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The discomfort produced by noise and whole-body vertical vibration presented separately and in combination

Yu Huang and Michael J. Griffin [a)]

Human Factors Research Unit

Institute of Sound and Vibration Research

University of Southampton, SO17 1BJ

United Kingdom

[a)]Author to whom correspondence should be addressed. Electronic mail: M.J.Griffin@soton.ac.uk

Abstract

This study investigated the prediction of the discomfort caused by simultaneous noise and vibration from the discomfort caused by noise and the discomfort caused by vibration when they are presented separately. Twenty-four subjects used absolute magnitude estimation to report their discomfort caused by seven levels of noise (70 to 88 dBA SEL), seven magnitudes of vibration (0.146 to 2.318 $ms^{-1.75}$), and all 49 possible combinations of these noise and vibration stimuli. Vibration did not significantly influence judgements of noise discomfort, but noise reduced vibration discomfort by an amount that increased with increasing noise level, consistent with a 'masking effect' of noise on judgements of vibration discomfort. A multiple linear regression model or a root-sums-of-squares model predicted the discomfort caused by combined noise and vibration, but the root-sums-of-squares model is more convenient and provided a more accurate prediction of the discomfort produced by combined noise and vibration.

Practitioner summary: The total discomfort produced by combined noise and vibration, ψ_c, can be well predicted from the root-sums-of-squares (r.s.s.) of the noise discomfort, ψ_s, and the vibration discomfort, ψ_v, when each stimulus is presented alone (i.e., $\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}$).

1. INTRODUCTION

People experience vibration and noise in transport and in buildings. Many studies have investigated human reactions to noise (e.g. noise annoyance) or the sensations produced by vibration (e.g. vibration discomfort) and there are separate standards and guides for measuring, evaluating, and assessing noise and vibration with respect to human responses. However, it can be expected that there may be a collective response to a combination of noise and vibration that is greater than the reaction to either noise or vibration alone. A universal model is needed for predicting the discomfort caused by combined noise and vibration.

Some investigations of the combined effects of noise and vibration have assumed the discomfort caused by combined noise and vibration is equivalent to the summated discomfort caused by the two stressors acting separately (e.g. Innocent and Sandover 1972, Dempsey *et al.* 1979, Leatherwood 1979). However, some studies suggest a more complex response. Howarth and Griffin (1990, 1991) simulated the noise and vibration in a building near a railway and concluded there might be a complex interaction between the effects of the noise and vibration, and that an approximation to the annoyance produced by combined noise and vibration might be determined from a summation of the effects of the individual stimuli in a multiple linear regression model. Paulsen and Kastka (1995) investigated the subjective intensity and annoyance produced by combined noise and vibration in a flat during the passing of a nearby tram and from the working of a hammermill, and concluded that the combined effects were dominated by the noise but also influenced by the vibration.

There is evidence that judgements of one stimulus (noise or vibration) can be influenced by the presence of the other stimulus (vibration or noise). Sandover (1970), Miwa and Yonekawa (1973) and Huang and Griffin (2012, 2014a) found an antagonistic effect of noise on the sensation of vibration, while Seidel *et al*. (1989, 1990) reported synergistic effects of noise on judgements of vibration. Howarth and Griffin (1990, 1991) found both antagonistic and synergistic effects of noise on judgements of vibration, depending on the relative magnitudes of noise and vibration. Dempsey *et al*. (1976) and Kirby *et al*. (1977) also reported evidence of an influence of noise on judgements of vibration discomfort, but did not clearly indicate whether the effects were antagonistic or synergistic. Huang and Griffin (2012, 2014a) suggested antagonistic effects of vibration on judgements of noise discomfort, while Paulsen and Kastka (1995) and Parizet *et al.* (2004) suggested synergistic effects of vibration on, respectively, the annoyance and the discomfort caused by noise.

Effects of noise on judgements of vibration and effects of vibration on judgements of noise have rarely been found in the same study of the interactions and combined effects of noise and vibration. Howarth and Griffin (1990) found significant influences of noise on judgements of vibration annoyance but noise annoyance was unaffected by simultaneous vibration. In contrast, Paulsen and Kastka (1995) found vibration influenced noise annoyance but noise had a negligible influence on vibration annoyance. The dissimilarity in findings may have arisen from the different magnitudes of the stimuli that were studied: noise in the range 54 to 79 dBA and vibration in the range 0.02 to 0.13 ms^{-2} in the Howarth and Griffin study, but lower levels of noise (30 to 60 dBA) with similar magnitudes of vibration (0.05 to 0.32 mm/s) in the Paulsen and Kastka study. Differences in the frequency spectra of their stimuli, differences in methods, and differences in the phrasing of the questions may also have contributed to the apparently contrary findings. Equations have been proposed in some studies to predict subjective responses ('discomfort' or 'annoyance') to combined noise and vibration (e.g. Dempsey *et al.* 1979, Howarth and Griffin 1990, 1991, Paulsen and Kastka 1995, Seidel *et al.* 1990) but it is not known whether they apply to a wider range of stimuli.

In general, the findings of previous studies of 'discomfort' (e.g. Sandover 1970, Miwa and Yonekawa 1973, Huang and Griffin 2012, 2014a) suggest 'masking effects' of noise on judgements of vibration and 'masking effects' of vibration on judgements of noise when the stimuli are presented simultaneously at noise levels and vibration magnitudes that people feel 'noisy' or 'uncomfortable': sound pressure levels greater than 65 dBA (the daytime level in EU/DG Environment Directive, 2002) or acceleration greater than 0.32 ms^{-2} r.m.s. (BS 6841: 1987, ISO 2631-1: 1997). Any masking by noise on vibration discomfort, and any masking by vibration on noise discomfort can be assumed to be 'informational masking' (i.e., non-energetic masking; Durlach *et al.* 2003). Energetic masking may be equated with peripheral masking where there is excitation of an end organ by more than one stimulus (e.g. two tones exciting the same region on the basilar membrane). Informational masking may be equated with central masking, and include the perception of one stimulus distracting from the perception of another stimulus. Informational masking might also include one stimulus attracting attention to another stimulus (i.e., negative masking). Noise discomfort and vibration discomfort are mostly sensed via different mechanisms so informational masking is more likely than energetic masking.

For both noise and vibration, when another component of noise or vibration is added, the predicted discomfort is assumed to increase. There are complex methods for predicting the increase in discomfort (e.g. allowing for masking between stimuli) but simple meters for evaluating the severity of noise or vibration stimuli use the root-mean-square of the frequency-weighted stimuli. So the discomfort is not predicted to increase to a value equivalent to the sum of the physical magnitudes of the weighted components in the stimulus but to a value equivalent to the square-root of the sums-of-the-squares of the weighted physical magnitudes of the components in the stimulus. Similarly, the discomfort caused by multi-axis vibration is determined by the root-sums-of-squares (r.s.s.) of the weighted magnitudes in each axis (BS 6841: 1987, ISO 2631-1: 1997). It seems reasonable to investigate how well this 'root-sums-of-squares' method predicts the discomfort caused by combined noise and vibration.

This study was designed to investigate whether noise discomfort is influenced by the presence of vibration, whether vibration discomfort is influenced by the presence of noise, and how the total discomfort from combined noise and vibration can be predicted from the discomfort associated with each stimulus when presented alone. It was hypothesized that: (i) the discomfort, ψ_s, caused by a constant level of noise would reduce with increases in the magnitude of a simultaneous vibration, (ii) the discomfort, ψ_v, caused a constant magnitude of vibration would reduce with increases in the level of a simultaneous noise, (iii) the total discomfort, ψ_c, caused by combined noise and vibration may be predicted from a multiple linear regression model (i.e., $\psi_c = a + b\ \psi'_s + c\ \psi'_v$, where a, b and c are constants, and ψ'_s and ψ'_v represent noise discomfort in the presence of vibration and vibration discomfort in the presence of noise, respectively, and (iv) the total discomfort, ψ_c, can be predicted from the root-sums-of-squares (r.s.s.) of the noise discomfort, ψ_s, and the vibration discomfort, ψ_v, when each stimulus is presented alone (i.e., $\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}$).

