Difference thresholds for a vehicle on a 4-poster test rig

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Highlights

• Difference thresholds obtained for two roads with multi-axes vibration.

• Weber's law holds for the two roads and vehicle considered.

• Vertical component ride value can be used to estimate difference thresholds.

Abstract

Improving vibration-induced discomfort often requires a reduction in the vibration experienced by vehicle occupants. Simulation software and test equipment are able to measure changes in vibration that are too small for humans to perceive. It is therefore important to know how large the change in vibration should be, i.e. the difference threshold, for occupants to perceive an improvement in comfort. This study estimates difference thresholds for ten automotive engineers seated in a vehicle on a 4-poster test rig. Participants were exposed to multi-axis vibration. Component ride values were calculated by applying BS 6841 frequency weightings and multiplication factors to seat accelerations in the six directions. Difference thresholds were estimated for two road profiles using the vertical component ride value and combined point ride value (i.e. the root-sums-of-squares of the six component ride values). The two road profiles had different magnitudes, but the same spectral shape, resulting in median vertical component ride values of 0.58 and 1.01 $m.s.^{-2}$, root-mean-square. An up-down transformed response rule was used with a three-down-one-up response grouping to estimate difference thresholds at a 79.4% probability level. The median relative difference threshold for the two roads was 10.13 % and 8.58 % considering the vertical component ride value, and 10.99 % and 9.24 % considering the combined point ride value. No statistically significant difference was found between the medians of the relative difference threshold over the two roads considering either of the two ride values (*p*-value = 0.995 in both instances), suggesting that Weber's law holds.

Key words: difference threshold; whole-body vibration; multi-axis vibration; vibration-induced discomfort; ride comfort.

1 Introduction

Ride comfort of vehicles is a complex field that incorporates factors such as psychological effects, ergonomics, noise and vibration exposure. The discomfort arising from vibrations are considered in this study. Occupants' subjective evaluation of the vibration experienced while driving might influence their opinion of a vehicle [1, 2]. Therefore, in order to improve the experience of the occupants, vehicle manufacturers are continually improving their suspension systems and other vibration isolation elements.

Research on improving vibration comfort over recent years is based on the assumption that a reduction in vibration will result in an improvement in comfort [3]. Simulation models and test equipment are able to measure changes in vibration that are too small for humans to perceive [1]. Knowledge of the smallest change in magnitude of vibration that can be detected by humans is important during the implementation of design changes [1]. With this knowledge, the risk of costly design changes being implemented without the end user noticing a difference can be mitigated.

For vehicle vibration on a seat, Mansfield and Griffin [1] defines the difference threshold (DT) as: "...the minimum change in the magnitude of the whole-body vibration required for the seat occupant to perceive the change in magnitude." The DT is also referred to as the just noticeable difference. DTs are estimated at a specific stimulus magnitude. Weber's law states that the ratio between the reference stimulus magnitude (I) and the just noticeable change in stimulus magnitude (ΔI), are at a constant ratio known as the Weber fraction. The relative DT is obtained by taking the percentage of the Weber fraction (see Equation 1). The change in stimulus magnitude, ΔI, is also known as the absolute DT. DTs is an umbrella term used to refer to both the absolute and relative DT.

$$Relative\ difference\ threshold = \frac{\Delta I}{I} \times 100 \quad (1)$$

Mansfield and Griffin [1] state that although frequency weightings have been established to predict relative discomfort and compare different vehicles, there has been little research in the DTs of whole-body vibration. Pielemeier *et al.* [4] also discusses the importance of DTs in determining the required intensity accuracy of vibration simulators when performing subjective testing. They state that the DT is an important psychophysical parameter in understanding subjective vibration assessment. Three studies [3, 5, 6] investigated DTs for participants seated on a rigid surface exposed to sinusoidal vibration. Two other [1, 4] investigated DTs with participants seated on a car seat for random vibration. All five of these studies estimated DTs for vertical vibration only. When driving in a vehicle, occupants are exposed to not only vertical vibration, but also fore-aft, lateral, roll, pitch and yaw vibration. Knowledge of the DTs for whole-body vibration in a multi-axis vibration environment, such as a vehicle, would be beneficial in the evaluation of design changes. Furthermore, if Weber's law holds for DTs in a vehicle over different roads, it would reduce the amount of required experimental tests to determine the DTs for different road conditions.

This study aims to estimate the DTs for drivers seated in a vehicle, on a 4-poster test rig, exposed to all six axes of vibration as if driving in a straight line over two roads of different roughness. Secondly, the study aims to determine whether Weber's law holds over the two roads.

2 Materials

2.1 Participants

The participants consisted of ten male engineers who all work in the field of vehicle engineering. Only male participants were included as the effect of gender on DTs was outside the scope of the current study. Participants had a median age of 34 years (Inter quartile range (IQR) = 75th percentile – 25th percentile = 38 – 25 = 13 years), a median stature of 180 cm (IQR = 182 – 174 = 8 cm), and a median weight of 82 kg (IQR = 85 – 74 = 11 kg). Each participant was provided with an informed consent form stipulating the medical conditions listed in BS 7085 [7] that would deem them unfit to participate. The required ethical clearance was obtained from the Research Ethics Committee of the faculty of Engineering, Built Environment and Information Technology at the University of Pretoria (Ethical approval reference number EBIT/25/2016).

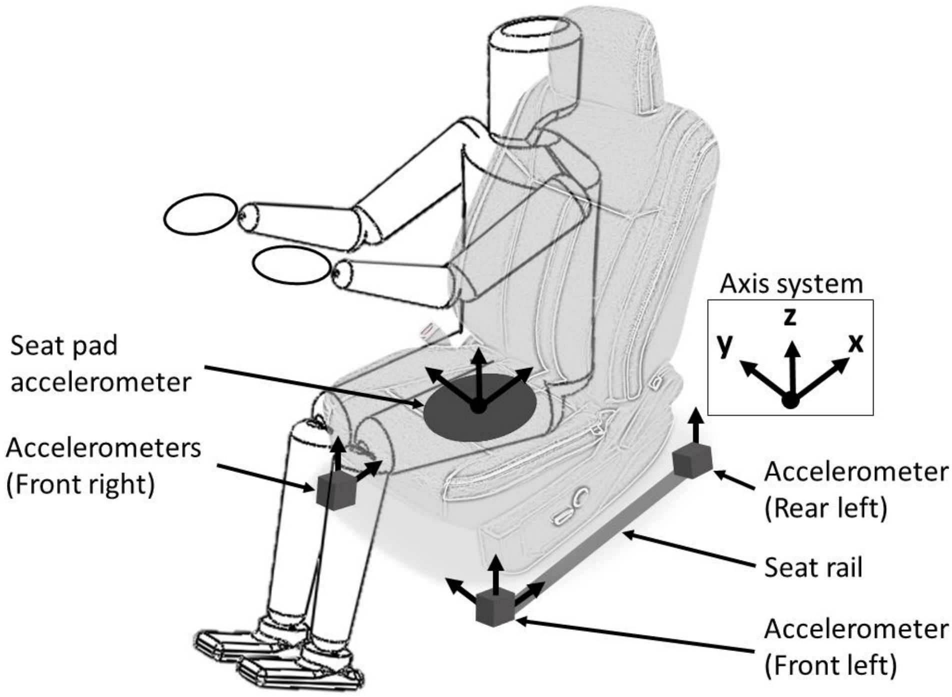

Figure 1. Participant seated on driver seat in vehicle, with accelerometer locations and measurement directions indicated

