Published as:
The effects of sound level and vibration magnitude on the relative discomfort of noise and vibration
Huang, Y. & Griffin, M. J. Jun 2012 In : Journal of the Acoustical Society of America. 131, 6, p. 4558-4569

Number of pages: 26

Number of references: 26

Number of figures: 8

Number of tables: 4

The effects of sound level and vibration magnitude on the relative discomfort of noise and vibration

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Abstract

The relative discomfort caused by noise and vibration, how this depends on the level of noise and the magnitude of vibration, and whether the noise and vibration are presented simultaneously or sequentially has been investigated in a laboratory study with 20 subjects. Noise and vertical vibration were reproduced with all 49 combinations of seven levels of noise and seven magnitudes of vibration to allow the discomfort caused by one of the stimuli to be judged relative to the other stimulus using magnitude estimation. In four sessions, subjects judged noise relative to vibration and vibration relative to noise, with both simultaneous and sequential presentations of the stimuli. The equivalence of noise and vibration was not greatly dependent on whether the stimuli were simultaneous or sequential, but highly dependent on whether noise was judged relative to vibration or vibration was judged relative to noise. When judging noise, higher magnitude vibrations appeared to mask the discomfort caused by low levels of noise. When judging vibration, higher levels of noise appeared to mask the discomfort caused by low magnitudes of vibration. The judgement of vibration discomfort was more influenced by noise than the judgment of noise discomfort was influenced by vibration.

PACs: 43.40.Ng, 43.50.Qp, 43.66.Wv

I. INTRODUCTION

In vehicles, aircraft, ships and buildings, both noise and vibration can influence human comfort. To understand subjective responses to combined noise and vibration it is helpful to know the relative importance of the two modalities.

According to Stevens' power law (Stevens, 1986), the subjective magnitude of sound (e.g. loudness), ψ_s, and the subjective magnitude of vibration (e.g. vibration discomfort), ψ_v, are related to the physical magnitude of sound, φ_s, and the physical magnitude of vibration, φ_v, by power functions:

$$\psi_s = k_s \varphi_s^{n_s} \tag{1}$$

$$\psi_v = k_v \varphi_v^{n_v}, \tag{2}$$

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.

If the subjective magnitudes of sound and vibration are judged to be equal, the subjective equivalence between noise and vibration can be expressed by:

$$k_s \varphi_s^{n_s} = k_v \varphi_v^{n_v}. \tag{3}$$

It follows that the subjective equivalence between noise and vibration is given by either:

$$\log_{10}(\varphi_s) = \log_{10}(k_v / k_s)^{1/n_s} + n_v / n_s \log_{10}(\varphi_v) \tag{4}$$

or

$$\log_{10}(\varphi_v) = \log_{10}(k_s / k_v)^{1/n_v} + n_s / n_v \log_{10}(\varphi_s) \tag{5}$$

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

$$\text{sound exposure level (dBA)} = L_{AE} = 10\log_{10}\left(\frac{1}{t_0}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}\mathrm{d}t\right) \tag{6}$$

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:

$$\text{vibration dose value (ms}^{-1.75}) = a_{VDV} = \left(\int_0^T a^4(t)\mathrm{d}t\right)^{1/4} \tag{7}$$

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

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 and vibration depend on the magnitudes of the stimuli (sound pressure or acceleration, respectively) and the durations of the stimuli. The sound exposure level doubles with a 4-fold increase in the duration of a sound whereas the vibration dose value doubles with a 16-fold increase in the duration of a vibration.

If $L_{AE} \propto 20 \log(\varphi_s)$ (from equation (6) assuming φ_s represents the *A*-weighted sound pressure) and $a_{VDV} \propto \varphi_v$, it follows from equation (4) that the subjective equivalence between the sound exposure level, L_{AE}, in dBA, and the vibration dose value, a_{VDV}, in ms$^{-1.75}$, is given by:

$$L_{AE} = k + 20\frac{n_v}{n_s}\log_{10}(a_{VDV}) \tag{8}$$

where k is a constant (dB). The relationship implies that when presented on a graph of $\log_{10}(a_{VDV})$ versus L_{AE}, the subjective equivalence between noise and vibration should have a slope, s, of $20(n_v/n_s)$ (dB/ms$^{-1.75}$).

The value of $20(n_v/n_s)$ can be anticipated from previous determinations of the growth function for noise, n_s, and the growth function for vibration, n_v. For vertical whole-body vibration, various values of the exponent, n_v, have been reported: between 0.86 and 1.04 for frequencies in the range 3.5 to 20 Hz (Shoenberger and Harris, 1971), 0.93 for frequencies from 5 to 80 Hz (Jones and Saunders, 1974), 1.04 to 1.47 for frequencies from 4 to 63 Hz (Howarth and Griffin, 1988), 1.18 for frequencies of 10 to 50 Hz (Howarth and Griffin, 1991) and 0.626 to 0.897 for frequencies between 2 and 50 Hz (Morioka and Griffin, 2006). The appropriate exponent seems to depend on the frequency of vibration and, perhaps, the magnitude of vibration.

For sound, an exponent of 0.60, 0.64, or 0.68 was originally proposed to relate the subjective magnitude of loudness to the sound pressure of 3000-Hz tones (Stevens, 1955, 1986). Although the value of 0.60 for the exponent is widely quoted and has been recognized as the standard value, Eisler (1976) reviewed studies of the exponent, n_s, conducted prior to 1975 and reported various values from 0.4 to 1.1. Ward *et al.* (1996) used three methods (category judgment, magnitude estimation, and cross-modality matching), and two sets of 1000-Hz tone stimuli (narrow-range set with stimuli from 55 to 82 dB in 3-dB steps; wide-range set with 40, 43, 61, 64, 67, 70, 73, 76, 94, and 97 dB stimuli), and obtained exponents of 0.411 and 0.244 for the narrow-range and the wide-range conditions, respectively, when using category judgment, 0.483 and 0.324 when using absolute magnitude estimation, and 1.017 and 0.759 when using cross-modality matching to the apparent brightness of a light.

Studies of subjective responses to both noise and vibration have also found a wide range of values for the exponent, n_s, for sound: 0.42 to 0.54 when 300-Hz bandwidth random noise centred on 2000 Hz was judged relative to 5 to 80-Hz sinusoidal vibration (Hempstock and Saunders, 1976), 0.72 when 20 to 3000-Hz train noise from buildings nearby a railway expressed in SEL were judged relative to 18- to 60-Hz train vibration (Howarth and Griffin, 1991), and 0.38 to 0.72 when low-frequency noise from a running car expressed in SEL was judged relative to vertical vibration of the car in the range 0.11 to 1.12 $ms^{-1.75}$ VDV (Huang and Griffin, 2010).

From the different exponents of n_v and n_s in previous studies, different slopes for the subjective equivalence between noise and vibration on a graph of $\log_{10}(a_{VDV})$ versus L_{AE} can be anticipated. For example, if n_v=0.70 (the median vibration exponent at frequencies in the range 2 to 50 Hz found by Morioka and Griffin, 2006), and n_s=0.72 (Howarth and Griffin, 1991), then the slope would be around 20 dB/($ms^{-1.75}$). However, these values for n_v and n_s were obtained with different experimental conditions (different methods, stimuli, subjects, etc.), so the slopes predicted by n_v and n_s from such unrelated experiments might not be appropriate.

The value of slope, $20(n_v/n_s)$, can be determined directly from experimental studies of the subjective equivalence between noise and vibration. Subjective responses to combined noise and vibration have been studied using artificial stimuli (e.g. sinusoidal or random noise and vibration) and reproductions of environmental stimuli (e.g., Hempstock and Saunders, 1972, 1973, 1975; Fleming and Griffin, 1975; Kjellberg *et al.*, 1985; Howarth and Griffin, 1990a, 1990b, 1991; Paulsen and Kastka, 1995; Parizet and Brocard, 2004). Calculations of the physical magnitudes of noise and vibration that are subjectively equivalent show a wide range of values for $20(n_v/n_s)$: 29.3 dB/($ms^{-1.75}$) for reproductions of noise and vibration in buildings near a railway (Howarth and Griffin, 1990a), 33.0 dB/($ms^{-1.75}$) for sinusoidal stimuli (Fleming and Griffin, 1975), 14.4 dB/($ms^{-1.75}$) for noise and vibration recorded in a flat during the passing of a nearby tram (Paulsen and Kastka, 1995).