2. METHOD

2.1 Subjects

Twenty-four subjects (12 male and 12 female), with median age 24 years (range 20 to 34 years), stature 170 cm (range 153 to 196 cm), and weight 62 kg (range 42 to 108 kg) volunteered to take part in the experiment. The subjects were students or staff of the University of Southampton.

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton. Informed consent to participate in the experiment was given by all subjects.

2.2 Apparatus

Subjects sat on a rigid flat wooden surface secured to a rigid aluminium-framed seat with a rigid vertical flat backrest mounted on the Human Factors Research Unit 1-m vertical vibrator. The subjects sat upright without contacting the backrest and with their feet resting on the vibrator table (Figure 1).

FIGURE 1 ABOUT HERE

A piezoresistive accelerometer (Entran Devices, NJ, USA, Model EGCS-10-/V10/L4M) secured to the seat monitored the vertical acceleration. The vibration stimuli were generated and controlled by a Pulsar digital controller (Servotest, Egham, UK).

Subjects were exposed via a pair of headphones (ATH M50) to sound stimuli generated and controlled using Adobe Audition 3 (Adobe Systems, CA, USA) software and an E-MU 0404 USB 2.0 Audio/MIDI Interface (Creative, Singapore). Sound levels from the headphones were calibrated and measured using a 'Kemar' (Knowles Electronics Manikin for Acoustic Research) artificial manikin. The Kemar incorporates an ear simulator (G.R.A.S. IEC 700) that houses a microphone (G.R.A.S. Type 40AG) to measure sound levels at the eardrum. A B&K calibrator (Type 4231) and a B&K sound level meter (Type 2250) were used to calibrate and measure the sounds. The sound pressure level, L_{Aeq}, was calculated using the diffuse field in BS EN ISO 11904-2 (2004) and applying the A-weighting to the one-third-octave band spectra measured by the B&K 2250 sound level meter.

2.3 Stimuli

Seven levels of a random sound, band-pass filtered between 50 and 500 Hz, were generated with sound pressure levels ranging from 64 to 82 dBA in 3 dB steps (ISO 1996-1: 2003). Seven magnitudes of a random vibration, band-pass filtered between 5 and 10 Hz, were generated with frequency-weighted vibration magnitudes from 0.079 to 1.262 ms^{-2} r.m.s. in 2 dB steps (using weighting W_b; BS 6841: 1987). The sound and vibration stimuli had durations of 4 s, with 0.2-s cosine tapers at the start and end.

The sound exposure level, L_{AE}, and the vibration dose value, a_{VDV}, are the currently standardised expressions for predicting how subjective impressions of sound or vibration depend on the sound pressure or the acceleration, respectively, and their durations.

The sound exposure level, SEL, of a discrete noise event is given in ISO 1996-1 (2003) by:

$$\text{sound exposure level (dBA)} = L_{AE} = 10\log_{10}\left(\frac{1}{t_0}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}\mathrm{d}t\right) \quad (1)$$

where $p_A(t)$ is the instantaneous A-weighted sound pressure starting at time t_1 and ending at time t_2, p_0 is the reference sound pressure (20 μPa), and t_0 is the reference duration (1 s).

The vibration dose value, VDV, of vibration event is given in BS 6841 (1987) and ISO 2631-1 (1997) by:

$$\text{vibration dose value (ms}^{-1.75}) = a_{VDV} = \left(\int_0^T a^4(t)\mathrm{d}t\right)^{¼} \quad (2)$$

where $a(t)$ is the frequency-weighted acceleration and T is the duration of the measurement period in seconds.

For the 4-s stimuli used in the current study, the ratio of the sound pressure level to the sound exposure level was -6 dB, and the ratio of the r.m.s. acceleration to the vibration dose value was 0.51 ($ms^{-2}/ms^{-1.75}$). The background vibration was not perceptible and the background noise level measured at the ear when wearing the headphones was around 55 dBA.

2.4 Procedure

The subjects were instructed to sit with a comfortable upright posture with their eyes closed and wearing the headphones. Judgements of ‘discomfort’ were obtained using the method of absolute magnitude estimation (AME) (Stevens 1971, Huang and Griffin 2014b). The subjects were presented with a series of stimuli and asked to judge the discomfort of the stimuli using any numerical number they felt appropriate.

The experiment was performed in three sessions. In session A, subjects used magnitude estimation to report the discomfort caused by the each of the seven levels of noise in the presence of each of the seven magnitudes of vibration and with no vibration. In Session B, subjects used magnitude estimation to report the discomfort caused by the each of the seven magnitudes of vibration in the presence of each of the seven levels of noise and with no noise. In session C, subjects used magnitude estimation to report the overall discomfort caused by each of the 63 stimuli: 49 combinations of the seven magnitudes of vibration and the seven levels of noise, plus seven levels of noise with no vibration and seven magnitudes of vibration without noise.

Subjects experienced the three sessions on different days and in a balanced order. All stimuli in each session were presented once in an independent random order. Before commencing each session, subjects were provided with written instructions, which indicated they could use any numerical values to rate the subjective magnitudes of the stimuli, but did not indicate any numerical examples. Subjects then practiced judging the median, high, and low magnitude stimuli until they felt confident with absolute magnitude estimation.

Magnitude estimates obtained from each individual in each session were divided by the median magnitude estimate over all stimuli in that session and then multiplied by '100' (Stevens 1971). This 'normalised' (or 'equalised') the data and placed the magnitude estimates of each subject on a similar scale so that they could be compared and analysed using the same procedures.

The magnitude estimates of noise discomfort, ψ_s, and the magnitude estimates of vibration discomfort, ψ_v, were assumed to be related to the physical magnitudes of sound, φ_s, and the physical magnitudes of vibration, φ_v, respectively, according to Stevens' power law (Stevens, 1986):

$$\psi_s = k_s \varphi_s^{n_s} \tag{3}$$

$$\psi_v = k_v \varphi_v^{n_v} \tag{4}$$

where k_s and k_v, are constants and n_s and n_v are the rates of growth of subjective sensations produced by the sound and the vibration, respectively.

Expressed logarithmically, Equations (1) and (3) become:

$$\log_{10}(\psi_s) = \log_{10}(k_s) + (n_s/20) \times L_{AE} \tag{5}$$

where $L_{AE} \propto 20\ \log(\varphi_s)$ is the equivalent continuous A-weighted sound exposure level (ISO 1996-1, 2003), assuming φ_s represents the A-weighted sound pressure, and Equations (2) and(4) become:

$$\log_{10}(\psi_v) = \log_{10}(k_v) + n_v \times \log_{10}(a_{VDV}) \tag{6}$$

where $a_{VDV} \propto \varphi_v$ is the W_b-weighted vibration dose value (BS 6841: 1987, ISO 2631-1: 1997).

3 RESULTS

3.1 Discomfort of noise in the presence of vibration

Median magnitude estimates of the discomfort produced by each of the seven levels of noise during simultaneous presentation of each of the seven magnitudes of vibration, and with no vibration, are shown in Table 1. They are also shown in Figure 2 as a function of noise level, L_{AE}, and as a function of vibration magnitude, a_{VDV}. Linear regression between the median values of $\log_{10}(\psi_s)$ and L_{AE} using Equation (5) produced the slopes, intercepts, and the coefficients of correlation between the logarithms of the magnitude estimates of noise discomfort (i.e., $\log_{10}(\psi_s)$) and the sound exposure levels (i.e., L_{AE}) at each magnitude of vibration, as shown in Table 1.