2.2 Apparatus

A left hand drive Range Rover Evoque eD4 Sports Utility Vehicle was placed on a 4-poster test rig. The rig consisted of four actuators that actuate in the vertical direction only. Actuators under the front wheels were 40 kN actuators (PL z40NQ160, Schenck) and under the rear wheels 25 kN actuators (PL z25NQ160, Schenck). The vehicle's wheels interfaced with the actuators through round plates with an inner flat surface and elevated sides that is rigidly fixed to the actuators. The rig was controlled by an Instron 8800ml controller using Instron RS Studio ml as part of Instron RS LabSite Modulogic 2.0 software suite. The actuators could excite a frequency range of 0 Hz – 40 Hz at the required displacements. Acceleration was measured on the driver seat surface and on three locations on the seat rail (or seat guide) as shown in Figure 1. A tri-axial accelerometer (4630-005, Measurement Specialties) was used at the front left point of the seat rail. Two accelerometers (M352C68, PCB Piezotronics (x-axis); 4000A-005, Measurement Specialties (z-axis)) were used at the front right point of the seat rail. A single accelerometer (4000A-005, Measurement Specialties) was used to measure acceleration in the z-axis at the rear left point of the seat rail. Acceleration (x-, y- and z-axis) was measured on the seat surface below the ischial tuberosities of the driver using a seat pad accelerometer (356B40, PCB Piezotronics). The x-axis is in the fore-aft direction, the y-axis in the lateral direction and the z-axis in the vertical direction. Data was sampled at 2000 Hz using a Prosig P8020 with a 400 Hz anti-aliasing filter. The semi-anechoic chamber in which the 4-poster test rig is situated created an environment with limited aural and visual inputs. Aural inputs to participants from sounds generated by the actuators, suspension and tyres were reduced by using earplugs. The use of earplugs eliminated the high frequency squeaking sounds from the tyres on the actuator plates, while lower frequency sounds were less attenuated. Participants were not given specific instructions with regard to keeping their eyes open or closed. The air conditioner of the vehicle was set to 21.5°C.

3 Method

DTs were determined for participants seated in the driver seat of a vehicle. The vehicle was excited by two road profiles on a 4-poster test rig. Participants' DTs were determined during two sessions over a 5-day period. One of the two road profiles was considered during each session. The order in which the two roads were presented to participants over the two sessions was randomized. Participants were given exactly the same briefing during their first session. They were instructed to hold the steering wheel with both hands as they would usually do as a driver, wear their safety belt and to keep a comfortable but good upright posture, with their lower back against the backrest. They were informed that a session would take between 40 minutes and 1 hour 40 minutes and that they may indicate to stop the test at any point. A break of 15 minutes was taken after approximately 60 minutes of testing.

Participants were presented with two stimuli of 20 seconds each, with a pause of 2 seconds between them. The two stimuli represented a reference and an alternative stimulus, referred to as a trial. Reference and alternative stimuli within a trial were presented to the participant in a random order. In the current study, the magnitude of the alternative stimulus was greater than that of the reference stimulus. After the participant was presented with the two stimuli, the participant was asked: "Did you feel more discomfort during the first or the second stimulus?". A 'correct' response was recorded if the participant was able to identify the larger stimulus of the two. This assumes that the stimulus with the larger magnitude should generally be perceived as more uncomfortable. The reference stimulus stays the same between trials, with the magnitude of the alternative stimulus governed by the psychophysical testing method used.

3.1 Psychophysical testing method

The up-down transformed response (UDTR) rule with a three-down-one-up response grouping was selected as the psychophysical testing method. The UDTR rule governs the magnitude of the alternative stimuli based on the previous trial's response. It essentially aims to place observations near the magnitude of the stimulus at which the probability of a 'correct' response is at a specific level (i.e. a percentage point). The response grouping depends on the percentage point to be estimated [8, 9]. For a percentage point at 0.794 probability level, a down group is formed by three consecutive correct responses, •••, and an up group by any of the following sequence of responses, × or •× or ••×. Circles indicate 'correct' responses and crosses 'incorrect' responses. It implies that the magnitude of the alternative stimulus is reduced by one level only after three consecutive correct responses (a down group), and increased by one level after any one of the up groups. This response grouping is referred to as a three-down-one-up. The UDTR rule converge at the stimulus magnitude, x, where the probability of obtaining a down group is the same as obtaining an up group [9]. Therefore, using a three-down-one-up response grouping $[P(x)]^3$ = 0.5. This results in $P(x)$ = 0.794, where $P(x)$ is the probability of obtaining a correct response at stimulus magnitude x. In this case x is the magnitude of the alternative stimulus. The three-down-one-up response grouping was selected as it gives a good compromise between the probability level and duration of testing, and was used in previous studies [1, 3, 6].

Figure 2 gives a visual layout of an example UDTR rule with a three-down-one-up response grouping. A peak (responses P_1, P_2, P_3 and P_4) is formed when the gradient of the procedure changes from an increasing alternative stimulus to a decreasing alternative stimulus. A trough (responses T_1, T_2, T_3 and T_4) is formed when the gradient changes from a decreasing alternative stimulus to an increasing alternative stimulus. Peaks and troughs are referred to as reversals. A peak and a trough together form a set. In this study the test continued until eight reversals (four sets) were obtained.

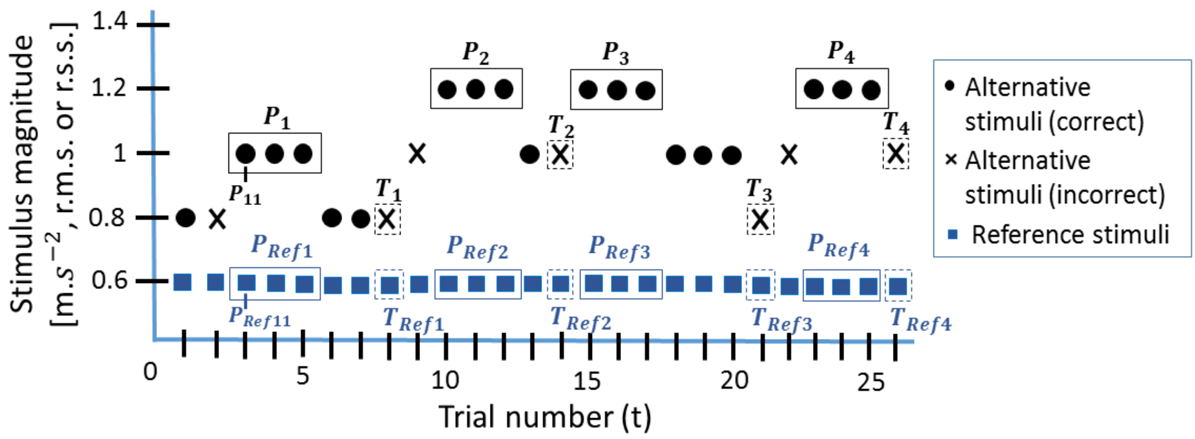

Figure 2: Example of a test procedure using the up-down transformed response rule with a three-down-one-up response grouping. Note that in the current study the stimulus magnitude is quantified using the vertical component ride value [m.s^{-2}, r.m.s.] and combined point ride value [m.s^{-2}, r.s.s.], as discussed in section 3.3.