Different values for the exponents, n_v and n_s, and their ratio $20(n_v/n_s)$ might arise for several reasons: the effect may be real and reflect real changes in the rates of growth with different stimuli, or it may be artefactual (e.g. due to the use of different psychophysical methods, range effects, order of presenting stimuli, etc.) and reflect the methods used in the different experiments. The variation could alternatively reflect an interaction (e.g. masking) in which judgements of noise (or vibration) are affected by the presence of vibration (or noise). The limited number of studies currently available show divergent results but insufficient information to understand the causes of the differences.

This study was primarily designed to test three hypotheses: (i) the subjective equivalence between noise and vibration (e.g., $L_{AE} = k + 20(n_v/n_s)\log_{10}(a_{VDV})$), would differ depending on whether noise is judged relative to vibration or vibration is judged relative to noise, (ii) the slope, $s = 20(n_v/n_s)$, would depend on both the level of noise (because high magnitudes of vibration may influence judgements of low levels of noise) and the magnitude of vibration (because high levels of noise may influence judgements of low magnitudes of vibration), and (iii) the influence of noise on judgements of vibration, and the influence of vibration on judgements of noise, would be less when noise and vibration are presented sequentially than when they are presented simultaneously.

II. METHOD

A. Subjects

Twenty subjects (10 male and 10 female), with median age 23 years (range 19 to 30 years), stature 169 cm (range 162 to 196 cm), and weight 60 kg (range 46 to 110 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.

B. 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.

A piezoresistive accelerometer (Entran International, 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, 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.

C. Stimuli

Sound and vibration were recorded inside a car (2171cc petrol engine, 4488 mm length, 1757 mm width, 1369 mm height, 2725 mm wheelbase, and 1890 kg gross vehicle weight). An *HVLab* SIT-pad containing an accelerometer (Entran International, Model EGCSY-240D-10) was used to record the *z*-axis acceleration on the driver's seat and a Rion sound level meter (NL-28) held at the head position of the front passenger recorded and measured the sound.

Synchronous noise and vibration of 4-s duration was selected with the car running at 40 mph on an asphalt road. The r.m.s. acceleration, a_{rms}, and vibration dose value, a_{VDV}, of this vibration were 0.32 ms^{-2} and 0.63 ms$^{-1.75}$, respectively, using frequency weighting W_b (BS 6841, 1987, and ISO 2631-1, 1997). The A-weighted sound pressure level, L_{Aeq} was 65 dBA, so the A-weighted sound exposure level of the 4-s stimulus, L_{AE}, was 71 dBA (ISO 1996-1, 2003).

The vibration and sound stimuli used in the experiment were developed from the selected sample by applying a cosine taper to the first and last 0.2 s. The time series and the frequency spectra of the vibration and sound stimuli are shown in Figure 1. With an exposure duration of 4 s, seven sound stimuli were generated with levels from 70 to 88 dBA in 3 dB steps (ISO 1996-1, 2003), and seven vibration stimuli were generated with vibration dose values of 0.092, 0.146, 0.231, 0.366, 0.581, 0.92 and 1.458 ms$^{-1.75}$ (BS 6841, 1987, ISO 2631-1, 1997). 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 in the ear position when wearing the headphones was around 50 dBA.

FIGURE 1 ABOUT HERE

D. Procedure

The subjects were instructed to sit with a comfortable upright posture with their eyes closed and wear the headphones. Judgments of ‘discomfort’ were obtained using the method of magnitude estimation (Stevens, 1986). The sound and vibration stimuli were presented in pairs with one of the two stimuli identified as the reference stimulus.

The experiment was undertaken in four sessions. In session A, subjects were presented with all 49 possible combinations of the seven levels of noise and the seven magnitudes of vibration. The pairs of stimuli (i.e. sound and vibration) were presented simultaneously in an independent random order. For each presentation, the subjects were asked to state the discomfort caused by the noise, assuming the discomfort caused by the reference vibration was 100. Session B was similar to session A, except the subjects were asked to state the discomfort caused by the vibration, assuming the discomfort caused by the reference noise was 100. Session C was similar to session A, except the vibration was presented prior to the noise and subjects judged the discomfort caused by the noise assuming the discomfort caused by the reference vibration was 100. Session D was similar to session C, except the noise was presented prior to the vibration and subjects judged the discomfort caused by the vibration assuming the discomfort caused by the reference noise was 100. Subjects experienced the four sessions on different days and in a balanced order. When presenting the noise and vibration sequentially (in sessions C and D), the stimuli were separated by a 1-s pause, and each pair of noise and vibration stimuli was presented twice (e.g. noise-vibration-noise-vibration) before obtaining a response so as to minimise any order effect (Davidson and Beaver, 1977).

Before commencing the experiment, subjects were provided with written instructions and practiced judging the lengths of lines drawn on paper and then judging some combined noise and vibration stimuli until they felt confident with magnitude estimation.

III. RESULTS

A. Discomfort of noise judged relative to simultaneous or sequential reference vibration

Median subjective magnitudes of the discomfort associated with the seven levels of noise (as a function of L_{AE}) relative to the seven magnitudes of vibration during the simultaneous and sequential presentations of noise and vibration are shown in Tables I and II, respectively, where the subjective magnitude of the discomfort associated with each of the reference magnitudes of vibration is always 100.

TABLES I AND II ABOUT HERE

Linear regression analyses were performed between the median values of the dependent variable, $\log_{10}(\psi_s)$, and the independent variable, L_{AE}, for each vibration stimulus. The intercepts, the slopes, and the correlation coefficients are shown in Tables I and II. From the linear relationships, the sound exposure levels that produced the same discomfort as each reference vibration magnitude (i.e. a subjective magnitude of 100) were obtained and are shown as the L_{AE1} and L_{AE2} columns in Tables I and II, respectively.

From equation (8), linear regression between the L_{AE} and a_{VDV} values in Table I, gave the relationship for subjective equality of discomfort between simultaneous noise and vibration:

$$L_{AE} = 82.1 + 13.0 \times \log_{10}(a_{VDV}) \tag{9}$$

Linear regression between the L_{AE} and a_{VDV} values in Table II gave the relationship for subjective equality of discomfort between sequential noise and vibration:

$$L_{AE} = 79.8 + 12.4 \times \log_{10}(a_{VDV}) \tag{10}$$

The same procedures applied to the magnitude estimates provided by each subject showed no difference in the slopes, s, between simultaneous and sequential presentation (p=0.145 Wilcoxon), but a significant increase in the intercepts k with simultaneous presentation (p=0.007 Wilcoxon).

B. Discomfort of vibration judged relative to simultaneous or sequential reference noise

Median subjective magnitudes of the discomfort associated with the seven magnitudes of vibration (as a function of a_{VDV}) relative to the seven levels of noise during the simultaneous and sequential presentation of noise and vibration are shown in Tables III and IV, respectively, where the subjective magnitude of the discomfort associated with each of the reference magnitudes of noise is always 100.

TABLES III AND IV ABOUT HERE

Linear regression analyses were performed between the median values of the dependent variable, $\log_{10}(\psi_V)$, and the independent variable, a_{VDV}, for each noise stimulus. The intercepts, the slopes, and the correlation coefficients are shown in Table III and IV. From the linear relationships, the vibration dose values that produced the same discomfort as each reference noise level (i.e. a subjective magnitude of 100) were obtained and are shown as the a_{VDV1} and a_{VDV2} columns in Tables III and IV, respectively.

From equation (8), linear regression between the L_{AE} and a_{VDV} values in Table III, gave the relationship for the subjective equality of discomfort between simultaneous noise and vibration:

$$L_{AE} = 84.8 + 30.4 \times \log_{10}(a_{VDV}) \tag{11}$$

Linear regression between the L_{AE} and a_{VDV} values in Table IV gave the relationship for subjective equality of discomfort between sequential noise and vibration:

$$L_{AE} = 84.4 + 32.6 \times \log_{10}(a_{VDV}) \tag{12}$$

The same procedure applied to the magnitude estimates provided by each subject showed no difference in the slopes, s, or the intercepts, k, between simultaneous and sequential presentation (slope: p=0.478; intercept: p=0.351; Wilcoxon).

C. Contours of equivalence between sound and vibration

Contours showing the noise and vibration that produced equivalent discomfort in the four sessions are shown in Figure 2 and compared in Figure 3.

FIGURES 2 and 3 ABOUT HERE

The slopes, s, were significantly greater when judging vibration relative to noise than when judging noise relative to vibration (p=0.015 for simultaneous stimuli, p=0.001 for sequential stimuli, Wilcoxon). Similarly, the intercepts, k, were significantly greater when judging vibration relative to noise than when judging noise relative to vibration (p=0.011 for simultaneous stimuli, p=0.002 for sequential stimuli, Wilcoxon).