TABLE 1, FIGURE 2 ABOUT HERE

When the same procedure was applied to the magnitude estimates provided by each subject, it was found that at each noise level, the presence of vibration had no significant effect on the judgement of the discomfort produced by the noise ($p > 0.23$; Friedman).

Without vibration, the rate of growth in discomfort produced by noise (i.e., the slope $n_s/20$ in Equation (5)) was 0.036 with an intercept (i.e., $\log_{10}(k_s)$) of -0.792). With simultaneous vibration, the median slopes varied from 0.037 to 0.045 and the intercepts varied from -0.523 to -0.898, but with no significant difference between the slopes or between the intercepts due to variations in the magnitude of vibration ($p = 0.49$; Friedman).

3.2 Discomfort of vibration in the presence of noise

Median magnitude estimates of the discomfort produced by each of the seven magnitudes of vibration when presented simultaneously with each of the seven levels of noise, and with no noise, are shown in Table 2. They are also shown in Figure 3 as a function of noise level, L_{AE}, and as a function of vibration magnitude, a_{VDV}. Linear regression analyses between the median values of $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$ using Equation (6) produced the slopes, intercepts, and the coefficients of correlation between the logarithms of the magnitude estimates of vibration discomfort (i.e., $\log_{10}(\psi_v)$) and the logarithms of the vibration dose values (i.e., $\log_{10}(a_{VDV})$) at each level of noise, as shown in Table 2.

TABLE 2, FIGURE 3 ABOUT HERE

The upper part of Figure 3 shows a trend for the presence of noise to reduce the discomfort caused by vibration and, together with Table 2 suggests a 'masking effect' of noise on judgements of vibration discomfort that increases with increasing levels of noise. However, the multiple statistical analyses on the individual magnitude estimates show that, after Bonferroni correction (Shaffer 1995), at each vibration magnitude, the noise had no significant effect on the judgement of the discomfort produced by vibration (corrected $p > 0.05$; Friedman).

Linear regression analyses between $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$ using Equation (6) were applied to the magnitude estimates provided by each subject. Without noise, the rate of growth in vibration discomfort (i.e., the slope n_v in Equation (6)) was 0.891 with an intercept (i.e., $\log_{10}(k_v)$) of 2.277. With simultaneous noise, the median slopes tended to increase from 0.812 to 0.963, except for the slope of 0.902 with noise at 70 dBA SEL ($p < 0.01$; Friedman), and the intercepts varied from 2.257 to 2.300, but with no significant difference between the intercepts due to variations in the level of noise.

3.3 Discomfort of combined noise and vibration

1. General results

Median magnitude estimates of the discomfort produced by all combinations of the seven magnitudes of vibration and the seven levels of noise are shown in Table 3. They are illustrated in Figure 4 as a function of noise level, L_{AE}, and as a function of vibration magnitude, a_{VDV}.

TABLE 3, FIGURE 4 ABOUT HERE

Linear regression between median values of $\log_{10}(\psi_c)$ and L_{AE} when judging noise without vibration produced a rate of growth in noise discomfort (i.e., the slope $n_s/20$ in Equation (5)) of 0.035 with an intercept (i.e., $\log_{10}(k_s)$) of -0.923 with a correlation coefficient of 0.99 ($p < 0.01$; Spearman):

$$\log_{10}(\psi_s) = -0.923 + 0.035\, L_{AE}. \tag{7}$$

Linear regression between median values of $\log_{10}(\psi_c)$ and $\log_{10}(a_{VDV})$ when judging vibration without noise, produced a rate of growth in vibration discomfort (i.e., the slope n_v in Equation (6)) of 0.947 with an intercept (i.e., $\log_{10}(k_v)$) of 1.852 with a correlation coefficient of 0.99 ($p < 0.01$; Spearman):

$$\log_{10}(\psi_v) = 1.852 + 0.947 \log_{10}(a_{VDV}). \tag{8}$$

When the same procedures were applied to the magnitude estimates provided by each subject, the total discomfort increased as the noise level increased at each vibration magnitude, and as the vibration magnitude increased at each noise level (p < 0.001; Friedman). There was no significant difference in the slope (i.e., $n_s/20$), or the intercept (i.e., $\log_{10}(k_s)$) between session C (discomfort with combined noise and vibration) and session A (noise discomfort) when judging noise discomfort without vibration (p = 0.07 for slope, and p = 0.24 for intercept; Wilcoxon). There was no significant difference in the slope (i.e., n_v) between session C (discomfort with combined noise and vibration) and session B (vibration discomfort) but a smaller intercept (i.e., $\log_{10}(k_v)$) in session C than in session B when judging vibration discomfort without noise (p = 0.14 for slope, and p < 0.001 for intercept; Wilcoxon).

2. Multiple linear regression model

Assume the discomfort caused by combined noise and vibration, ψ_c can be predicted by:

$$\psi_c = a + b\,\psi'_s + c\,\psi'_v, \tag{9}$$

where a, b and c are constants, and ψ'_s and ψ'_v represent the discomfort caused by noise in the presence of vibration and the discomfort caused by vibration in the presence of noise, respectively.

The median magnitude estimates at each combination of the seven levels of noise (70 to 88 dBA) and the seven magnitudes of vibration (0.146 to 2.318 $ms^{-1.75}$) were obtained from judgements of the discomfort caused by noise in the presence of vibration (i.e., ψ'_s in Table 1), the discomfort caused by vibration in the presence of noise (i.e., ψ'_v in Table 2), and the discomfort caused by combined noise and vibration (i.e., ψ_c in Table 3). These values were used to obtain by multiple linear regressing the relation between the dependent variable, ψ_c, and the two independent variables, ψ'_s and ψ'_v:

$$\psi_c = 18.46 + 0.47\,\psi'_s + 0.20\,\psi'_v. \tag{10}$$

The correlation coefficient for this multiple regression was 0.96 (p < 0.01; Spearman).

3. The root-sum-of-squares model

The magnitude estimates for discomfort produced by combined noise and vibration, ψ_c, for the 49 combinations of noise and vibration (seven levels of noise combined with each of seven magnitudes of vibration) were predicted from the median magnitude estimates of the discomfort caused by the seven levels of noise without vibration, ψ_s, in Table 3 and the median magnitude estimates of the seven magnitudes of vibration without noise, ψ_v, in Table 3, using:

$$\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}. \quad (11)$$

The median measured values of ψ_c in Table 3 are compared with the predicted values in Figure 5. The correlation coefficient between the measured and the predicted values was 0.99 (p < 0.01; Spearman), greater than that of Equation (10).

The predictions did not improve by using the discomfort caused by noise in the presence of vibration (i.e., the appropriate value of ψ'_s in Table 1) and the discomfort caused by vibration in the presence of noise (i.e., the appropriate value of ψ'_v in Table 2): the correlation between the measured and predicted values reduced to 0.89 (p < 0.01; Spearman).

FIGURE 5 ABOUT HERE

4 DISCUSSION

4.1 Influence of vibration on the discomfort of noise

From Table 1, when noise stimuli were presented without vibration, the slope (i.e., n_s/20) of 0.036 was similar to Stevens' proposed value of 0.033 (Stevens, 1986). When noise was presented with simultaneous vibration (from 0.146 to 2.318 $ms^{-1.75}$), the slope was in the range 0.037 to 0.045 (Table 1), but not significantly dependent on the vibration magnitude. In a previous study, when the magnitude of the simultaneous vibration increased from 0.092 to 1.457 $ms^{-1.75}$, the slopes increased from 0.022 to 0.028, consistent with a 'masking effect' of high magnitude vibration on the discomfort caused by low levels of noise (Huang and Griffin 2012). Relative magnitude estimation (RME) was employed in that study, with subjects judging noise discomfort relative to vibration discomfort, whereas absolute magnitude estimation (AME) was employed in present study, with subjects giving the numerical values of noise discomfort without a reference.