3.2 Estimation of difference threshold

The previous section described the test method for data collection in order to estimate the percentage point of interest. Several methods exist [9, 10] to estimate the percentage point from the gathered data. The method developed by Wetherill *et al.* [8, 11] is used for its simplicity and efficiency. In this method, the average of the peaks and troughs are used to provide the estimate of the alternative stimulus magnitude at which there is a 79.4% probability that the larger of the two stimuli in a trial will be identified by the participant.

Equation 2 presents the implementation of this method and the estimation of the absolute DT for each participant. Equation 3 calculates the reference stimulus magnitude for each participant. The relative DT for a participant is calculated by substituting equation 2 and 3 into equation 1.

$$\Delta I = \frac{\sum_{i=k}^{m}\left[\frac{1}{n}\sum_{j=1}^{n}\left(P_{ij} - P_{Refij}\right) + \left(T_i - T_{Refi}\right)\right]}{2(m-k)} \qquad (2)$$

$$I = \frac{\sum_{i=k}^{m}\left(\sum_{j=1}^{n} P_{Refij} + T_{Refi}\right)}{(n+1)(m-k)} \qquad (3)$$

In the equations above, m is the number of sets, k is the number of the first set used in the calculation, and n is the number of consecutive correct responses which is governed by the selected response grouping. The first set of every participant was excluded from the calculation to eliminate starting errors [12]. Therefore, k = 2, m = *4* and n = 3 for the current study. P_{ij} is the alternative stimulus magnitude of the j^{th} trial associated with the peak in the

i^{th} set. P_{Refij} is the reference stimulus magnitude of the j^{th} trial associated with the peak in the i^{th} set. T_i is the alternative stimulus magnitude associated with the trough in the i^{th} set. And T_{Refi} is the reference stimulus magnitude associated with the trough in the i^{th} set.

The equations for calculating the absolute and relative DTs presented here allow for variability in the reference and alternative stimulus magnitude between trials. It is expected that there will be variability in the magnitude of these stimuli due to inter- and intra-participant variability, especially in the measurements from the seat pad. As the reference stimulus magnitude may contain some variability between trials, it is proposed here that the average of the reference stimuli associated with the peaks and troughs of the sets be used for the calculation of the reference stimulus magnitude I. The magnitude of the stimuli in equations 2 and 3 are quantified following the guidelines set out in the BS 6841 standard on evaluating the effect of whole-body vibration on comfort.

3.3 Quantification of stimulus magnitude

The effect of whole-body vibration on comfort was evaluated according to BS 6841 [13], instead of the more recent ISO 2631-1 [14], in order to compare relative DTs obtained in this study with those obtained by Mansfield and Griffin [1]. This was the only other study that determined DTs for participants on a vehicle seat exposed to random vibration in the vertical direction, which was based on in-vehicle measurements. For a comparison between the evaluation methods in BS 6841 [13] and ISO 2631 [14] of whole-body vibration in vehicles see Griffin [15] and Paddan and Griffin [16]. In the vehicle environment, the translational and rotational vibration at the seat, backrest and feet affects the comfort of the occupant. The vibration between the steering wheel and hands may also contribute. In the current study, only the translational and rotation vibration on the seat was measured. Backrest vibration was not measured due to limitations on the number of seat pad accelerometers available. Due to the relative low sensitivity to vibrations at the feet (considering the multiplication factors in BS6841 [13]), these measurements were not taken. BS6841 [13] does not provide weighting functions and multiplication factors for steering wheel vibrations and therefore these were not measured.

Seat acceleration in each axis (fore-aft, lateral, vertical, roll, pitch and yaw) is weighted in the frequency domain during post processing using the applicable weighting function and multiplication factor as defined in BS 6841 [13]. This results in the component ride values

(CRV) of the three translational vibrations (i.e. CRVx, CRVy, CRVz) and the three rotational vibrations (i.e. CRVrx, CRVry and CRVrz) at the seat. The root-mean-square (r.m.s.) is used to represent the magnitude of the acceleration since the crest factor for all stimuli was below six [13]. All frequency content below 0.5 Hz and above 80 Hz is discarded. The vertical component ride (CRVz) value might be sufficient to quantify discomfort, however, it is not recommended to neglect the other components if they are in excess of 25 % of the dominant component [13, 17]. Therefore, in order to account for the contribution of the other components to discomfort, the combined point ride value (PRVc) at the seat is calculated by taking the root-sums-of-squares (r.s.s.) of the six component ride values. The vertical component ride value and combined point ride value are used to quantify the stimulus magnitudes in equations 2 and 3.

Note that the seat accelerations used in calculating ride values are obtained in one of two ways. The first approximates the vibration (translation and rotation) at the location of the seat pad using the six translational measurements taken by the accelerometers on the seat rail and the equations in Griffin [17]. This assumes that the seat and seat rail form a rigid body. This results in seat vibrations that are independent of the dynamic interaction of the response of the driver's body and the compliant seat. Ride values presented in section 3.4 are calculated using seat accelerations approximated as described above. This was done as no participants were seated on the seat during stimuli generation and selection. The stimulus magnitudes in equations 2 and 3 are quantified by the ride values calculated from seat acceleration obtained in the second way. The rotational seat vibration (i.e. the roll, pitch and yaw) is calculated as discussed above, but with the translational seat vibration (i.e. lateral, fore-aft and vertical) as measured by the seat pad accelerometer.

3.4 Stimuli

Two road profiles were generated from a proving ground test track used for ride comfort evaluations. Vehicle speed over the test track was 80 km/h. One road profile, referred to as the 'rough' road, was generated by scaling the magnitude of the vertical displacement of the test track down to 71 % of the original. This allows for a 40 % increase during the UDTR rule before exceeding the original displacements of the test track. A second road profile was generated by scaling the magnitude of the test track down to 30 % to resemble a less rough road. This second road profile is referred to as the 'smooth' road. These two road profiles, differing only in magnitude, were the excitation input to the vehicle on the 4-poster. Each road profile consists of four displacement time-histories. The displacement time-histories represent the vertical road height under each wheel and is the command signal for the actuators. The displacement input to each wheel is distinct, i.e. the left track is not a copy of the right track (perfect cross-correlation) and the rear track is not a delayed copy of the front track (perfect auto-correlation). Figure 3 shows the power spectral density of the vertical displacement of the 4-poster's front left actuator superimposed on general road classes [18].