IV. DISCUSSION

A. Equivalence between sound and vibration in different studies

Several previous studies have produced information on the subjective equivalence of sound and vibration. In a study of the subjective equivalence of 1-kHz pure tones (SPLs from 65 to 100 dBA) and 10-Hz sinusoidal whole-body vertical vibration (at 0.20, 0.30, 0.40, 0.50, 0.60, 0.80, 1.00, and 1.20 ms^{-2} r.m.s.) subjects were presented with the noise and the vibration simultaneously and asked to say which of the two stimuli they would prefer to reduce (Fleming and Griffin, 1975). The L_{AE} and a_{VDV} values can be calculated from the L_{Aeq} and the r.m.s. acceleration to provide the relation:

$$L_{AE} = 93.6 + 33.0 \times \log_{10}(a_{VDV}) \tag{13}$$

Using sequential presentations of 2.5-s stimuli, Hempstock and Saunders (1973, 1975) asked subjects to adjust the level of noise (300-Hz bandwidth random noise centred on 2000 Hz) to be subjectively equivalent to various levels of sinusoidal vibration (5, 10, 20, 30, 40, and 80 Hz presented at 0.5, 1.0, 2.0, 4.0, and 6.0 ms^{-2} r.m.s.). When presented as in equation (8), the slopes range from 16.2 to 29.1 ($ms^{-1.75}$) with intercepts from 72 to 88 over the vibration frequencies. Using the median slopes and intercepts, further analysis provides the following relation between the a_{VDV} and the L_{AE}:

$$L_{AE} = 80.0 + 20.8 \times \log_{10}(a_{VDV}) \tag{14}$$

Using simultaneous presentations of broad-band noise (L_{Aeq} from 15 dB to 115 dB) and vertical vibration (0.95, 1.1, 1.4, and 2.0 ms^{-2} r.m.s. at 3.1 Hz, and 1.3, 1.6, 2.4 and 3.5 ms^{-2} r.m.s. at 6.3 Hz) recorded in forklift trucks, Kjellberg *et al.* (1985) asked subjects to adjust the noise to a level that gave the same discomfort the vibration. The subjective equivalence of noise and vibration can be obtained from their results and expressed as:

$$L_{AE} = 75.5 + 40.0 \times \log_{10}(a_{VDV}) \tag{15}$$

Howarth and Griffin (1990) employed a method similar to Fleming and Griffin (1975), but with simultaneous simulations of the noise and vertical vibration recorded over 24 seconds in a building adjacent to a railway during the passage of a train. With L_{AE} in the range 59 to 84 dBA and a_{VDV} in the range 0.07 to 0.40 $ms^{-1.75}$ (W_b weighted), the subjective equality between the stimuli was expressed by:

$$L_{AE} = 89.2 + 29.3 \times \log_{10}(a_{VDV}) \tag{16}$$

The annoyance caused by reproductions of the noise and vibration in a flat produced by a passing tram was studied by Paulsen and Kastka (1995). With vibration in the range 0.03 to 0.4 mm/s (velocity) and noise in the range 28 to 61 dBA (L_{Aeq}), equivalence between the simultaneous noise and vibration was given by:

$$L_{AE} = 51.9 + 14.4 \times \log_{10}(a_{VDV}) \quad (17)$$

With simultaneous simulations of the noise and vertical vibration measured in a car (11 levels of noise: L_{AE} from 61 to 91 dBA in 3 dB steps; 10 magnitudes of vibration: a_{VDV} from 0.11 to 1.12 ms$^{-1.75}$), Huang and Griffin (2010) used the method of magnitude estimation to obtain equivalent comfort:

$$L_{AE} = 80.4 + 14.7 \times \log_{10}(a_{VDV}) \quad (18)$$

The subjective equivalence between noise and vibration implied by the findings of previous studies are compared with the four contours from the present study in Figure 4.

FIGURE 4 ABOUT HERE

The slopes of the equivalent comfort contours obtained in sessions A and C of the present study (i.e. 13.0 and 12.4 dB/(ms$^{-1.75}$)), when judging the discomfort of noise relative to either simultaneous or sequential vibration (equations 9 and 10), may seem reasonably consistent with the slopes of 20.8 dB/(ms$^{-1.75}$) obtained by Hempstock and Saunders (1975) and 14.7 dB/(ms$^{-1.75}$) obtained by Huang and Griffin (2010). Although the slope of 14.4 dB/(ms$^{-1.75}$) obtained by Paulsen and Kastka (1995) is also similar, the intercept differs, possibly due to their subjects judging much lower levels of sound relative to similar magnitudes of vibration. It has been reported that irrelevant noises (e.g., sinusoidal noise or white noise) are evaluated louder than real noises (e.g., Suzuki *et al.*, 2006), suggesting the intercepts may be greater when using artificial stimuli than when using real stimuli, consistent with Howarth and Griffin (1990) finding a slightly lower intercept than Fleming and Griffin (1975) even though they used the same method.

The slopes of equivalent comfort contours obtained in sessions B and D of the present study (i.e. 30.4 and 32.6 dB/(ms$^{-1.75}$)), when judging the discomfort of vibration relative to simultaneous or sequential noise (equations 11 and 12), are reasonably consistent with the slope of 33 dB/(ms$^{-1.75}$) obtained by Fleming and Griffin (1975), the slope of 40 dB/(ms$^{-1.75}$) obtained by Kjellberg *et al.* (1985), and the slope of 29.3 dB/(ms$^{-1.75}$) obtained by Howarth and Griffin (1990).

Some of the differences between the equivalent comfort contours might be explained by the 'range effect' (Poulton, 1973). Hempstock and Saunders (1975) employed the same noise levels as Fleming and Griffin (i.e., 65 to 100 dBA) but a wider range of vibration magnitudes (0.5 to 6.0 ms^{-2} r.m.s compared with 0.2 to 1.2 ms^{-2} r.m.s.), consistent with them finding a lower slope (i.e. 20.8 dB/($ms^{-1.75}$) compared with 33.0 dB/($ms^{-1.75}$)). Paulsen and Kastka employed lower levels of sound than others and found a lower slope, also consistent with the 'range effect'. It might also be significant that Kjellberg *et al.* (1985) used a wide range of sound levels (15 to 115 dB) and greater vibration magnitudes (0.95 to 3.5 ms^{-2} r.m.s.), and obtained a greater slope, also consistent with a 'range effect'.

In the present study, the slopes of the equivalent comfort contours obtained when judging noise relative to vibration (13.0 and 12.4 dB/($ms^{-1.75}$) in sessions A and C, respectively), are much less than when judging vibration relative to noise (30.4 and 32.6 dB/($ms^{-1.75}$) in sessions B and D, respectively), yet both could be considered consistent with the findings of previous studies. The difference in slopes may be associated with whether subjects focus on the noise or focus on the vibration (i.e. whether the noise or vibration is dominant). Paulsen and Kastka (1995) asked subjects to 'indicate on a scale from 0 to 9 how strong the perceived noise was', so the noise level was the dominant modality, as in the Huang and Griffin (2010) study, and in sessions A and C of the present study, where similar slopes were obtained. In the Hempstock and Saunders (1975) study, when the subjects were asked to adjust the noise level to be equivalent to a fixed magnitude of vibration, the median slope was 20.8 dB/($ms^{-1.75}$), broadly consistent with other studies where the discomfort caused by the noise was the principal dependent variable.

Paulsen and Kastka found that the slope obtained for the modality 'noise' was independent of the question (i.e. 'annoyance' or 'intensity'), whereas the evaluation of the modality 'vibration' was dependent on how the question was expressed to the subjects (Paulsen and Kastka, 1995). When being asked to evaluate noise, subjects may be more likely to focus on the modality 'noise', whereas when they are asked to evaluate vibration, or not told which modality (i.e. noise, or vibration) to evaluate, subjects may focus on the more unusual modality of 'vibration'. In sessions B and D of the present study, subjects judged the discomfort of vibration relative to simultaneous or sequential noise, and the principal dependent variable (i.e. discomfort caused by vibration) may have been the dominant modality. When the discomfort caused by vibration was the dependent variable, Hempstock and Saunders (1975) found slopes from 37.0 to 47.6 dB/(ms$^{-1.75}$), consistent with the results of sessions B and D of the present study.

