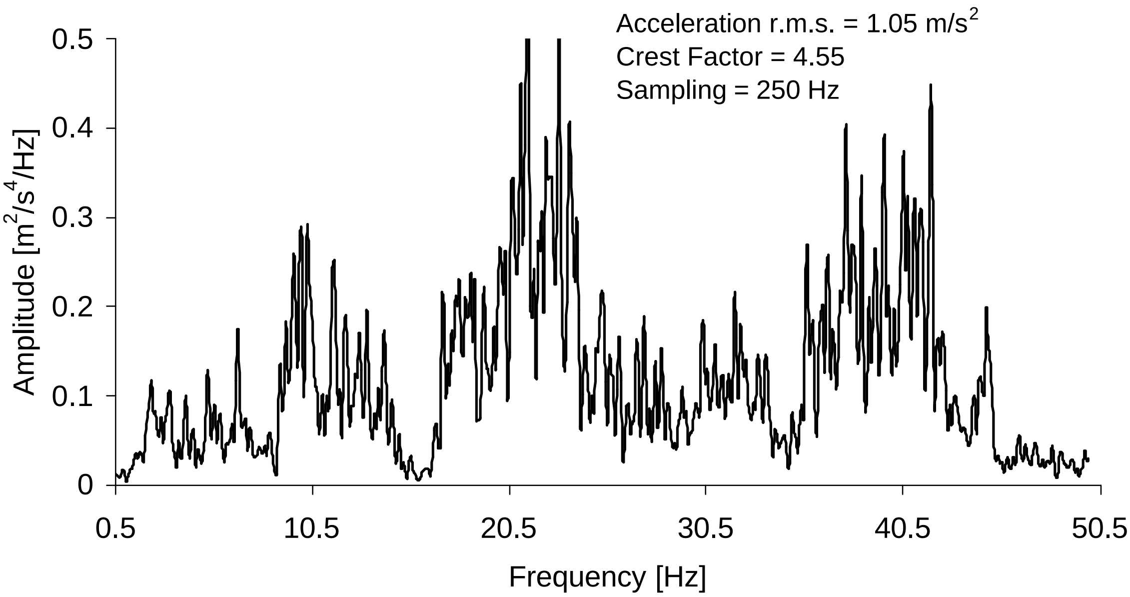

Figure 3) Autopower spectral density function of the cobblestone fore-and-aft direction road acceleration stimuli.

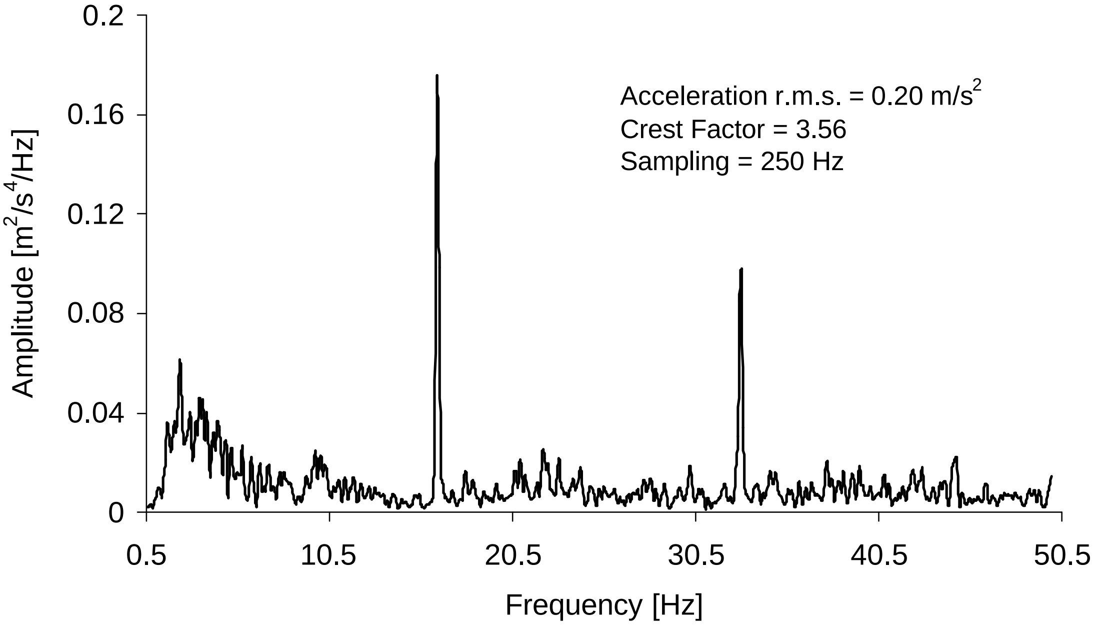

Figure 4) Autopower spectral density function of the motorway fore-and-aft direction road acceleration stimuli.