The absence of a statistically significant effect of vibration on the slopes in the present study, unlike Huang and Griffin (2012), might be explained if there was a more variable response associated with AME than RME (Mellers 1983, Huang and Griffin 2014b). However, when noise was presented with different magnitudes of vibration, the inter-subject variability (ratio of the inter-quartile range to the median value) in the slopes was in the range 0.41 to 0.64 with AME in the present study, which is not greater than the range 0.49 to 0.93 with RME in the previous study.

Any ‘masking effect’ of vibration on judgements of noise discomfort may have been magnified with RME (a cross-modality procedure in which noise is judged relative to vibration) because vibration was emphasized by employing it as a reference. In the previous study with RME, when the greatest magnitude of vibration (1.457 $ms^{-1.75}$) was employed as a reference, the median noise discomfort was ‘35’ for the lowest noise level (70 dBA), and ‘110’ for the highest noise level (88 dBA). In the present study with AME, when presented with a similar magnitude of vibration (1.431 $ms^{-1.75}$), the median noise discomfort was ‘42’ for the lowest noise level (70 dBA) and ‘210’ for the highest noise level (88 dBA). It seems the ‘masking effect’ (informational masking) of vibration on judgements of noise discomfort is dependent on the psychophysical method, being greater with RME when noise discomfort is judged relative to a reference magnitude of vibration than with AME.

The slopes obtained previously (Huang and Griffin 2012) were less than in the present study, possibly due to what Stevens and Greenbaum (1966) called the ‘regression effect’ and Poulton (1979) called the ‘contraction bias’ causing overestimation of the discomfort caused by low magnitude stimuli and underestimation of the discomfort caused by high magnitude stimuli. By not using numerical prompts in the AME instructions (e.g., ‘100’ for the discomfort caused by the reference when using RME) subjects are less likely to locate their ratings at the centre of the range, thus reducing the regression effect. For example, when using the median magnitude of vibration (0.366 $ms^{-1.75}$) as a reference to define a discomfort magnitude estimate of ‘100’ in the previous study with RME, the median discomfort caused by seven levels of noise ranged from ‘85’ to ‘200’, whereas when presented with a similar magnitude of vibration (0.363 $ms^{-1.75}$) in the present study, the discomfort caused by the same seven levels of noise ranged from ‘45’ to ‘211’.

4.2 Influence of noise on the discomfort of vibration

From Table 2, when the 5-10 Hz vibration stimuli were presented without noise, the slope (i.e., n_v) of 0.973 is in broad agreement with rates of growth of subjective sensations reported previously (e.g., 1.04 for 5-Hz vibration by Shoenberger and Harris (1971), 0.93 for sinusoidal vibration from 5 to 80 Hz by Jones and Saunders (1974), 1.04, 1.06, and 1.09 for 4-, 8- and 11.3-Hz vibration by Howarth and Griffin (1988), and 1.04 for vibration in buildings with spectra from 18 to 60 Hz due to the passage of nearby trains by Howarth and Griffin (1990)).

When the vibration stimuli were presented with simultaneous noise (at levels from 70 to 88 dBA), the slope varied and showed some evidence of a slight increase (Table 2). In a previous study, when the level of a simultaneous reference noise increased from 70 to 88 dBA, the slope increased from 0.397 to 0.928 (Huang and Griffin 2012). Similar to the discussion in Section IV.A, the reduced slope in the previous study might have been caused by the 'regression effect' when using the RME method.

Noise has been found to reduce magnitude estimates of discomfort for low magnitude vibration when judging vibration relative to noise using RME (Huang and Griffin 2012). There may be some evidence of a similar effect of noise on the judgement of vibration discomfort in the present study with AME, but it is much less obvious than in Huang and Griffin (2012). In the previous study with RME, when the highest level of noise (88 dBA) was employed as a reference, the median value of relative vibration discomfort was '10' for the lowest magnitude of vibration (0.092 $ms^{-1.75}$), and '100' for the greatest magnitude of vibration (1.458 $ms^{-1.75}$), whereas in the present study with AME, when presented with the same level of noise (88 dBA) the median value of vibration discomfort was '28' for the lowest magnitude of vibration (0.146 $ms^{-1.75}$), and '321' for the greatest magnitude of vibration (2.318 $ms^{-1.75}$). It seems the 'masking effect' (informational masking) of noise on judgements of vibration discomfort is greater with RME than with AME.

The less obvious effect of noise on the slopes in the present study than in Huang and Griffin (2012) cannot be explained by more variable responses with AME than RME (Mellers 1983, Huang and Griffin, 2014b). When judging vibration discomfort in the presence of different levels of noise, the range of inter-subject variability in the slopes with AME in the present study (0.35 to 0.54) is not greater than that with RME in the previous study (0.35 to 0.76).

Noise has previously been reported to reduce judgements of vibration discomfort (i.e., 'positive masking') by Sandover (1970), Miwa and Yonekawa (1973), and Howarth and Griffin (1990). A synergistic effect (i.e., 'negative masking') in which higher levels of noise increased the annoyance caused by higher magnitudes of vibration was found by Howarth and Griffin (1990) but not observed in the present study, possibly because of the different ranges of stimuli employed in the two studies: Howarth and Griffin (1990) investigated lower levels of noise (40 to 65 dBA SPL) and lower magnitudes of vibration (0.02 to 0.125 ms^{-2} r.m.s.) than the present study (SPL from 64 to 82 dBA and r.m.s. acceleration from 0.079 to 1.262 ms^{-2}).

4.3 The discomfort of combined noise and vibration

4.3.1. Range of discomfort magnitudes

From Tables 1 to 3, the ranges of median magnitude estimates of discomfort were from 35 to 236, with a ratio of 1:7 for ψ_s (and ψ'_s) in session A (noise discomfort), from 23 to 379 with a ratio of 1:16 for ψ_v (and ψ'_v) in session B (vibration discomfort), and from 11 to 192 with a ratio of 1:17 for ψ_c in session C (discomfort with combined noise and vibration).

The range of magnitude estimates for discomfort caused by combinations of noise and vibration (i.e., ψ_c) was greater than that for noise discomfort (i.e., ψ_s (and ψ'_s)) and greater than for vibration discomfort (i.e., ψ_v (and ψ'_v)), but not as great as the sum of the ranges of noise discomfort and vibration discomfort. This might be explained by a 'response equalizing bias' and a 'transfer bias' from ratio scales to interval scales (Poulton 1979). The response equalizing bias means subjects tend to use the same range of numbers whatever the range of stimuli, so subjects might intentionally or unintentionally give smaller magnitude estimates for the discomfort caused by the combination of two stimuli in session C (discomfort with combined noise and vibration) than the discomfort caused by single stimuli in session A (noise discomfort) and session B (vibration discomfort), so as to avoid the summation of the discomfort exceeding their psychological ranges. The transfer bias in the present experiment comes from transferring ratio scales to interval scales. Subjects used ratio scales to rate noise discomfort and vibration discomfort, but to estimate their total discomfort they may have used interval scales to summate noise discomfort and vibration discomfort. The transfer bias from the ratio scales to an interval scale may have reduced the range of ψ_c because ratio scales are usually greater than interval scales.