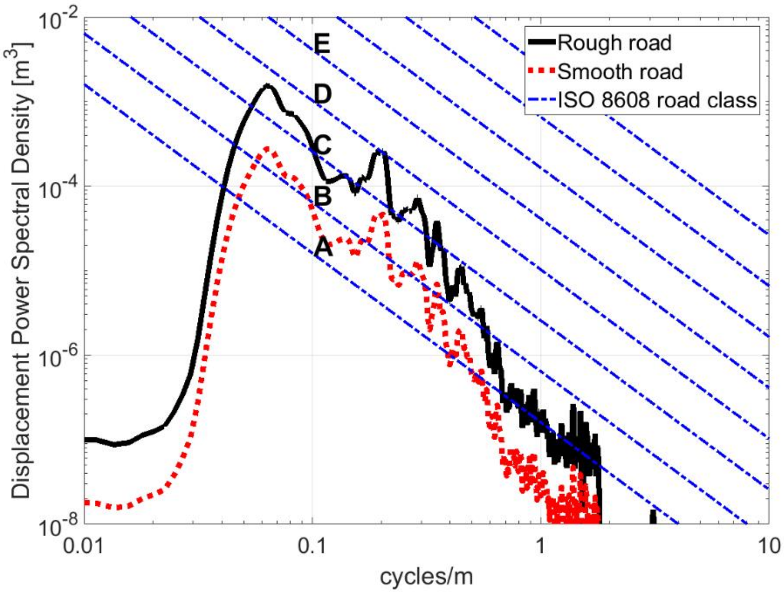

Figure 3. Power spectral density of the vertical displacement of the 4-poster's front left actuator superimposed on general road classes [18]

The displacement inputs from the two road profiles to the vehicle, results in the two reference stimuli, i.e. the seat vibrations associated with the two roads. The weighted and unweighted seat vibration for the two reference stimuli are presented in Table 1, with Figure 4 showing the time histories of the unweighted seat vibration. The alternative stimuli for the two roads were generated by multiplying the magnitude of the four displacement inputs of the specific road with a multiplication factor. The multiplication factors were determined through an iterative process based on the vertical acceleration on the seat rail's front left position. Ten alternative stimuli were generated, thereby providing ten levels of alternative stimuli for each of the two reference stimuli. Each level has approximately a 3% increase in the weighted r.m.s. of the vertical acceleration as measured on the seat rail's front left position, as indicated in Figure 5. Figure 5 shows the relationship between the change in vibration magnitude (weighted) at the front left seat rail in the vertical direction and the change in vibration magnitude at the seat as quantified by the ride values. The change in magnitude is calculated by subtracting the weighted magnitude of the reference stimulus from the weighted magnitude of the alternative at a specific level and dividing by the weighted magnitude of the reference. For both roads, the vertical component ride value (CRVz) and the combined point ride value (PRVc) seem to have a similar increase than the weighted vertical acceleration at the front left seat rail, with the other ride values having a larger increase. Therefore, although participants were exposed to six axes of vibration while seated in the vehicle, it was deemed adequate for this study to use the weighted vertical acceleration measured at the front left point on the seat rail, to generate the alternative stimuli.

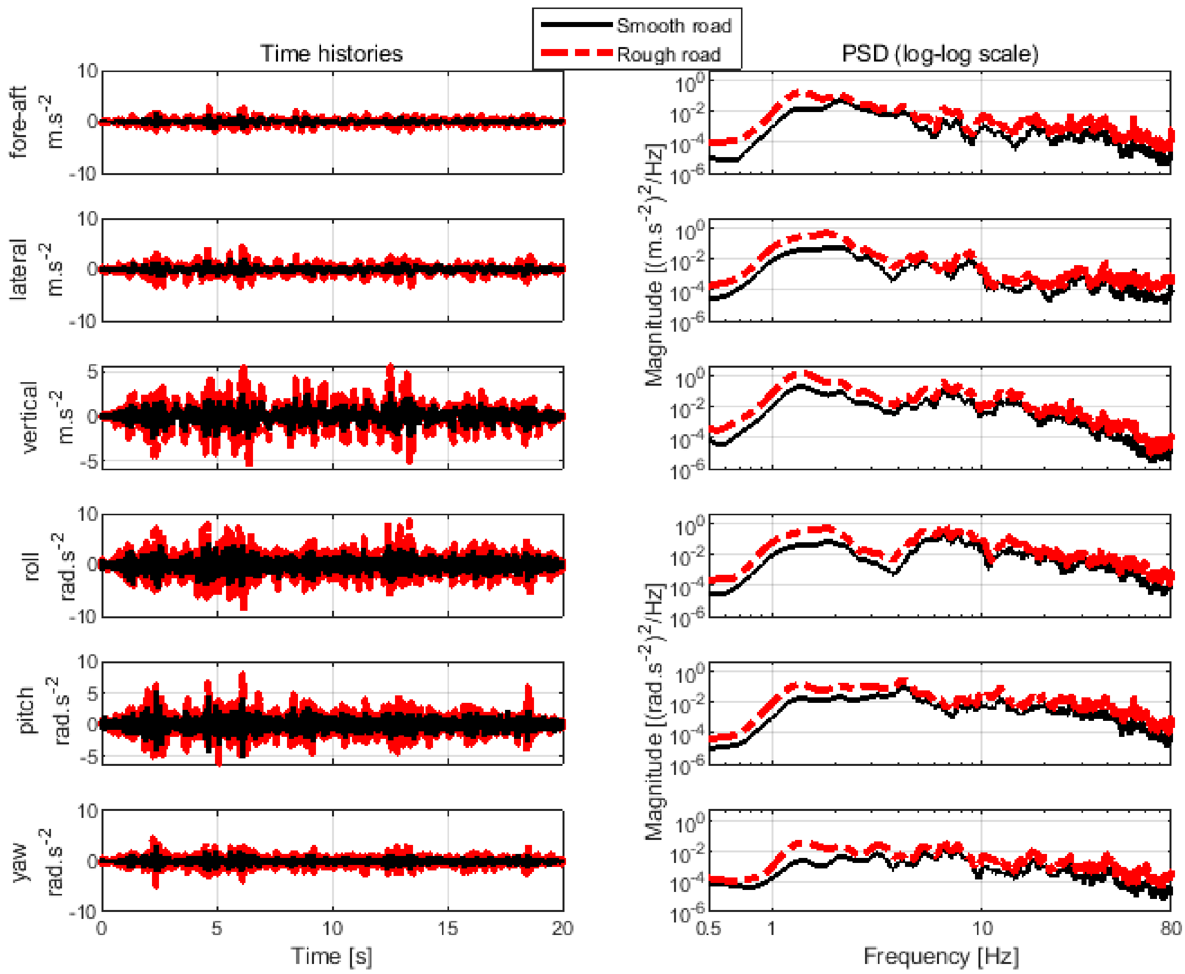

Figure 4. Time histories and power spectral density functions of unweighted seat vibrations, estimated from seat rail measurements, for the vehicle subjected to the two road profiles.