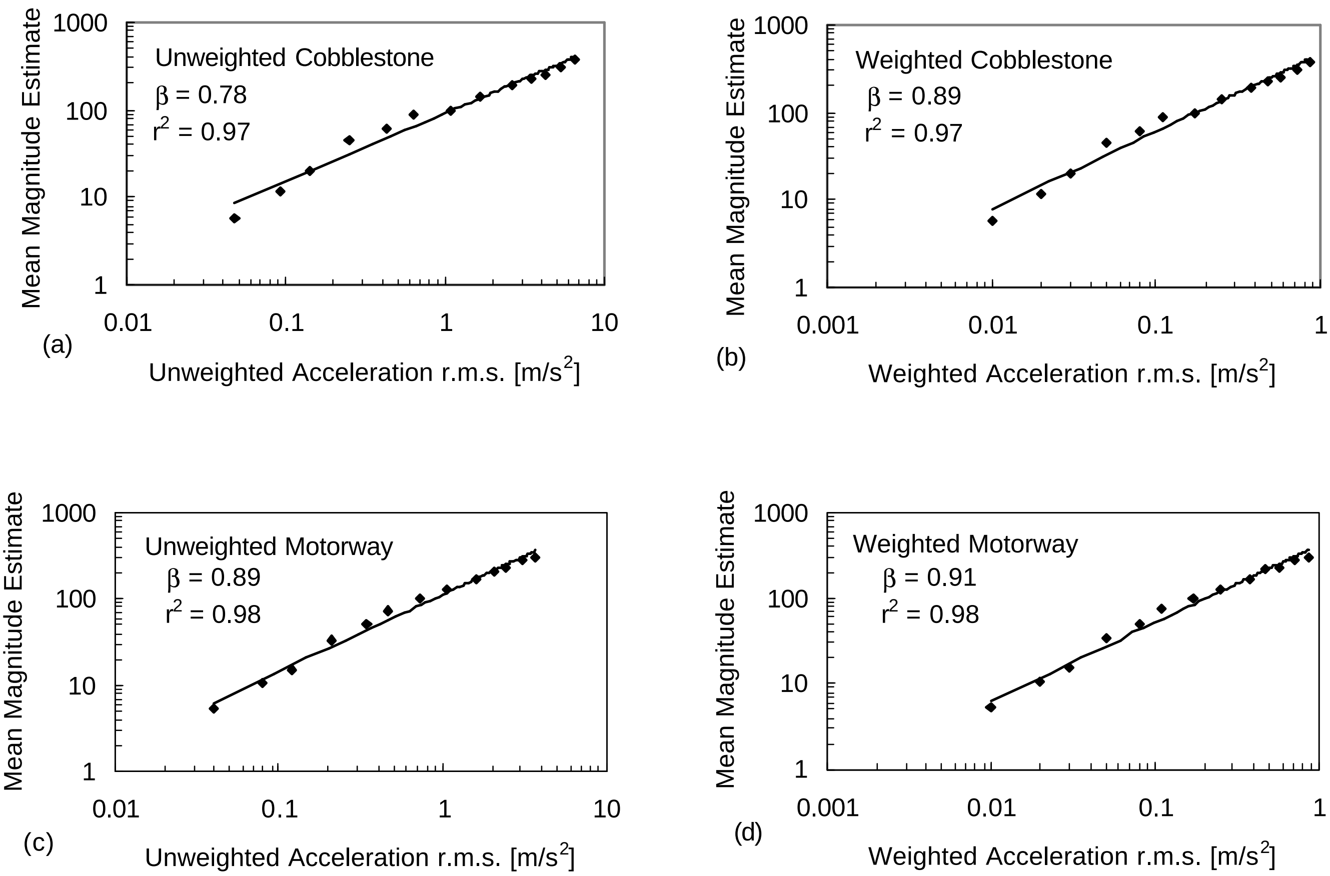

Figure 5) Mean magnitude estimates as a function of the:

a) unweighted cobblestone acceleration r.m.s. values [m/s^2]

b) frequency-weighted cobblestone acceleration r.m.s. values [m/s^2]

c) unweighted motorway acceleration r.m.s. values [m/s^2]

d) frequency-weighted motorway acceleration r.m.s. values [m/s^2]