4.3.2. The effect of noise (or vibration) on the subjective judgements of vibration (or noise)

A 'masking effect' of noise on judgements of vibration discomfort was observed in the present study and in some previous studies (e.g. Sandover 1970, Miwa and Yonekawa 1973, Howarth and Griffin 1990, Huang and Griffin 2012). A 'masking effect' of vibration on judgements of noise discomfort was not observed in the present study, possibly due to the relatively higher levels of the noise stimuli (70 to 88 dBA) than the magnitudes of the vibration stimuli (0.146 to 2.318 $ms^{-1.75}$) (i.e., the noise stimuli produced relatively greater discomfort than the vibration stimuli). Similarly, some previous studies with relatively high levels of noise and low magnitudes of vibration (e.g. Dempsey *et al.* (1976) with

SPLs from 70 to 85 dBA and r.m.s. accelerations from 0.3 to 1.2 ms^{-2}, Howarth and Griffin (1990) with SPLs from 40 to 65 dBA and r.m.s. accelerations from 0.02 to 0.125 ms^{-2}, and Seidel *et al.* (1990) with SPLs from 65 to 85 dBA and r.m.s. accelerations from 0.55 to 2.2 ms^{-2}) also found no significant influence of vibration on judgements of noise discomfort. Paulsen and Kastka (1995) employed relatively low levels of noise (32 to 60 dBA SPL) and high magnitudes of vibration (0.05 to 0.32 mm/s) and found the highest magnitude of vibration had a small but significant influence on judgements of noise. It may be presumed that a masking effect of vibration on noise discomfort will be observed if much lower levels of noise or much greater magnitudes of vibration are employed than in the present study.

4.3.3. Models for predicting the discomfort of combined noise and vibration

A multiple regression model and a root-sums-of-squares (r.s.s.) model were proposed in Section III.C to predict the discomfort caused by combined noise and vibration from the discomfort caused by noise and the discomfort caused by vibration. From Equation (10) and Figure 5(a), the multiple regression process was able to provide a reasonably accurate prediction. However, the multiple regression equation might not be applicable when the magnitudes of stimuli exceed the ranges investigated (i.e., 70 to 88 dBA SEL and 0.146 to 2.318 $ms^{-1.75}$ VDV), or when the physical characteristics of the stimuli (e.g., the frequency spectra of noise and vibration, the direction of vibration) differ from those investigated. The prediction equations in previous studies (e.g. Dempsey *et al.* 1979, Leatherwood 1979, Howarth and Griffin 1990a, 1991, Paulsen and Kastka 1995; Seidel *et al*. 1990) have similar limitations and, additionally, they require subjective judgements of each of the stimuli in the presence of all the other stimuli.

Equation (11) suggests the subjective magnitude of the discomfort caused by combined noise and vibration can be well predicted by the root-sums-of-squares (r.s.s.) of the subjective magnitude of the noise discomfort and the subjective magnitude of the vibration discomfort. This gave a better prediction of the combined discomfort than the multiple regression equation (i.e., Equation (10)), as shown in Figure 5. The r.s.s. model implies an interaction between noise and vibration in the subjective judgements: the relative contribution to the total discomfort caused by either stimulus (noise or vibration) reduces as the magnitude of the other stimulus (vibration or noise) increases. When either stimulus (noise or vibration) has a high magnitude and the other stimulus (vibration or noise) has a low magnitude, the total discomfort will be dominated by the higher magnitude stimulus.

The ‘masking effect’ in the r.s.s. model is symmetrical whereas only the ‘masking’ of noise on the vibration discomfort was observed in the present experiment. When a noise and a vibration produce similar discomfort, it seems more likely that judgements of vibration discomfort are ‘masked’ by noise than judgements of noise discomfort are ‘masked’ by vibration. However, noise discomfort may be masked by vibration if lower levels of noise or greater magnitudes of vibration are employed. When vibration and noise that produce similar discomfort are presented simultaneously, the total discomfort is greater than the discomfort caused by either stimulus alone (about 41% greater due to the squaring and square root procedure), and much less than the sum of the magnitude estimates of discomfort caused by each stimuli alone.

4.3.4. Application of the r.s.s. model for predicting the discomfort of combined noise and vibration

To predict the discomfort caused by combined noise and vibration from Equation (11) it is necessary first to calculate the discomfort caused separately by the noise component and the vibration component. Equations (7) and (8) can be written in the form of Equations (3) and (4) to predict the discomfort caused by noise without vibration, and the discomfort caused by vibration without noise:

$$\psi_s = 0.119 \times 10^{0.035 L_{AE}}, \quad (12)$$

and

$$\psi_v = 70.8 \times (a_{VDV})^{0.947}. \quad (13)$$

The discomfort caused by combined noise and vibration, ψ_c, can then be found by substituting ψ_s and ψ_v from Equations (12) and (13) in Equation (11):

$$\psi_c = [(0.119 \times 10^{0.035 L_{AE}})^2 + (70.8 \times (a_{VDV})^{0.947})^2]^{0.5} \quad (14)$$

for L_{AE} in the range 70 to 88 dBA, and a_{VDV} in the range 0.146 to 2.318 ms$^{-1.75}$. The correlation coefficient between the measured and the predicted values from Equation (14) (based on the physical magnitudes of stimuli) was 0.98 ($p < 0.01$; Spearman), slightly less than that between the measured and the predicted values from Equation (11) (based on the subjective magnitudes of stimuli).

The r.s.s. model is compatible with the psychophysical equations suggested in other studies (e.g. Howarth and Griffin 1990, 1991). Howarth and Griffin’s study (1990) found the following equations to predict the discomfort caused by noise the discomfort caused by vibration:

$$\psi_s = 0.217 \times 10^{0.039 L_{AE}} \quad (15)$$

and

$$\psi_v = 245 \times (a_{VDV})^{1.04}. \tag{16}$$

Substitute Equations (15) and (16) into Equation (11), the total annoyance could be predicted by

$$\psi_c = [(0.217 \times 10^{0.039L_{AE}})^2 + (245 \times (a_{VDV})^{1.04})^2]^{0.5} \tag{17}$$

for L_{AE} in the range 54 to 79 dBA and a_{VDV} in the range 0.07 to 0.40 ms$^{-1.75}$. The predicted values are highly correlated with the values predicted by the multiple regression equation proposed by Howarth and Griffin (1990) (0.98; $p < 0.01$, Spearman).

The r.s.s. model (i.e., Equation (11)) could be used to predict the discomfort caused by combined noise and vibration from the physical magnitudes of the stimuli, by using the psychophysical relationships between the subjective magnitudes of noise and vibration and their physical magnitudes. Some care may be required as different psychophysical relations may be obtained in different studies (e.g. Howarth and Griffin (1990) and the present study) according to the ranges of stimuli investigated and their physical characteristics (e.g. the frequency spectra of noise and vibration, the direction of vibration). For low-frequency random noise from 70 to 88 dBA and low-frequency random vertical whole-body vibration from 0.146 to 2.318 ms$^{-1.75}$ as in the present study, the discomfort caused by combined noise and vibration seems to be well predicted by Equation (14).

5 CONCLUSIONS

Judgments of the discomfort caused by whole-body vibration can be reduced by the presence of noise, with the ‘masking effect’ increasing with increasing noise level. No statistically significant influence of vibration on judgements of noise discomfort were found, possibly due to the levels of noise and the magnitudes of vibration employed in the study.

The discomfort caused by combined noise and vibration was well predicted from the discomfort caused by noise in the presence of vibration, ψ'_s, and the discomfort caused by vibration in the presence of noise, ψ'_v, using multiple linear regression (i.e., $\psi_c = 18.46 + 0.47\ \psi'_s + 0.20\ \psi'_v$). Alternatively, the noise discomfort, ψ_s, and the vibration discomfort, ψ_v, can be combined in a root-sums-of-squares psychophysical model to predict the discomfort of combined noise and vibration, ψ_c (i.e., $\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}$). This root-sums-of-squares model is simpler, provided a better prediction, and is more convenient because standardised evaluations of noise and vibration can be used to estimate the discomfort caused by combined noise and vibration. For low-frequency random noise in the range 70 to 88 dBA and low-frequency random vertical whole-body vibration in the range 0.15 to 2.32 $ms^{-1.75}$, as used in the current study, the discomfort cause by combined noise and vibration was well predicted by: $\psi_c = [(0.119 \times 10^{0.035L_{AE}})^2 + (70.8 \times (a_{VDV})^{0.947})^2]^{0.5}$ where L_{AE} is the sound exposure level according to ISO 1996-1 (2003), and a_{VDV} is the vibration dose value according to BS 6841 (1987) or ISO 2631-1 (1997).