Both Fleming and Griffin (1975) and Howarth and Griffin (1990) asked subjects to state whether they would prefer the vibration or the noise to be reduced, allowing either the vibration or the noise to be dominant, and they obtained similar slopes (33 and 29.3 dB/(ms$^{-1.75}$)). Their slopes are similar to those obtained in the present study when judging the discomfort of vibration relative to noise (30.4 dB/(ms$^{-1.75}$) in session B and 32.6 dB/(ms$^{-1.75}$) in session D), suggesting their subjects may have focused more on the vibration than on the noise. Perhaps the vibration was less familiar to subjects and so demanded their attention.

Assuming n_s=0.67 and n_v=0.70, Huang and Griffin (2010) hypothesized a slope of about 21 dB/(ms$^{-1.75}$), similar to the average of the slopes of 13.0 and 12.4 dB/(ms$^{-1.75}$) from sessions A and C, and 30.4 and 32.6 dB/(ms$^{-1.75}$) from sessions B and D in present experiment. Hempstock and Saunders (1975) obtained different slopes 16.2 to 29.1 dB/(ms$^{-1.75}$) from differing values of n_s and n_v when altering the level of dependent noise to be equal to the discomfort of a fixed value of the independent vibration, and found an average slope of 21.3 dB/(ms$^{-1.75}$). The value of 21 dB/(ms$^{-1.75}$) as the slope of the equivalence comfort contour may seem a sensible compromise for practical applications, but it will yield equivalence that differs from the experimental values when applied over a wide range of noise or vibration levels. An understanding for the reasons for the differing slopes would therefore appear to have both practical and academic value.

The slopes reported above are dependent on the durations of the stimuli, because the time-dependency used to express exposure to noise (i.e. SEL) differs from the time dependency used to express exposure to vibration (i.e. VDV). For example, if the findings of Howarth and Griffin (1990) using 24-s stimuli are expressed in terms of SPL and r.m.s. acceleration, a slope of 27.6 dB/(ms^{-2}) is obtained compared to 29.3 dB/(ms$^{-1.75}$) when the findings are expressed in terms of SEL and VDV. For shorter durations, such as 10-s stimuli used by Fleming and Griffin (1975) and the 4-s stimuli used by Huang and Griffin (2010) and in present study, the differences in the slopes of equivalence comfort contours expressed by SPL and r.m.s. acceleration, or by SEL and VDV are relatively small. However, there remains uncertainty as to how much of the difference can be attributed to differences between the time-dependencies of noise and vibration because the VDV and the SEL may not be suitable indicators of the effect of duration on the equivalence between noise and vibration. The time-dependence of the subjective equivalence between noise and vibration appears to merit further consideration.

B. Influence of vibration on the discomfort of noise

From Stevens' power law for sound, $\psi_s = k_s \varphi_s^{n_s}$, the relation between the dependent variable, ψ_s, and the independent variable, L_{AE}, can be written:

$$\log_{10}(\psi_s) = \log_{10}(k_s) + n_s/20 \times L_{AE} \quad (19)$$

Linear regressions between the logarithm of the sound discomfort, ψ_s, and the sound level, L_{AE}, judged relative to the discomfort caused by each of the seven reference magnitudes of vibration are shown for simultaneous and sequential presentations in Figures 5 and 6, respectively. When the magnitude of the simultaneous reference vibration increased from 0.092 $ms^{-1.75}$ to 1.457 $ms^{-1.75}$, there was a trend for the median slope to increase from 0.022 to 0.028 (p=0.053, Friedman; Table I). When the reference vibration was presented sequentially, there was a non-significant increase in slope from 0.019 to 0.024 (p=0.226, Friedman; Table II).

FIGURES 5 AND 6 ABOUT HERE

If the discomfort caused by the noise was unaffected by the vibration, Figures 5 and 6 would show seven parallel lines differing due to the different levels of the reference noise. However, as the level of the reference vibration increased, the slopes increased, so the difference in discomfort caused by the lowest and the highest magnitudes of vibration reduced as the level of the noise increased.

It seems reasonable to suppose that judgements provided by the subjects may have been influenced by a 'range effect' (Poulton, 1973) and a 'masking effect'. A range effect will tend to cause overestimation of the subjective magnitudes of very low magnitude stimuli and underestimation of the subjective magnitudes of very high magnitude stimuli. A masking effect would involve one stimulus reducing the subjective severity of the other stimulus.

It would appear that a masking effect could fully explain the findings: when subjects focused on the noise and gave numerical ratings of the discomfort caused by noise, the higher magnitudes of vibration may have masked their perceptions of the lower levels of noise (lower left of Figures 5 and 6). The 'masking effect' reduced as the level of noise increased (moving to the right in Figures 5 and 6) and as the magnitude of the vibration reduced (moving up in Figures 5 and 6). Although there may have been a range effect it does not seem that a range effect can explain the findings: a range effect would tend to overestimate the subjective magnitudes of the low level noise stimuli in the lower left of Figures 5 and 6, yet they seem to be underestimated. Although a range effect might explain low values in the lower right of Figures 5 and 6, it does not seem plausible for these higher subjective magnitudes to be influenced by a range effect if the lower subjective magnitudes in the lower left of Figures 5 and 6 are not so influenced. Similar reasoning suggests it is unlikely an increase in ratings in the upper left of Figures 5 and 6, or a reduction in ratings in the upper right of Figures 5 and 6, could be fully explained by a range effect. It is tentatively concluded that although there may have been both a masking effect and a range effect, the ‘masking effect’ was greater than the ‘range effect’, and that the findings might be fully explained by some form of ‘masking’ of noise by the vibration.

It would be reasonable for any such ‘masking’ to be less with sequential presentations of the noise and vibration, consistent with the significant increase in the intercept *k*’ with simultaneous presentation (see Section 3.1). This suggests the discomfort of noise is masked more by simultaneous vibration than by sequential vibration: with the same reference, higher levels of noise were needed to produce equivalent discomfort in session A than in session C (Table I and II).

The findings suggest it may be necessary to include a masking effect of vibration on judgements of noise discomfort in the prediction of the relative (and combined) importance of noise and vibration, irrespective of whether the vibration and noise are simultaneous or sequential.

C. Influence of noise on the subjective discomfort of vibration

From $\psi_v=k_v\varphi_v^{n_v}$, the relation between the dependent variable, $\log_{10}(\psi_v)$, and the independent variable, $\log_{10}(a_{VDV})$, can be written as:

$$\log_{10}(\psi_v) = \log_{10}(k_v) + n_v/20 \times \log_{10}(a_{VDV}) \qquad (20)$$

From Tables III and IV, linear regressions between the logarithm of the vibration discomfort, ψ_v, and the vibration exposure, a_{VDV}, judged relative to the discomfort caused by each of the seven reference levels of noise are shown for simultaneous and sequential presentations in Figures 7 and 8.

FIGURES 7 AND 8 ABOUT HERE

In Figures 7 and 8, the slopes increase as the level of the reference noise increase, consistent with subjects giving either: (i) reduced discomfort ratings for the lower magnitudes of vibration relative to the higher levels of the reference noise (lower left of Figures 7 and 8), or (ii) increased discomfort ratings for the higher magnitudes of vibration relative to the higher levels of the reference noise (lower right of Figures 7 and 8), or (iii) increased discomfort ratings for the lower magnitudes of vibration relative to the lower levels of the reference noise (upper left of Figures 7 and 8), or (iv) lower discomfort ratings for the higher magnitudes of vibration relative to the lower levels of the reference noise (upper right of Figures 7 and 8).

It would appear that a masking effect could fully explain the findings: when subjects focused on the vibration, their perceptions of the lower magnitudes of vibration (lower left of Figures 7 and 8) may be masked by the higher levels of noise. The 'masking effect' reduced as the magnitude of vibration increased (moving to the right in Figures 7 and 8) and as the level of the noise reduced (moving up in Figures 7 and 8). Similar to the situation when subjects focused on the noise, a range effect does not fully explain the findings. Although there may have been both a range effect and a masking effect, the 'masking effect' was greater than any 'range effect', and the findings could be fully explained by some form of 'masking' of vibration by the noise.

It is possible that the higher magnitudes of the vibration test stimuli masked the lower levels of the noise reference stimuli (upper right of Figures 7 and 8). If this occurred, subjects will have increased their subjective magnitudes for the higher magnitudes of the vibration test stimuli because the subjective magnitude of the noise reference was reduced as a result of 'masking' by the vibration. Any overestimate of the subjective ratings may have been reduced to some extent by the 'range effect'.