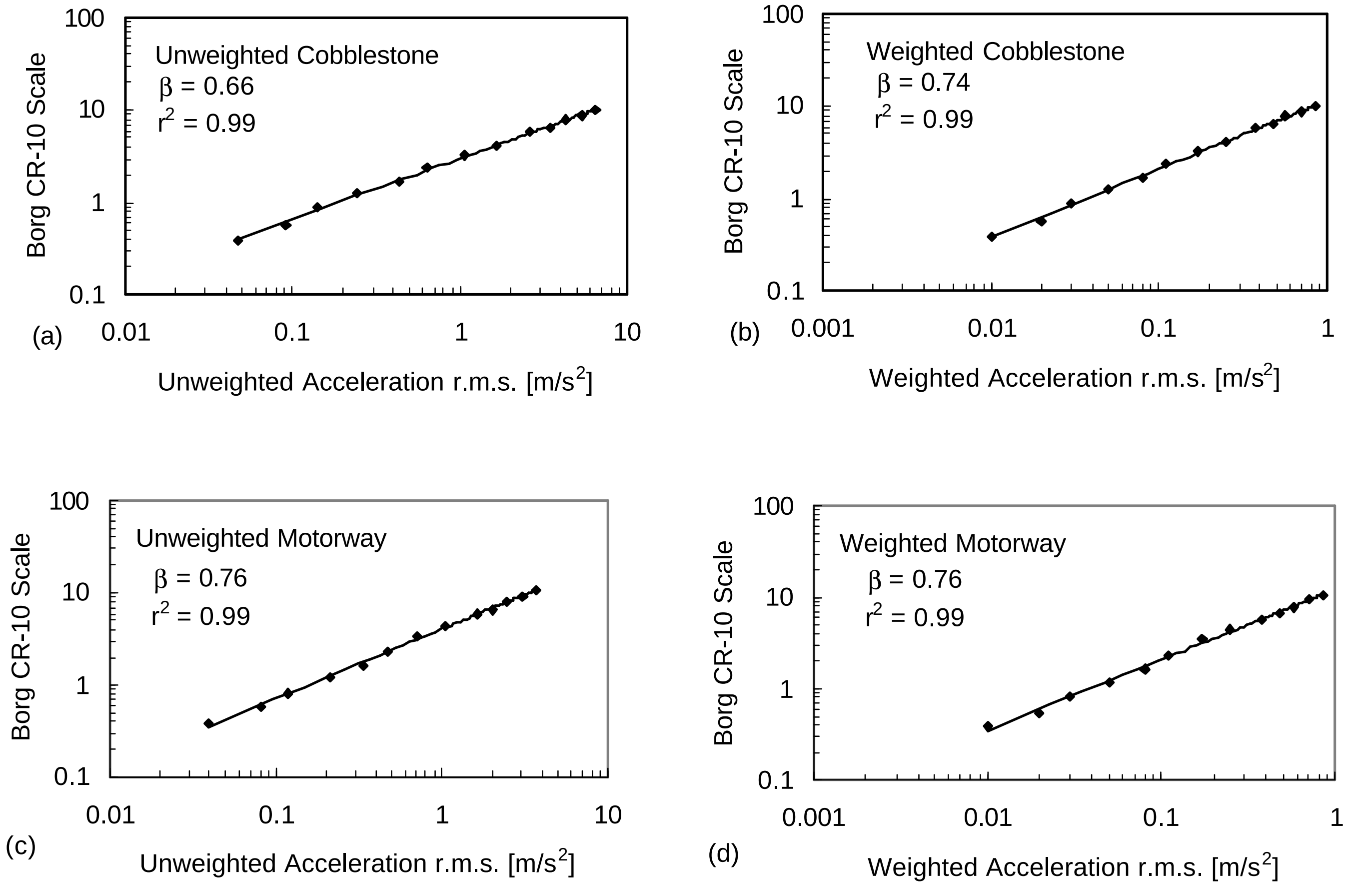

Figure 6) Mean Borg CR-10 estimates as a function of the:

a) unweighted cobblestone acceleration r.m.s. values [m/s^2]

b) frequency-weighted cobblestone acceleration r.m.s. values [m/s^2]

c) unweighted motorway acceleration r.m.s. values [m/s^2]

d) frequency-weighted motorway acceleration r.m.s. values [m/s^2]