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Table 1. Magnitude estimates for the discomfort caused by noise, ψ_s (with V_0) and ψ'_s (with V_1-V_7) and linear regression analysis showing the relation between the subjective magnitude, $\log_{10}(\psi_s)$ (or $\log_{10}(\psi'_s)$), and the sound exposure level, L_{AE}, in the presence of different magnitudes of simultaneous vibration. Medians of 24 subjects.

			a_{VDV}(ms$^{-1.75}$)							
			V_0 0 ψ_s	V_1 0.146 ψ'_s	V_2 0.230 ψ'_s	V_3 0.363 ψ'_s	V_4 0.573 ψ'_s	V_5 0.906 ψ'_s	V_6 1.431 ψ'_s	V_7 2.318 ψ'_s
L_{AE} (dBA)	N_1	70	48.5	40.4	34.9	44.6	43.8	40.0	41.5	46.1
	N_2	73	60.8	60.6	50.0	60.8	55.6	61.0	73.9	56.4
	N_3	76	92.9	79.3	100.0	82.8	83.0	80.6	81.2	68.3
	N_4	79	105.2	114.0	111.7	107.5	107.5	100.0	120.1	102.6
	N_5	82	147.7	141.4	150.0	150.6	137.3	148.7	138.1	148.7
	N_6	85	166.7	178.4	195.2	175.0	185.7	194.7	178.6	195.2
	N_7	88	211.5	213.0	220.2	210.8	225.8	222.5	210.0	235.7

a_{VDV} (ms$^{-1.75}$)	Slope (n_s/20)	Intercept ($\log_{10}(k_s)$) (dB)	Correlation (r_s)
0	0.036	-0.792	0.991
0.146	0.040	-1.144	0.992
0.230	0.045	-1.523	0.973
0.363	0.038	-0.994	0.994
0.573	0.041	-1.187	0.997
0.906	0.042	-1.287	0.993
1.431	0.037	-0.898	0.980
2.318	0.042	-1.318	0.994

Equivalent continuous sound pressure level, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

Table 2. Magnitude estimates for the discomfort caused by vibration, ψ_v (with N_0) and ψ'_v (with N_1-N_7) and linear regression analysis showing the relation between the subjective magnitude, $\log_{10}(\psi_v)$ (or $\log_{10}(\psi'_v)$), and the vibration dose value, a_{VDV}, in the presence of different levels of simultaneous noise. Medians of 24 subjects.

			L_{AE}(dBA)							
			N_0	N_1	N_2	N_3	N_4	N_5	N_6	N_7
			0	70	73	76	79	82	85	88
			ψ_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v
a_{VDV} ($ms^{-1.75}$)	V_1	0.146	32	30	36.7	32.1	27.9	28.6	25	27.9
	V_2	0.230	48.5	50	50	46.6	50	50	46.4	41.4
	V_3	0.363	75	73.9	95	75	90	86.7	100	71.7
	V_4	0.573	134.9	107.9	117.1	118.7	129.2	116.0	116.0	100
	V_5	0.906	190.9	169.1	179.2	175.7	200	200	204.4	200
	V_6	1.431	273.3	265	250	245	262.8	300	281.7	300
	V_7	2.318	339.3	358.6	331.0	368.6	373.5	378.6	369.3	321.3

L_{AE} (dBA)	Slope (n_v) ($1/(ms^{-1.75})$)	Intercept ($\log_{10}(k_v)$)	Correlation (r_v^2)
0	0.891	2.277	0.984
70	0.902	2.257	0.998
73	0.812	2.263	0.993
76	0.893	2.260	0.999
79	0.924	2.293	0.991
82	0.945	2.300	0.994
85	0.963	2.296	0.984
88	0.957	2.258	0.988

Equivalent continuous sound pressure level, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

Table 3. Magnitude estimates for the discomfort caused by combined noise and vibration, ψ_c. Medians of 24 subjects.

		a_{VDV} (ms$^{-1.75}$)							
		V_0 0	V_1 0.146	V_2 0.230	V_3 0.363	V_4 0.573	V_5 0.906	V_6 1.431	V_7 2.318
L_{AE} (dBA)	N_0 0	0	11.3	14.6	30.4	49.2	68.6	107.9	131.2
	N_1 70	30.6	39.7	38.2	46.9	51.9	76.5	100	140.6
	N_2 73	42.9	46.4	60	55.4	61.4	80	108.1	143.2
	N_3 76	65.2	66.7	61.8	60	77.6	94.7	117.1	142.9
	N_4 79	76.0	72.8	73.2	85.7	96.9	100	118.4	149.6
	N_5 82	92.8	100	110.6	111.4	112.7	108.3	123.1	158.6
	N_6 85	116.2	112.2	121.5	119.1	129.6	140	158.6	171.9
	N_7 88	134.9	153.1	150	145.1	163.6	155.8	161.8	192.1

Equivalent continuous sound pressure level, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.55 \times a_{VDV}$.

FIGURE CAPTIONS

FIGURE 1. Subject on the test rig.

FIGURE 2. Subjective magnitudes of different levels of noise as a function of SEL (above) and as a function of VDV (below). + = no vibration stimuli.

FIGURE 3. Subjective magnitudes of different magnitudes of vibration as a function of SEL (above) and as a function of VDV (below). x = no noise stimuli.

FIGURE 4. The discomfort of combined noise and vibration as a function of SEL (above) and a function of VDV (below). x = no noise stimuli; + = no vibration stimuli.

FIGURE 5. Comparison of median magnitude estimates with predicted magnitude estimates of: (a) the multiple linear regression equation, and (b) the root-sum-of-squares model.