It seems that noise may have masked the subjective magnitude of vibration no matter whether the noise and vibration were presented simultaneously or sequentially: in both Figures 7 and 8 the slopes of the regressions between the individual judgements of the subjective magnitude of vibration and the physical magnitude of vibration reduced as the level of the noise reduced (Friedman, $p<0.05$). The apparent influence of the noise on judgements of vibration was less when the stimuli were presented sequentially than when they were presented simultaneously: the differences in subjective magnitudes for the same physical magnitude of vibration between Figures 7 and 8 reduced as the level of the noise reduced, although none of the differences were statistically significant. The same tendency is apparent in Figure 3: the equivalent comfort contours obtained in session B (simultaneous noise and vibration) and session D (sequential noise and vibration) differ with low magnitude vibration (although not significantly) but become more similar as the vibration magnitude increases. This may be consistent with Kirby *et al.* (1977) who studied the ride quality of sinusoidal vertical vibration and broad-band noise presented simultaneously and concluded that the response was caused by both vibration and noise when there were relatively low levels of the stimuli but that the effect of the noise diminished as the level of the vibration increased.

The findings indicate it may be necessary to include a 'masking effect' of noise on judgements of the discomfort caused by low magnitude vibration within any prediction of the relative (and combined) importance of noise and vibration, irrespective of whether the vibration and noise are simultaneous or sequential. Comparing Figures 5 and 6 with Figures 7 and 8, the judgement of vibration seems more likely to be influenced by the noise when vibration is the principal dependent variable than the judgment of noise is influenced by vibration when noise is the principal dependent variable. This is consistent with the findings of Paulsen and Kastka (1995) and might be influenced by the subjects being less familiar with judging vibration.

D. Application of results

To determine which of the two stimuli, noise or vibration, causes greater discomfort when they occur together, the summary information in Figure 3 may be useful. If a combination of noise and vibration falls to the left of (or above) an appropriate equivalence curve, a reduction of noise will be more beneficial. If a combination of noise and vibration falls to the right of (or below) the equivalence curve, a reduction of vibration would be more beneficial.

For sound levels greater than 60 dBA, if noise is the principal dependent variable, the equivalence found in sessions A and C may be appropriate, where the average value of the two intercepts, 81.0 dB, and the average slope, 12.7 dB/(ms$^{-1.75}$), can be used to approximate equations (9) and (10) to within 1.5 dB. If vibration is the principal dependent variable, the equivalence found in sessions B and D may be appropriate, where the average intercept, 84.6 dB, and the average slope, 31.5 dB/(ms$^{-1.75}$), approximate equations (11) and (12) to within 1 dB.

V. CONCLUSIONS

The subjective equivalence between noise and vibration depends on whether the discomfort caused by noise is judged relative to the discomfort caused by vibration (i.e., noise is the dominant stimulus), or the discomfort caused by vibration is judged relative to the discomfort caused by noise (i.e., vibration is the dominant stimulus).

The subjective equivalence of noise and vibration is not greatly affected by whether the noise and vibration are presented simultaneously or sequentially.

When judging the discomfort caused by noise, higher magnitude vibrations tend to mask the discomfort caused by low levels of noise, and the equivalence between noise and vibration may be described by $L_{AE} = 81.0 + 12.7 \log_{10}(a_{VDV})$. When judging the discomfort caused by vibration, higher levels of noise tend to mask the discomfort caused by low magnitudes of vibration, and the equivalence between noise and vibration may be described by $L_{AE} = 84.6 + 31.5 \log_{10}(a_{VDV})$. The judgement of vibration is more influenced by noise than the judgment of noise is influenced by vibration.

It may be necessary to incorporate masking effects in any method of predicting the relative or combined importance of noise and vibration. A ‘range effect’ may cause underestimation of the subjective magnitudes of high physical magnitudes of stimuli, and overestimation of the subjective magnitudes of low physical magnitudes of stimuli, but the ‘range effect’ may be less important than the ‘masking effect’.

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Table I. Magnitude estimates for the discomfort of noise relative to the discomfort of simultaneous vibration, and linear regression analysis showing the sound exposure level, L_{AE1}, equivalent to each reference vibration dose value. Medians of 20 subjects.

		VDV ($ms^{-1.75}$)						
		V_1 0.092	V_2 0.146	V_3 0.231	V_4 0.366	V_5 0.581	V_6 0.920	V_7 1.458
L_{AE} (dBA)	N1 70	115	100	100	85	70	45	35
	N2 73	120	102.5	100	95	77.5	50	50
	N3 76	127.5	120	100	95	92.5	75	60
	N4 79	165	140	120	110	100	85	80
	N5 82	200	180	150	135	110	90	85
	N6 85	250	200	200	175	150	117.5	100
	N7 88	250	250	200	200	185	150	110

a_{VDV} ($ms^{-1.75}$)	Slope ($n_{s1}/20$)	Intercept ($\log_{10}(k_{s1})$) (dB)	Correlation (r_{s1}^2)	L_{AE1} (dBA)
0.092	0.022	0.488	0.974	68.7
0.146	0.023	0.336	0.987	72.4
0.232	0.020	0.541	0.943	73.0
0.366	0.021	0.395	0.970	76.4
0.579	0.023	0.225	0.979	77.2
0.920	0.028	-0.340	0.985	83.6
1.457	0.027	-0.269	0.975	84.0

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

Table II. Magnitude estimates for the discomfort of noise relative to the discomfort of sequential vibration, and linear regression analysis showing the sound exposure level, L_{AE2}, equivalent to each reference vibration dose value. Medians of 20 subjects.

		VDV ($ms^{-1.75}$)						
		V_1 0.092	V_2 0.146	V_3 0.231	V_4 0.366	V_5 0.581	V_6 0.920	V_7 1.458
L_{AE} (dBA)	N1 70	120	100	100	97.5	75	70	50
	N2 73	130	120	100	90	80	75	50
	N3 76	145	147.5	122.5	110	95	80	75
	N4 79	175	140	117.5	132.5	110	97.5	87.5
	N5 82	200	200	160	145	125	110	107.5
	N6 85	200	200	200	180	140	125	112.5
	N7 88	275	250	215	200	200	172.5	120

a_{VDV} ($ms^{-1.75}$)	Slope ($n_{s2}/20$)	Intercept ($\log_{10}(k_{s2})$) (dB)	Correlation (r_{s2}^2)	L_{AE2} (dBA)
0.092	0.019	0.735	0.978	66.6
0.146	0.021	0.535	0.973	69.8
0.232	0.020	0.529	0.961	73.6
0.366	0.020	0.558	0.974	72.1
0.579	0.022	0.278	0.980	78.3
0.920	0.021	0.346	0.974	78.8
1.457	0.024	0.029	0.962	82.1

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

Table III. Magnitude estimates for the discomfort of vibration relative to the discomfort of simultaneous noise, and linear regression analysis showing the vibration dose value, VDV_1, equivalent to each reference noise level. Medians of 20 subjects.

		VDV ($ms^{-1.75}$)						
		V_1 0.092	V_2 0.146	V_3 0.231	V_4 0.366	V_5 0.581	V_6 0.920	V_7 1.458
L_{AE} (dBA)	N1 70	50	75	100	100	120	150	177.5
	N2 73	50	65	100	100	120	140	155
	N3 76	40	60	82.5	90	100	130	150
	N4 79	30	40	50	85	100	120	150
	N5 82	17.5	30	50	72.5	95	100	137.5
	N6 85	17.5	20	27.5	50	65	97.5	120
	N7 88	10	10	22.5	30	55	80	100

L_{AE} (dBA)	Slope (n_{v1}) (1/($ms^{-1.75}$))	Intercept ($\log_{10}(k_{v1})$)	Correlation (r_{v1}^2)	a_{VDV1} ($ms^{-1.75}$)
70	0.417	2.193	0.974	0.344
73	0.397	2.163	0.966	0.388
76	0.443	2.128	0.975	0.514
79	0.599	2.113	0.988	0.647
82	0.717	2.083	0.972	0.766
85	0.761	1.984	0.990	1.050
88	0.928	1.901	0.985	1.279

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

Table IV. Magnitude estimates for the discomfort of vibration relative to the discomfort of sequential noise, and linear regression analysis showing the vibration dose value, VDV_2, equivalent to each reference noise level. Medians of 20 subjects.