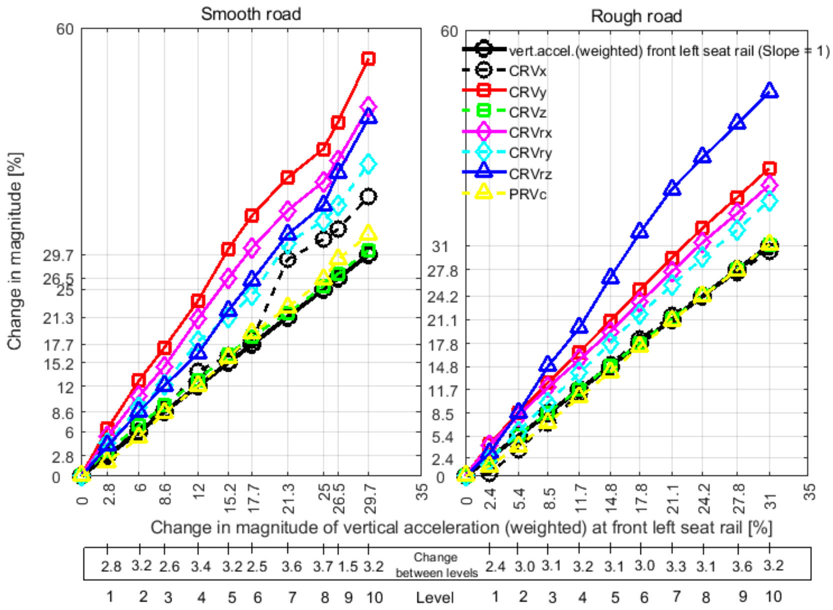

Figure 5. Relationship between the change in vibration magnitude measured at the front left position on the seat rail in the vertical direction (abscissa) and the change in seat vibration magnitude as quantified by the ride values (ordinate). The change in magnitude is calculated by subtracting the weighted magnitude of the reference stimulus from the weighted magnitude of the alternative at a specific level and dividing by the weighted magnitude of the reference. The percentage change between levels and the level number is given underneath the abscissa label.

Table 1. Seat vibrations estimated from seat rail measurements for the vehicle subjected to the two road profiles.

Unweighted	$m.s^{-2}$ r.m.s.			$rad.s^{-2}$ r.m.s.			
	Fore-aft	Lateral	Vertical	Roll	Pitch	Yaw	
Smooth road	0.28	0.37	0.66	0.95	0.64	0.37	
Rough road	0.53	0.78	1.36	1.68	1.11	0.62	
Weighted	$m.s^{-2}$ r.m.s.						$m.s^{-2}$ r.s.s.
	CRVx	CRVy	CRVz	CRVrx	CRVry	CRVrz	PRVc
Smooth road	0.18	0.23	0.54	0.11	0.05	0.01	0.62
Rough road	0.36	0.58	0.99	0.27	0.10	0.02	1.23

3.5 Statistical methods

Statistical analyses, including hypothesis testing, were done with IBM SPSS Statistics for Windows, Version 24.0 (IBM Corp., Armonk, NY, USA). Because of the small sample size, non-parametric hypothesis tests were used. In particular, to check whether Weber's law holds, Friedman's test and Dunn's multiple comparison tests were used to determine if the relative DTs differ significantly between the smooth and the rough road considering the vertical component ride value and the combined point ride value.

4 Results

The distributions of the absolute and relative DTs for the ten participants for the two roads are shown in the box plots in Figure 6, with Table 2 providing individual participant results. The median relative DT gives the value at which 50 % of the sample would have a 79.4 % probability of identifying the larger of the two stimuli. Likewise, the 75^{th} percentile for the relative DT is the value at which 75 % of the sample would have a 79.4 % probability of identifying the larger of the two stimuli. Friedman's test did indicate a significant difference between at least two median relative DTs across the two roads and the two ride values (*p*-value = 0.02). However, Dunn's multiple comparison tests only indicated significant differences between using the vertical component ride value on the rough road and the combined point ride value on the smooth road (*p*-value = 0.011). Importantly, there is no significant difference between the median relative DTs for the two roads using either of the two ride values. Table 3 presents the adjusted *p*-values (Bonferroni correction) for Dunn's multiple comparison tests.

The box plots in Figure 7 show the distribution of the unweighted and weighted seat acceleration magnitude of the six axes of vibration for the two reference stimuli, calculated from Eq.3, of all participants during the tests. The medians are presented in Table 4. This is similar to the expected reference stimulus magnitude presented in Table 1. From the weighted results in Figure 7 and Table 4, it is observed that the dominant vibration is in the vertical direction, as expected. For the smooth road the median weighted r.m.s. magnitude of acceleration for the lateral axis is larger than 25 % of the dominant vertical axes, with the fore-aft vibration just below 25 %. For the rough road the fore-aft, lateral and roll axes are larger than 25 % of the vertical axis. The lateral axes are the largest non dominant axis at 36 % for the smooth road and 55 % for the rough road.

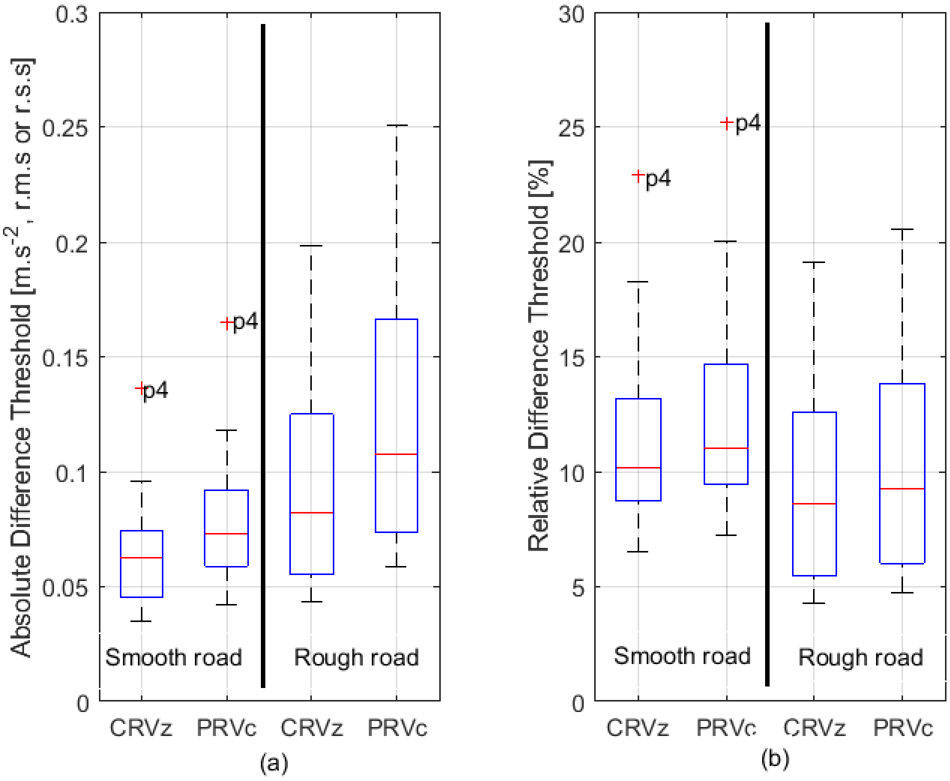

Figure 6: Box plots showing the distribution of the absolute difference thresholds (a) and the relative difference thresholds (b) for the ten participants considering the vertical component ride value (CRVz) and the combined point ride value (PRVc) at the seat for the two roads. (p4 – Participant 4). Vertical component ride value [m.s^{-2}, r.m.s.]; combined point ride value [m.s^{-2}, r.s.s.].