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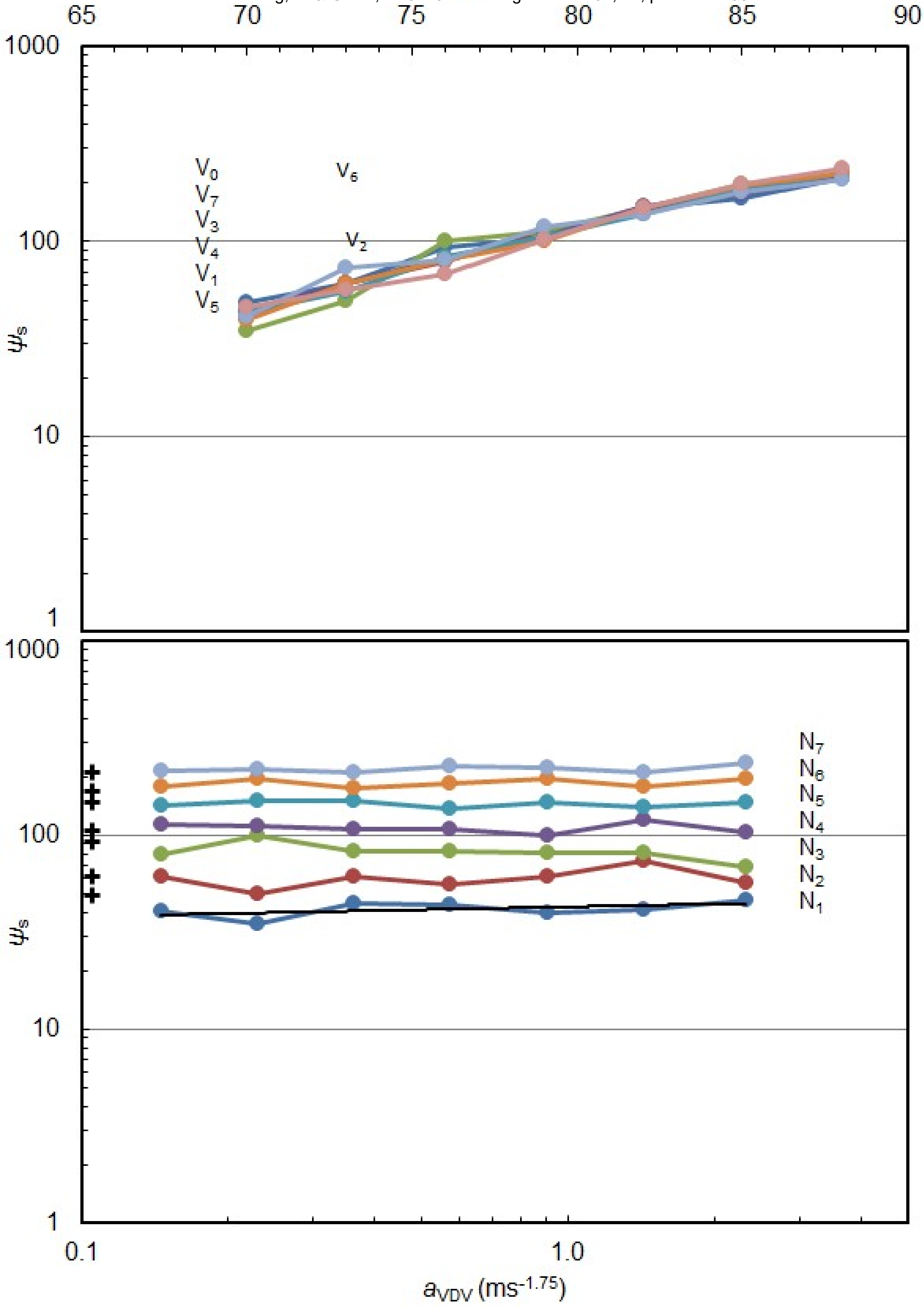

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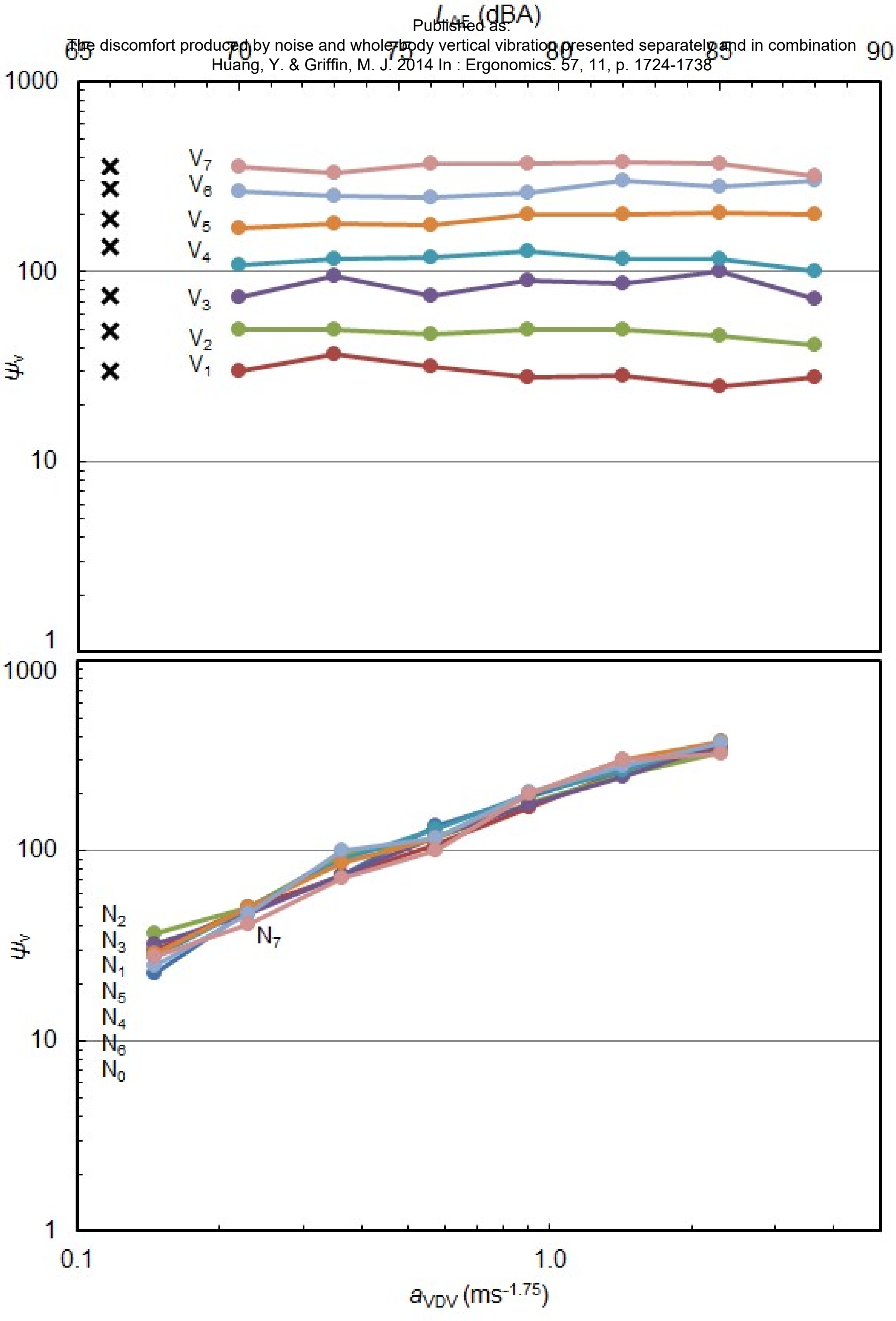

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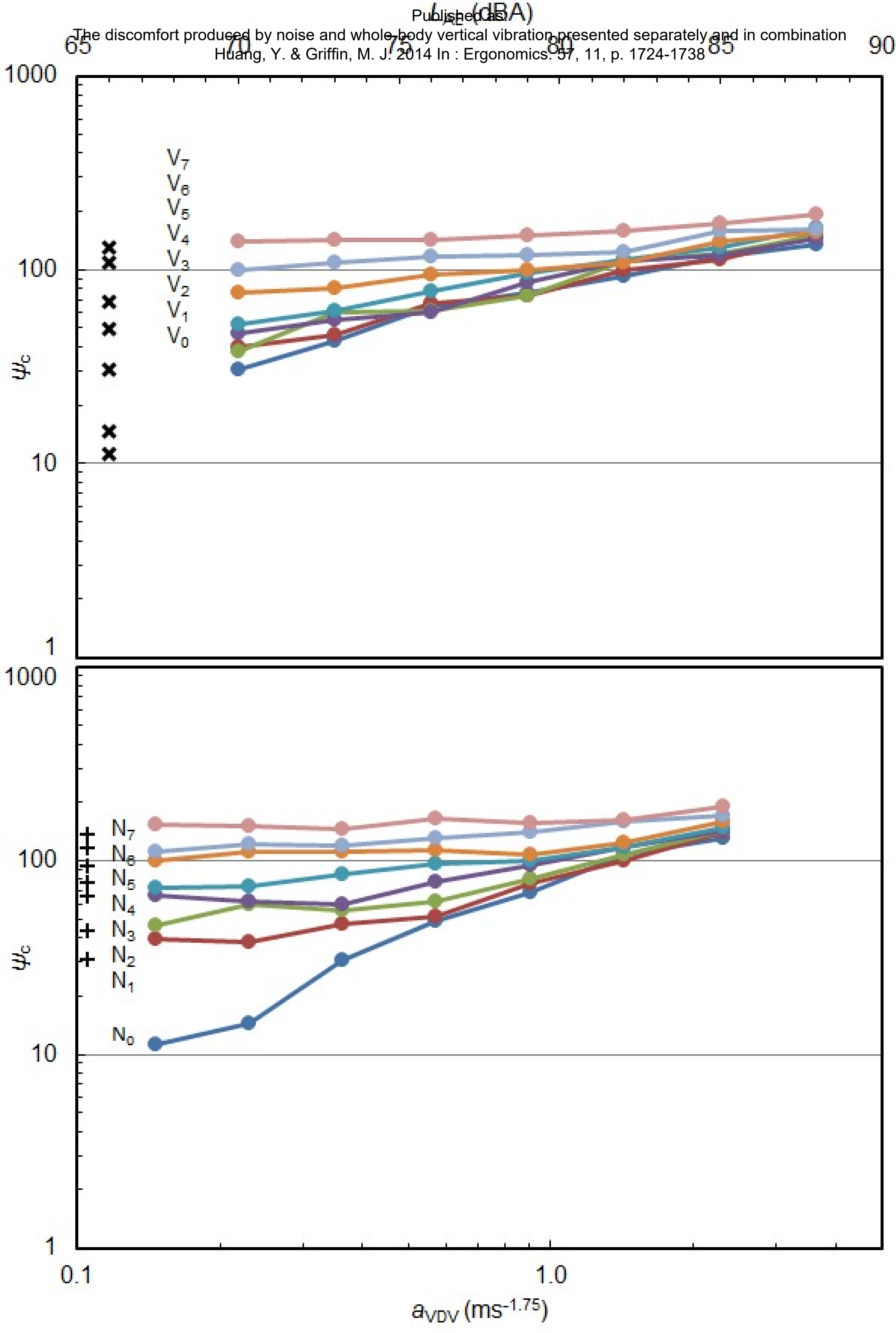