		VDV ($ms^{-1.75}$)						
		V_1 0.092	V_2 0.146	V_3 0.231	V_4 0.366	V_5 0.581	V_6 0.920	V_7 1.458
L_{AE} (dBA)	N1	47.5	80	90	100	112.5	150	190
	N2	30	50	80	100	117.5	130	177.5
	N3	30	42.5	70	95	105	120	150
	N4	20	30	65	80	100	120	150
	N5	17.5	30	50	60	90	100	150
	N6	20	20	20	45	75	100	102.5
	N7	10	20	22.5	35	60	85	100
L_{AE} (dBA)	Slope (n_{v2}) (1/$ms^{-1.75}$)		Intercept ($\log_{10}(k_{v2})$)		Correlation (r_{v2}^2)		a_{VDV2} ($ms^{-1.75}$)	
70	0.438		2.197		0.971		0.355	
73	0.592		2.189		0.967		0.480	
76	0.567		2.134		0.969		0.578	
79	0.718		2.134		0.964		0.650	
82	0.733		2.081		0.984		0.774	
85	0.733		1.954		0.948		1.156	
88	0.837		1.923		0.988		1.236	

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

FIGURE CAPTIONS

FIG. 1. The time series and frequency spectrum of the sound (A-weighted) and vibration stimuli (W_b weighted).

FIG. 2. The subjective equivalence between noise and vibration in the different sessions of the study. Medians and inter-quartiles ranges of individual data from 20 subjects.

FIG. 3. Subjective equivalence between noise and vibration in the different sessions of the study. Medians from 20 subjects.

FIG. 4. Comparison of equivalence contours from the present study and previous studies.

FIG. 5. Linear regressions between the logarithm of the subjective magnitudes of noise discomfort and L_{AE1} when judged relative to seven different magnitudes of simultaneous vibration. Medians from 20 subjects.

FIG. 6. Linear regressions between the logarithm of the subjective magnitudes of noise discomfort and L_{AE2} when judged relative to seven different magnitudes of sequential vibration. Medians from 20 subjects.

FIG. 7. Linear regressions between the logarithm of the subjective magnitudes of vibration discomfort and VDV_1 when judged relative to seven different magnitudes of simultaneous noise. Medians from 20 subjects.

FIG. 8. Linear regressions between the logarithm of the subjective magnitudes of vibration discomfort and VDV_2 when judged relative to seven different magnitudes of sequential noise. Medians from 20 subjects.

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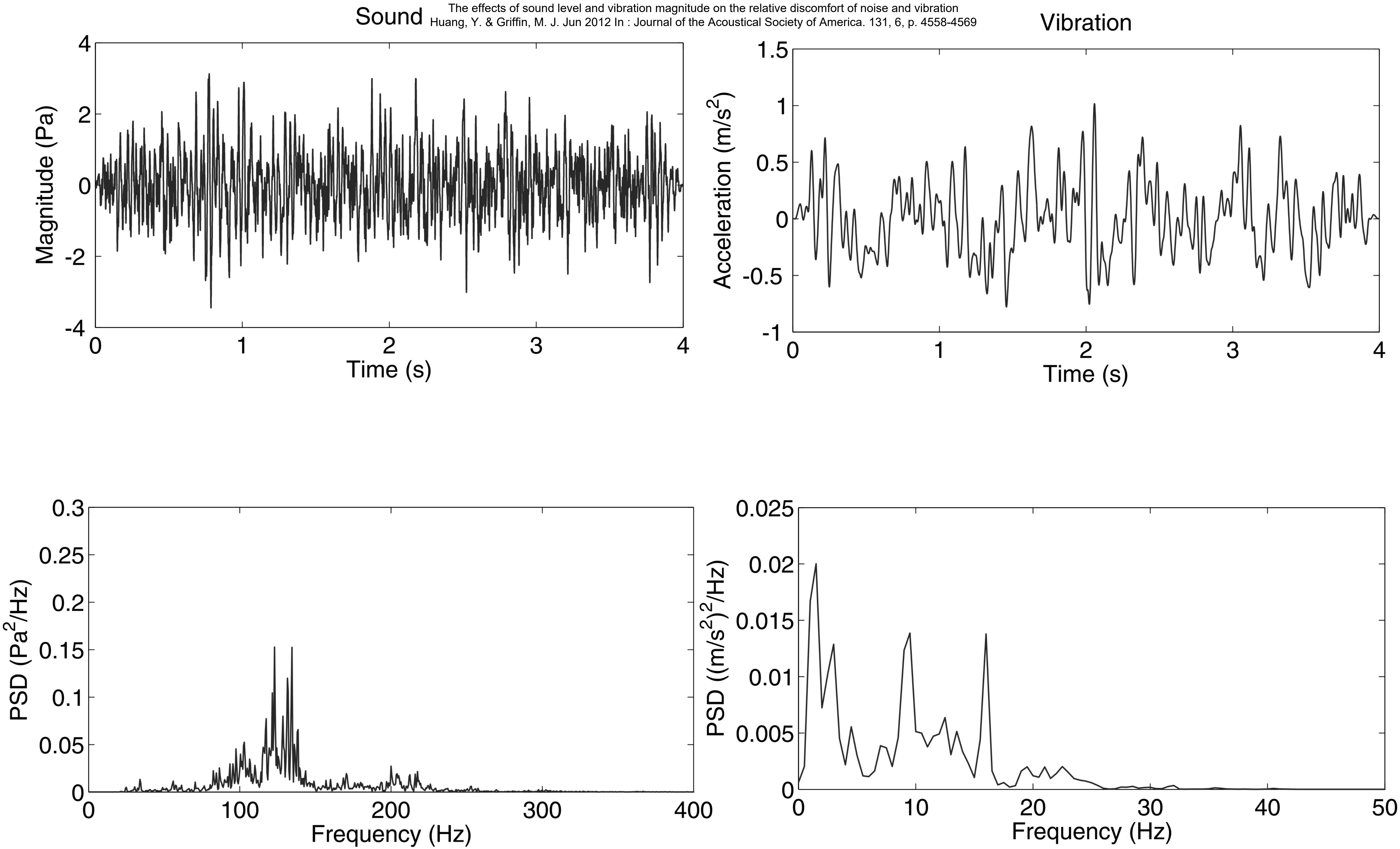

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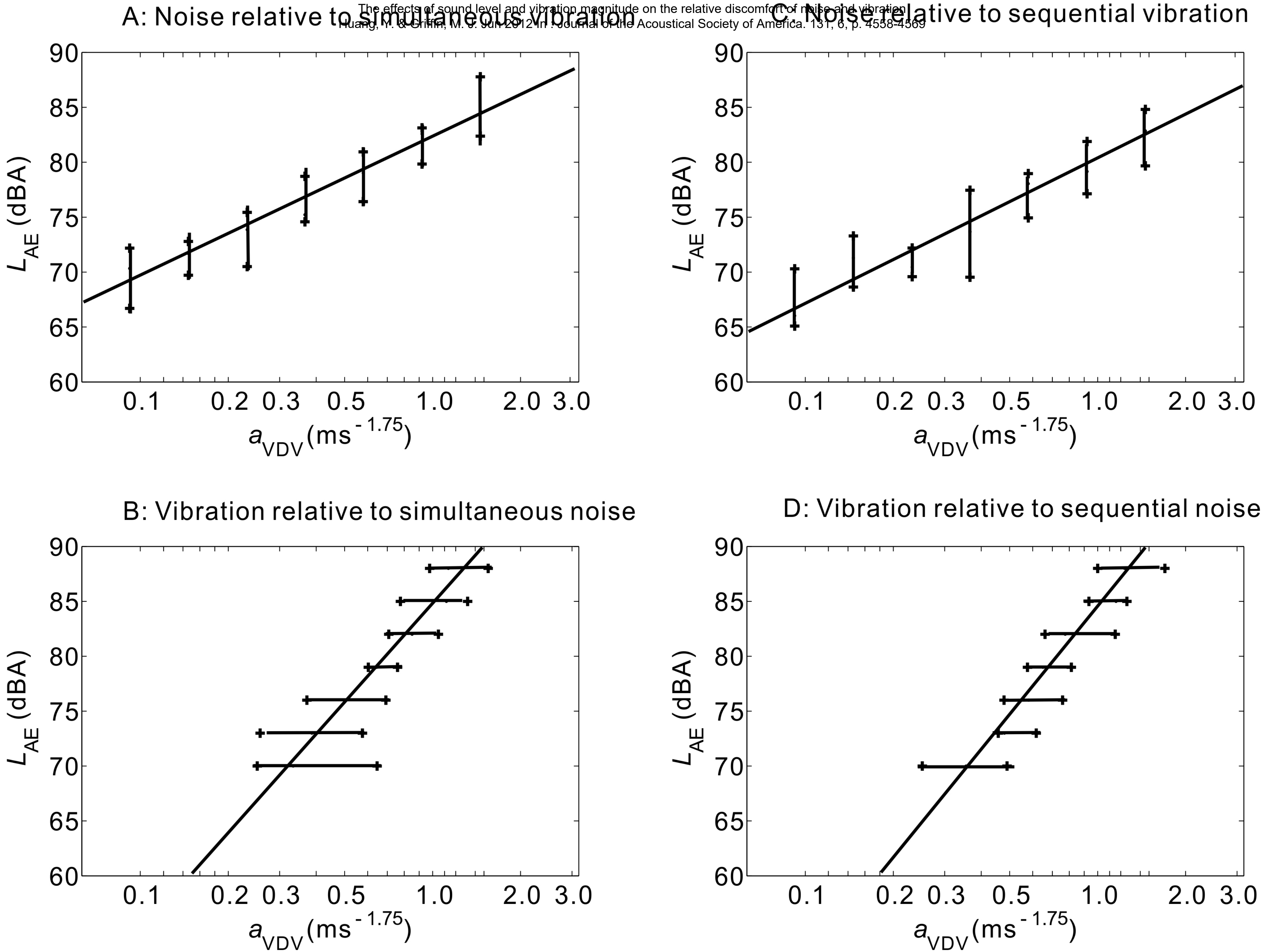