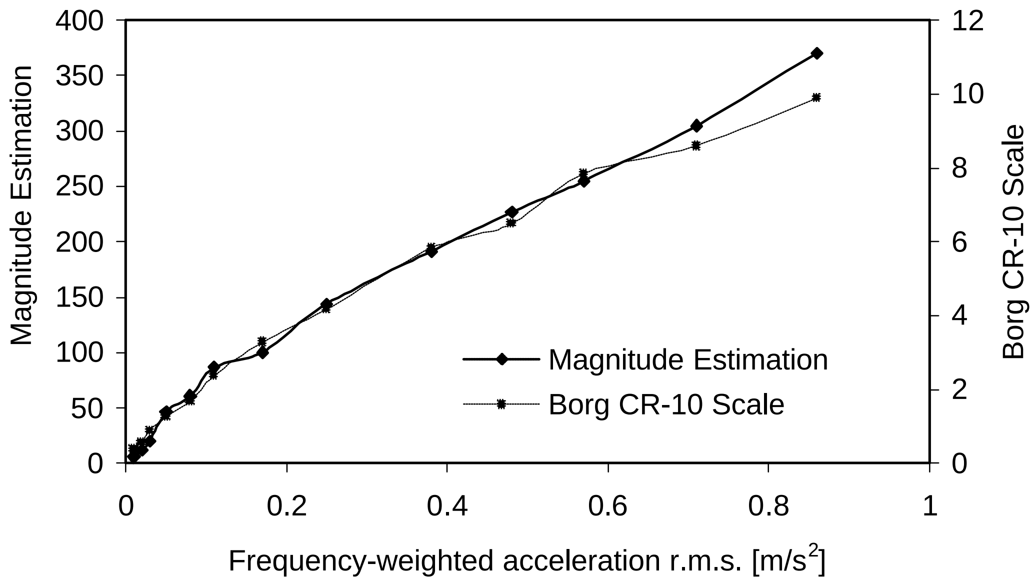

Figure 7) Mean subjective discomfort from magnitude estimation and from the Borg CR-10 scale for the cobblestone stimuli by averaging across all test participants.

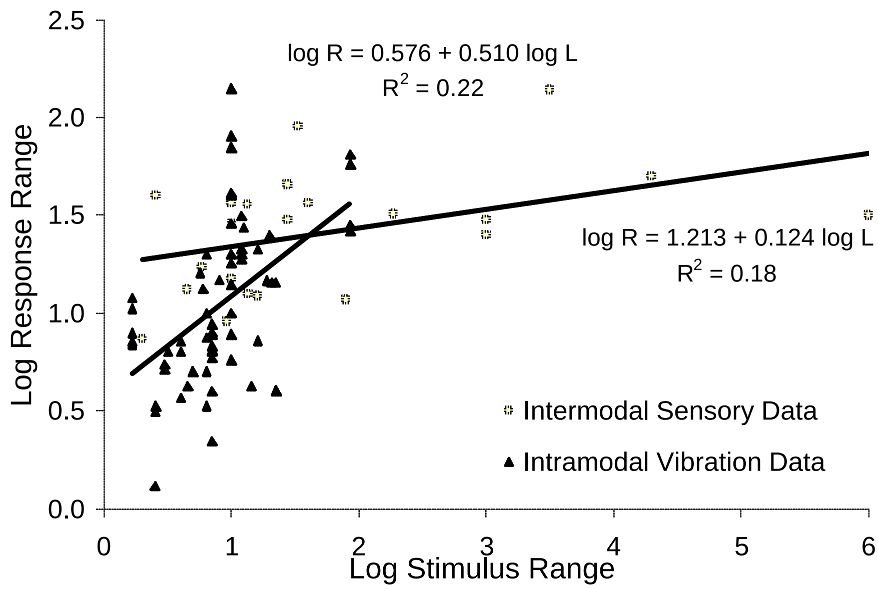

Figure 8) Logarithm of the range of the mean subjective numerical response as a function of the logarithm of stimulus range. Intermodal sensory data of 24 sensory modalities from Laming (1997), while intramodal vibration data from summary Table 2.