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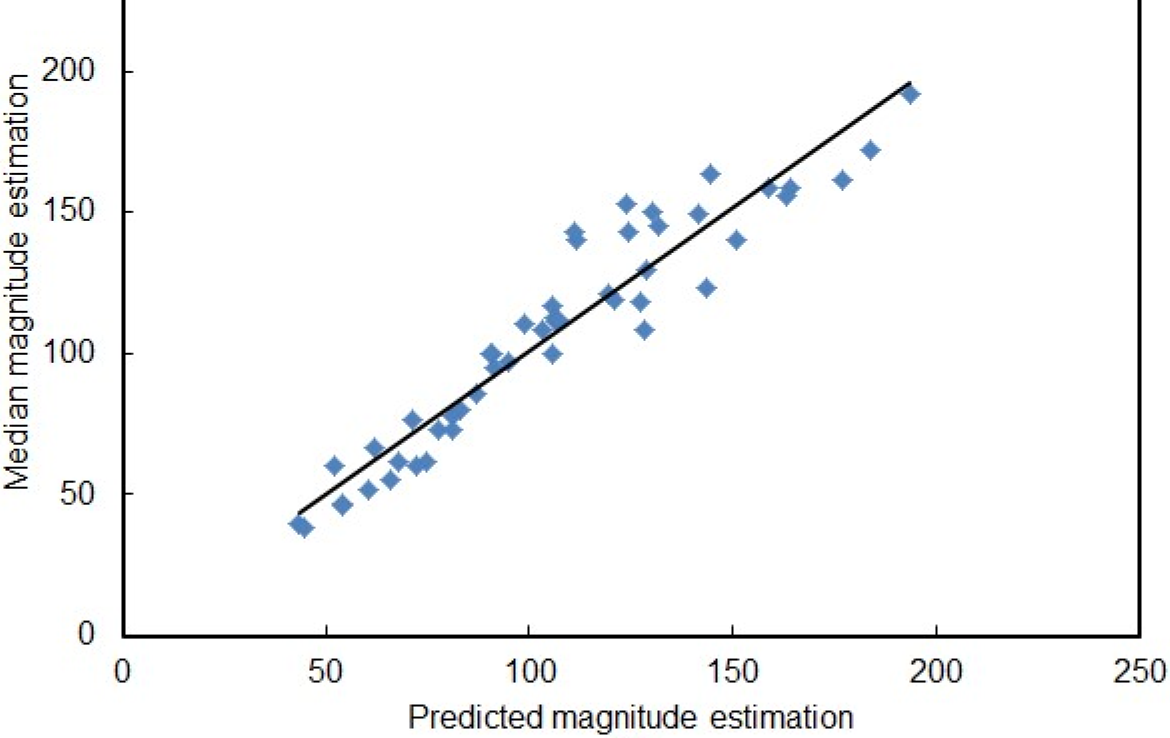
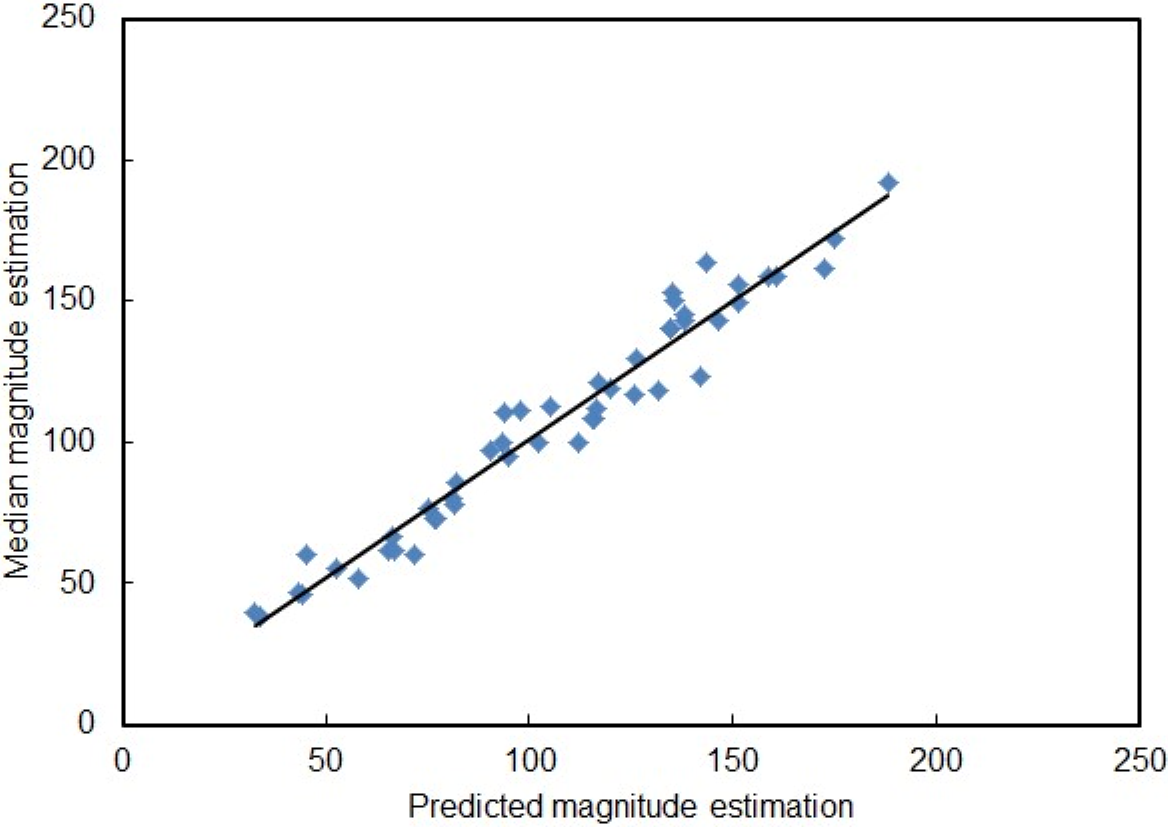


(a)



(b)