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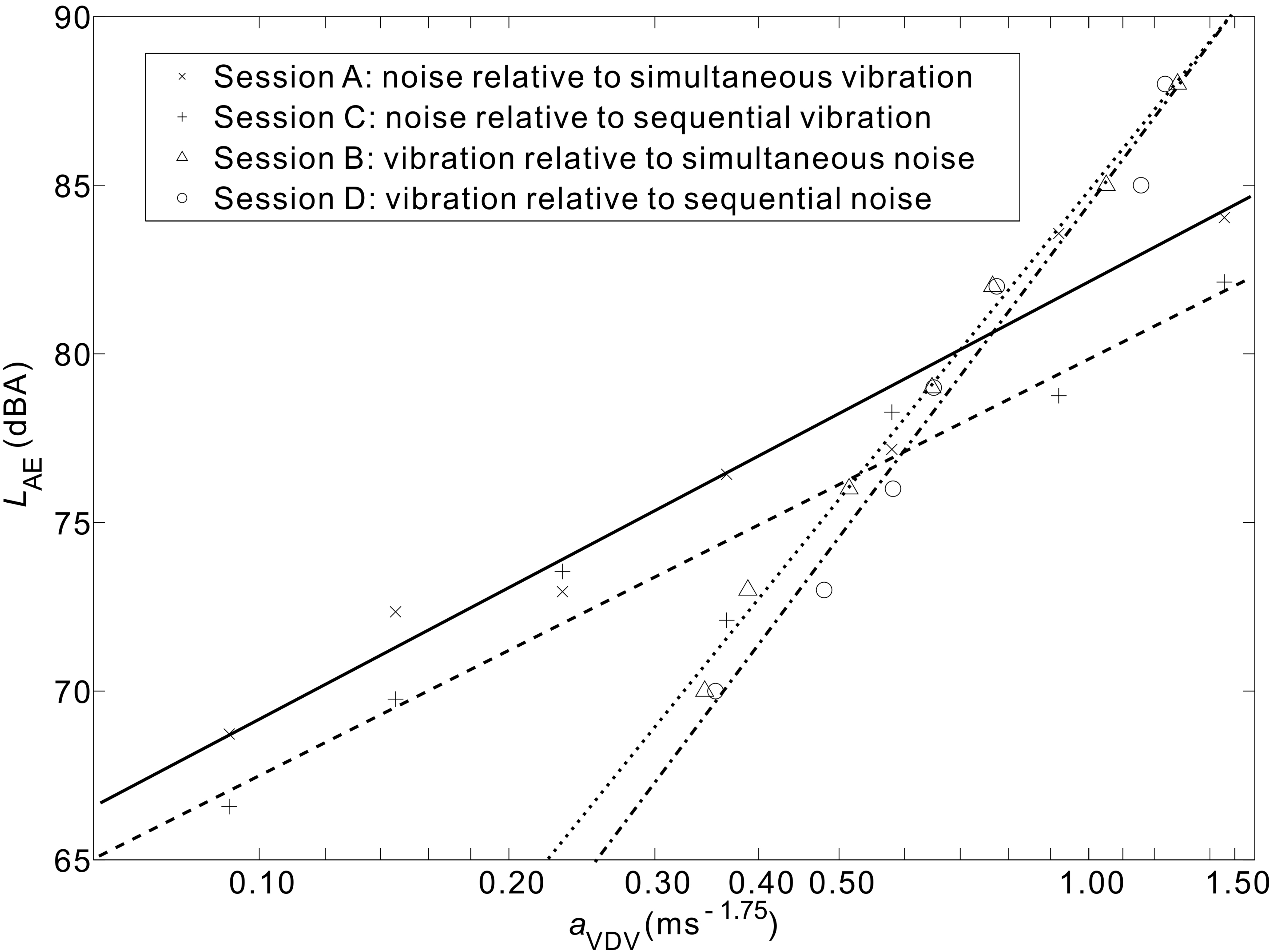

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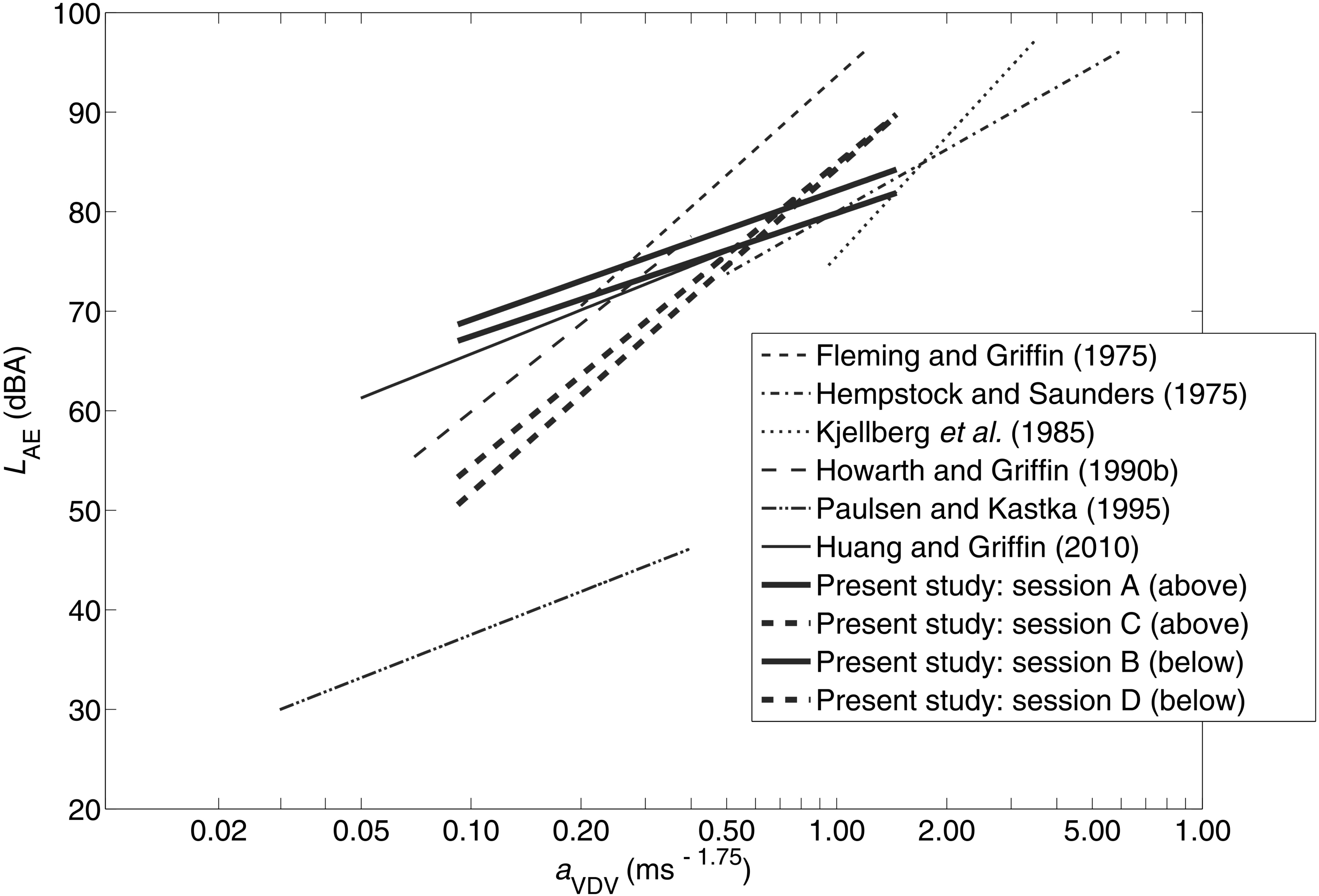