Table 2: Individual absolute and relative difference thresholds for the ten participants considering the vertical component ride value (CRVz) and the combined point ride value (PRVc). Vertical component ride value [m.s^{-2}, r.m.s.]; combined point ride value [m.s^{-2}, r.s.s.].

	Absolute difference threshold [m.s^{-2}, r.m.s. or r.s.s.]				Relative difference threshold [%]			
Road	Smooth		Rough		Smooth		Rough	
Participant	CRVz	PRVc	CRVz	PRVc	CRVz	PRVc	CRVz	PRVc
1	0.056	0.067	0.153	0.196	9.35	10.18	14.53	15.69
2	0.096	0.118	0.089	0.114	18.25	20.02	9.41	9.94
3	0.059	0.068	0.118	0.150	8.92	9.46	10.88	11.75
4	0.136	0.165	0.125	0.166	22.89	25.21	12.55	13.82
5	0.037	0.045	0.043	0.059	6.52	7.19	4.25	4.77
6	0.035	0.042	0.048	0.067	6.85	7.25	5.27	5.87
7	0.074	0.092	0.075	0.101	13.18	14.70	7.75	8.55
8	0.068	0.081	0.198	0.251	11.37	12.35	19.15	20.55
9	0.046	0.059	0.057	0.076	8.71	9.83	5.49	6.14
10	0.065	0.078	0.055	0.073	10.91	11.79	5.46	6.00
Minimum	0.035	0.042	0.043	0.059	6.52	7.19	4.25	4.77
25th percentile	0.046	0.059	0.055	0.073	8.71	9.46	5.46	6.00
Median	0.062	0.073	0.082	0.108	10.13	10.99	8.58	9.24
75th percentile	0.074	0.092	0.125	0.166	13.18	14.70	12.55	13.82
Maximum	0.136	0.165	0.198	0.251	22.89	25.21	19.15	20.54

*Table 3. Adjusted p-values (Bonferroni correction) for Dunn's multiple comparison tests (*p-value < 0.05: significant difference at 5% level)*

		Smooth road		Rough road	
		CRVz	PRVc	CRVz	PRVc
Smooth road	CRVz	-	0.500	0.995	1.000
	PRVc		-	0.011*	0.955
Rough road	CRVz			-	0.500
	PRVc				-

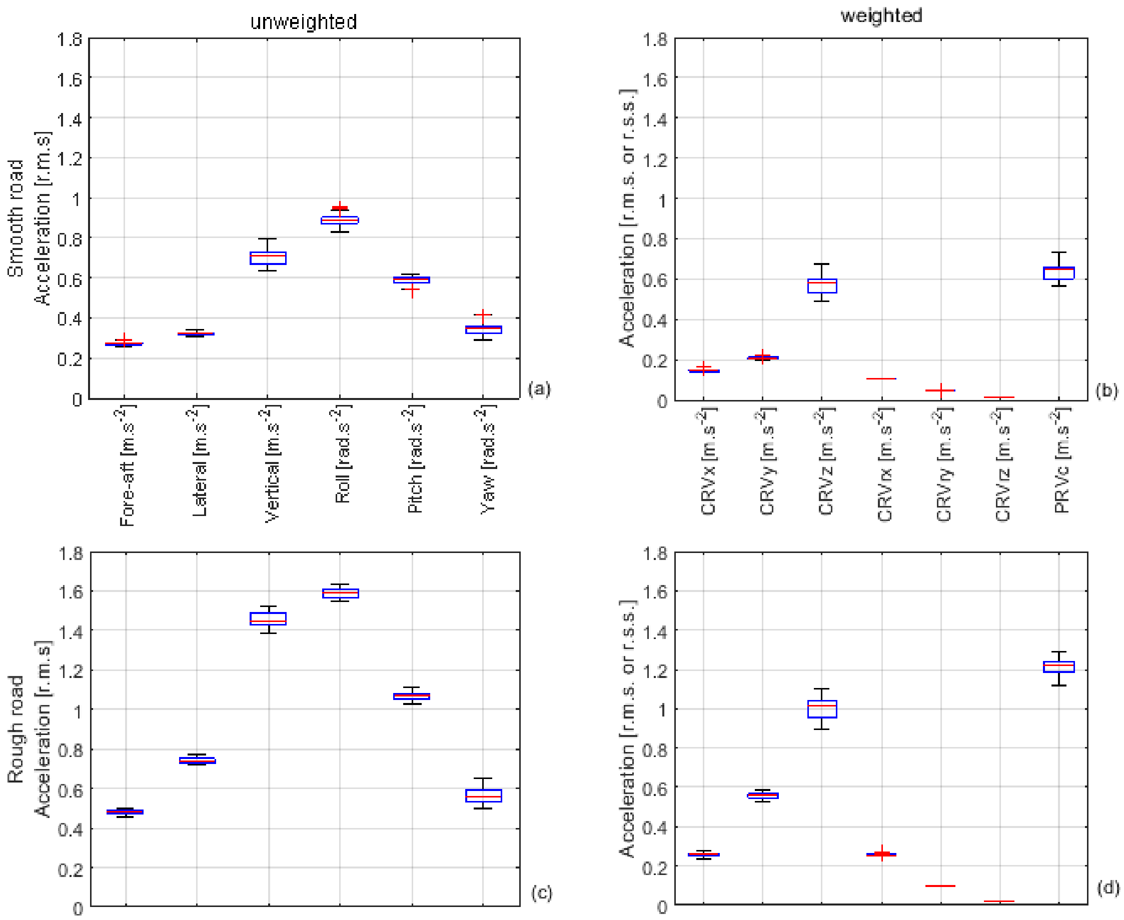

Figure 7: Box plots for the unweighted and BS 6841 weighted magnitude of seat vibration in the six axes experienced by participants during the reference stimuli (i.e. the stimulus magnitude I calculated from Eq.3) on the smooth road, a) unweighted b) weighted, and on the rough road, c) unweighted d) weighted. Vertical component ride value (CRVz) [m.s^{-2}, r.m.s.]; combined point ride value (PRVc) [m.s^{-2}, r.s.s.].

Table 4. Unweighted and weighted median magnitude of the six axes of seat vibration for the two reference stimuli (i.e. the stimulus magnitude I calculated from Eq.3).

Unweighted	m.s^{-2} r.m.s.			rad.s^{-2} r.m.s.			
	Fore-aft	Lateral	Vertical	Roll	Pitch	Yaw	
Smooth road	0.27	0.32	0.71	0.89	0.59	0.35	
Rough road	0.48	0.74	1.45	1.59	1.07	0.56	
	m.s^{-2} r.m.s.						m.s^{-2} r.s.s.
Weighted	CRVx	CRVy	CRVz	CRVrx	CRVry	CRVrz	PRVc
Smooth road	0.14	0.21	0.58	0.10	0.05	0.01	0.65
Rough road	0.26	0.56	1.01	0.26	0.10	0.02	1.22

5 Discussion

5.1 Difference thresholds

DTs were calculated for two reference stimulus magnitudes that stem from the two roads. The relative DTs indicate the required difference needed for participants to have a 79.4 % probability of identifying the larger of the two stimuli. In other words, modifications or adjustments to the vehicle's response that is below the relative DT might result in an insufficient amount of participants being able to identify the difference.

DTs were calculated considering the vertical component ride value as well as the combined point ride value. However, no significant differences between using the vertical component ride value and the combined point ride value on the two roads were found. This seems to suggest that despite other vibration components being larger than 25 % of the dominant vertical seat vibration, the vertical vibration is sufficient to quantify discomfort and can be used to estimate the relative DT. Studies [19, 20] on vibration in vehicles have found that for the vehicles and conditions considered, vibration in the vertical axis seems to be the dominant cause of discomfort and that the vertical acceleration had the best and only reliable correlation between the subjective and objective values. However, Gobbi *et al.* [21] found that for agricultural tractors, the vertical acceleration correlated well with the comfort perception only for single axis excitation of the tractor but was not sufficient to describe comfort of tractors when subjected to more complex excitations. Therefore, the reason that DTs can be determined using the vertical component ride value, may be due to this component being sufficient to quantify discomfort in a vehicle. However, an alternative reason may exist considering the following. Participants based their decisions, between the reference and alternative stimuli during the psychometric testing method, on all vibration inputs to them including vibrations at the backrest, feet and steering wheel. Therefore, the DTs determined implicitly took into account all vibrations, irrespective of which ride value is used in the calculation of the DT. Further investigation is required into the effect of the evaluation method (e.g. unweighted, BS6841 or ISO2631; combining multiple axes and locations or using the dominant axis on the seat only) on the DTs. Furthermore, the DTs were estimated for a driver in an environment that had limited visual and aural inputs, and without performing normal driving tasks. How these DTs would relate to a driver in a vehicle during actual driving scenarios (e.g. on a test track performing ride evaluations, in traffic, etc.) is unknown.

Figure 8 illustrates box plots for the relative DTs from the current study and three previously published studies [1, 3, 6]. All studies shown in Figure 8 determined relative DTs using the same psychophysical method and level of detection probability (i.e. 79.4 %). In contrast to the current study, these studies all exposed participants to seated whole-body vibration in the vertical direction only. Morioka and Griffin [3] and Forta *et al.* [6] both estimated DTs for 12 participants seated on a rigid surface exposed to sinusoidal vibrations. In the study of Morioka and Griffin [3], participants were exposed to four sinusoidal reference vibrations: two frequencies of 5 and 20 Hz and each at a magnitude of 0.1 and 0.5 $m.s^{-2}$, r.m.s. Median relative DTs range between 8.13 % and 12.25 %. Forta *et al*. [6] exposed participants to vertical sinusoidal vibration at eight frequencies and three magnitudes. Only the lower six frequencies are shown in Figure 8. Median relative DTs range between 9.5 % and 20.3 %. Mansfield and Griffin [1] estimated DTs for participants seated on an automobile seat exposed to vertical vibration recorded in a vehicle. The stimuli were reproductions of the vertical acceleration measured on the seat rail while driving over a tarmac and paved road. Ten male and ten female participants were exposed to four different reference stimuli. The tarmac stimuli were scaled and played to participants at weighted magnitudes of 0.2, 0.4 and 0.8 $m.s^{-2}$, r.m.s. and the paved road vibration stimulus were scaled to a weighted magnitude of 0.4 $m.s^{-2}$, r.m.s. Over the four stimuli, the median relative DTs range between 11.8 % and 14.1 %. Table 5 summarises the comparison of participant characteristics, stimuli and the median relative difference thresholds between studies. Differences in the various factors make it difficult to draw direct statistical comparisons between the studies. Differences in the range of the median values between these studies might be due to one or a combination of the factors. Mansfield and Griffin [1] did not find any consistent differences between the difference thresholds of the male and female participants. Gender may therefore not significantly affect the DTs, but the effect of the other factors are not clear. From a qualitative comparison, median relative DTs from the current study are on the lower end of the range compared to the other studies [1, 3, 6]. However, even with the various differences between studies, the median relative DTs are in close proximity of each other. If relative DTs determined from vertical whole-body vibration laboratory tests are close approximations to relative DTs for multi-axes whole-body vibration in complex environments, this would have beneficial implications with respect to experimental DT testing requirements. This requires further investigation.

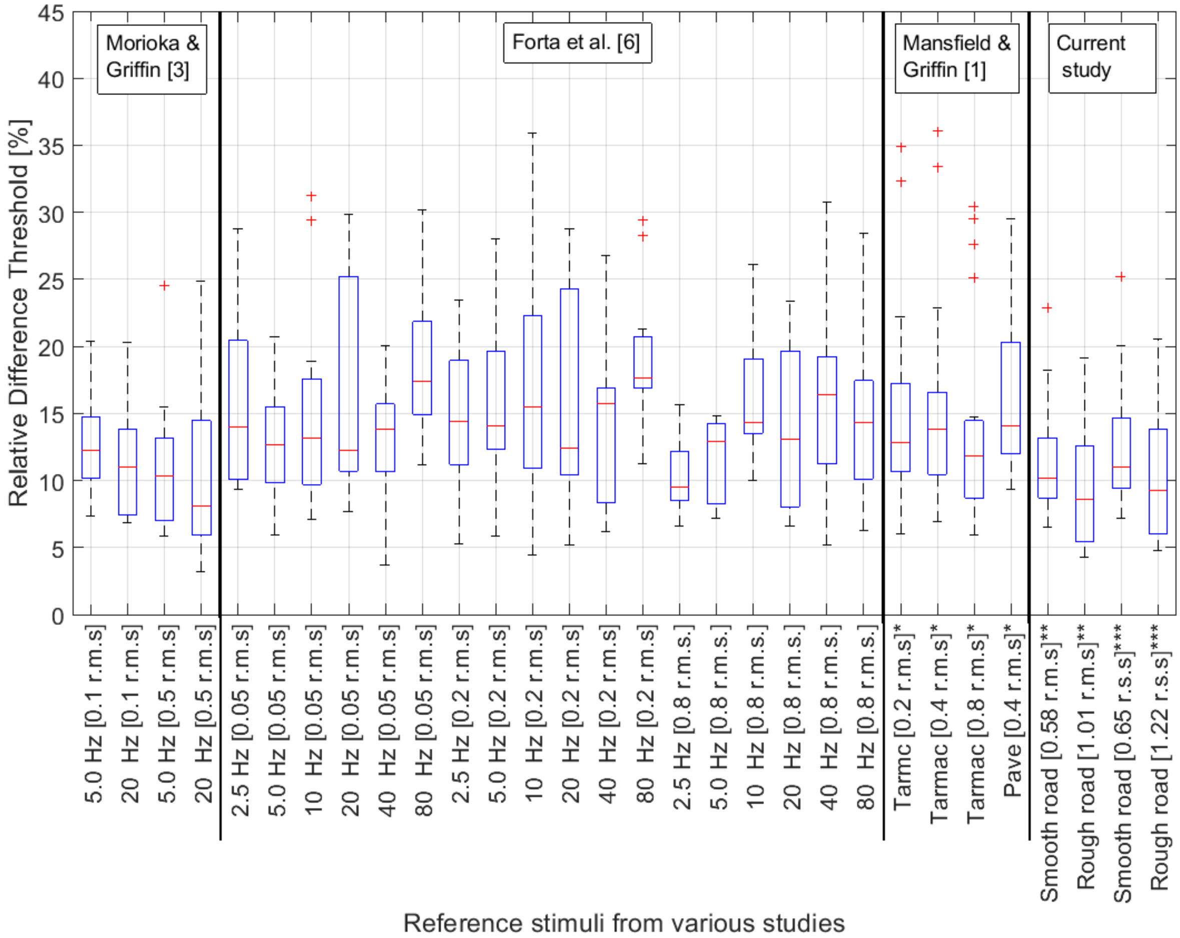

Figure 8: Box plots of the relative difference thresholds of published data in comparison with data from the current study.
** BS6841 weighted r.m.s. **Median r.m.s. of vertical component ride value. ***Median r.s.s. of combined point ride value*

Table 5. Comparison of participant characteristics, stimuli and median relative difference thresholds between studies

Factors		Mansfield & Griffin[1]	Morioka & Griffin [3]	Forta et al. [6]	Current study
Participant characteristics	Gender	Male (n = 10) Female (n = 10)	Male (n=12)	Male (n=12)	Male (n = 10)
	Background	Not specified	volunteers, staff and students	Not specified	Engineers
	Age [years]	28.1±5.6 (Males) 24.0±2.0(Female)	23.5 (21 – 30)	25 (23 - 29)	34 (38 - 25 =13)
	Stature [cm]	178±6	181.2	180 (169 - 194)	180 (182 - 174 =8)
	Weight [kg]	73.2±4.0	75.1	71 (57 - 92)	82 (85 - 74 =11)
	Notes:	Age, stature and weight given as Mean±SD	Age given as Mean (Range). Stature and weight given as an average.	Age, stature and weight given as Median (Range).	Age, stature and weight given as Median (IQR = 75th percentile – 25th percentile)
Stimulus	Length & sequence* [seconds]	10-2-10	4-1-4	2-1-2	20-2-20
	Frequency [Hz]	Tarmac track Pave track (See Figure 1 in [1])	5 and 20	2.5, 5, 10, 20, 40, 80, 160 and 315	Smooth road Rough road (See Figure 3 and 4 in current study)
	Magnitude [$m.s^{-2}$, r.m.s.]	0.2, 0.4 and 0.8 (Tarmac track) 0.4 (Pave track) BS6841 frequency weighted	0.1 and 0.5	0.05, 0.2 and 0.8	0.58 (Smooth road) 1.01 (Rough road) Median r.m.s. of the vertical component ride value
	Direction	Vertical	Vertical	Vertical	Multi-axis
	Waveform	Random	Sinusoidal	Sinusoidal	Random
Relative DTs [%] (range of medians)		11.8 – 14.1	8.13 – 12.25	9.5 – 20.3	8.58 – 10.99

* First stimulus – Pause in stimulus – Second stimulus.

5.2 Validity of Weber's law

No significant difference between the median relative DTs for the two roads using either the vertical component ride value or the combined point ride value were found. This implies that the reference stimulus magnitude (I) and the absolute DT (ΔI) are at a constant ratio. Therefore, for these two roads, it can be concluded that Weber's law holds for a relative DT calculated from either ride value when a driver is exposed to all six axes of vibration while seated in a vehicle. This study might not be sufficient to conclude that Weber's law holds for other roads, vehicles and speeds. Mansfield and Griffin [1] found that Weber's law holds for DTs estimated for stimuli with the same spectral shape but different magnitudes. They however did find a significant difference in the relative DT between two stimuli with different magnitude and spectral shape. Their results were inconclusive with respect to the applicability of the weighting function of the vertical seat vibration (W_b) to the estimation of DTs.

Additional experimental work is required to determine whether Weber's law holds for DTs determined for stimuli with different spectral shapes and magnitudes and whether the weighting functions are applicable in both cases with pure vertical and multi-axes vibration, in order to determine if the DTs in a vehicle on a road holds for other vehicle and road conditions.

5.3 Participant subjective feedback

Participants reported various strategies by which they evaluated the two stimuli. For the rough road, seven out of ten participants mentioned that they used upper body movement, particularly in the lateral direction, as an indicator to evaluate the discomfort of the road. For the smooth road, only three participants indicated that they used upper body movement as an indicator. Participant feedback seems to correlate with the fact that weighted lateral acceleration was 36 % of weighted vertical acceleration for the smooth road and 55 % of weighted vertical acceleration for the rough road.

5.4 Procedural observations

Seven participants on the smooth road and six participants on the rough road reached the floor of the test procedure (i.e. the lowest level of the alternative stimuli). This occurred when participants gave three consecutive correct responses with the alternative being only one level higher than the reference. If a participant reached the floor, trials continued until eight reversals were completed. An implication of participants reaching the floor could be that the DTs reported are higher than the actual thresholds. Only participant 4 reached the ceiling (i.e. the highest level of the alternative stimuli) and occurred on the smooth road. The outlier shown in Figure 6 corresponds to participant 4. From this participant's feedback it became apparent that he adopted a more holistic approach asking himself the question: "Would I accept this level of comfort for this vehicle?" The results from participants reaching either the floor or ceiling were included in the analysis.

The median time to test one participant on one road was 50 minutes (minimum 35, maximum 89 minutes). The median number of trials for a single test was 35 (minimum 25, maximum 54 trials). For both roads, the number of trials having the reference stimulus played before the alternative stimulus were the same as the number of trials having the alternative stimulus played first. Within the responses in which the participant was not able to identify the larger stimulus, a bias was observed towards selecting the second stimulus as being the larger stimulus, when in fact the first stimulus was the larger one. This occurred in 85 % of the trials with incorrect responses. Matsumoto *et al*. [5] commented on such a trend by stating that when the magnitudes of two stimuli, of any type, in a series are compared, the magnitude of the second stimulus tends to be judged relatively greater than the magnitude of the first stimulus.

5.5 Limitations of study

The cohort used consisted of male engineers with a technical background in vehicle engineering. The DT results obtained may therefore not be representative of the broader population. DTs determined in this study might not be applicable to other vehicles, road profiles and vehicle speeds.

6 Conclusion

DTs estimated in this study can be used to evaluate the perceptibility of design changes and modifications to the vehicle's response with respect to whole-body multi-axis vibration, at least for similar roads, vehicle and vehicle speed. No statistically significant difference was found between the medians of the relative DT over the two roads considering either of the two ride values. This suggests that Weber's law holds for the stimuli resulting from the vehicle's dynamic response over the two roads with different roughness considered. Also, no significant difference was found between the medians of the relative DT of the two ride values. This suggests that the vertical component ride value is sufficient to quantify discomfort arising from vehicle vibrations and can be used to estimate and implement the relative DT for whole-body multi-axis vibration in a vehicle.

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