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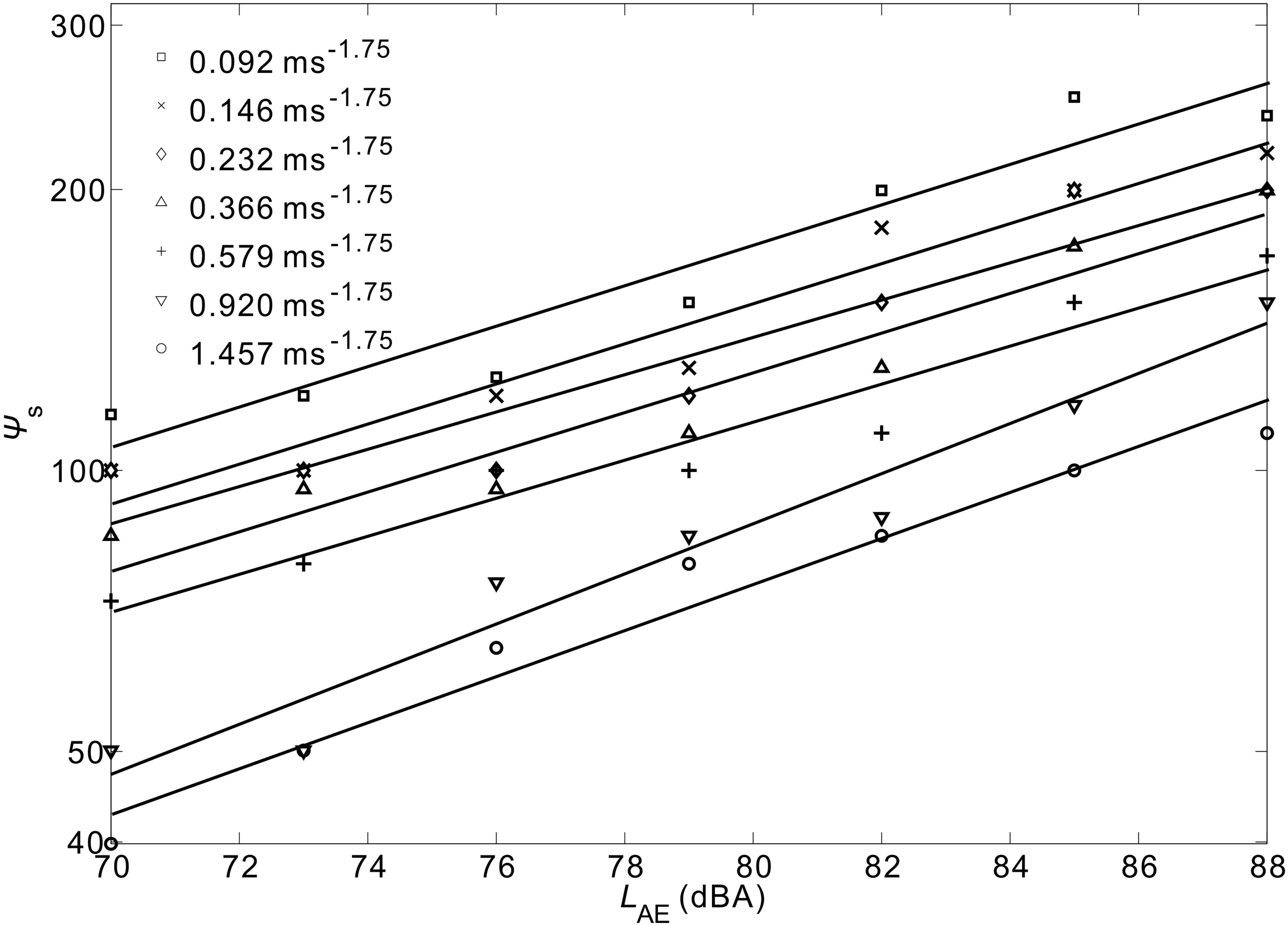

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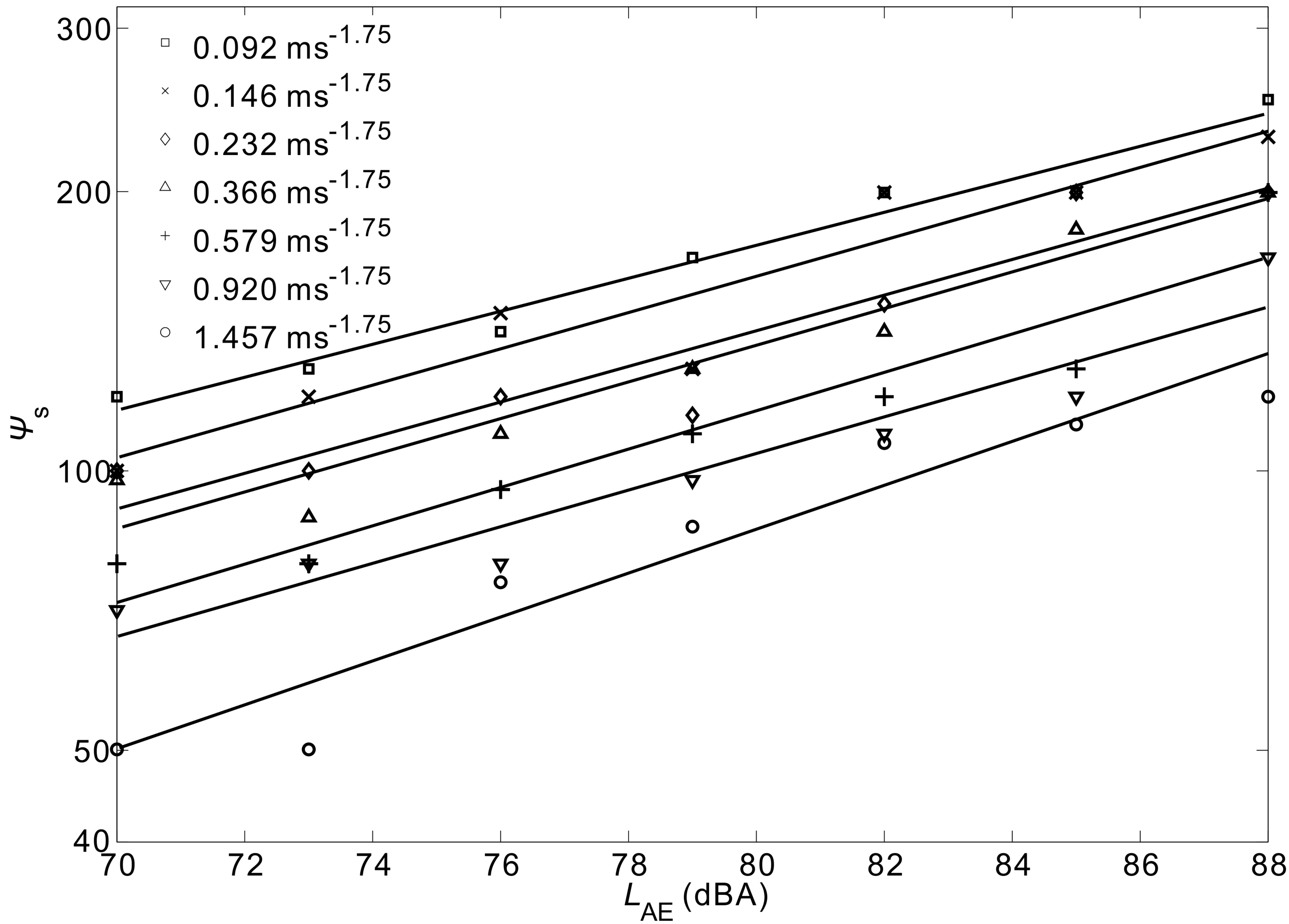

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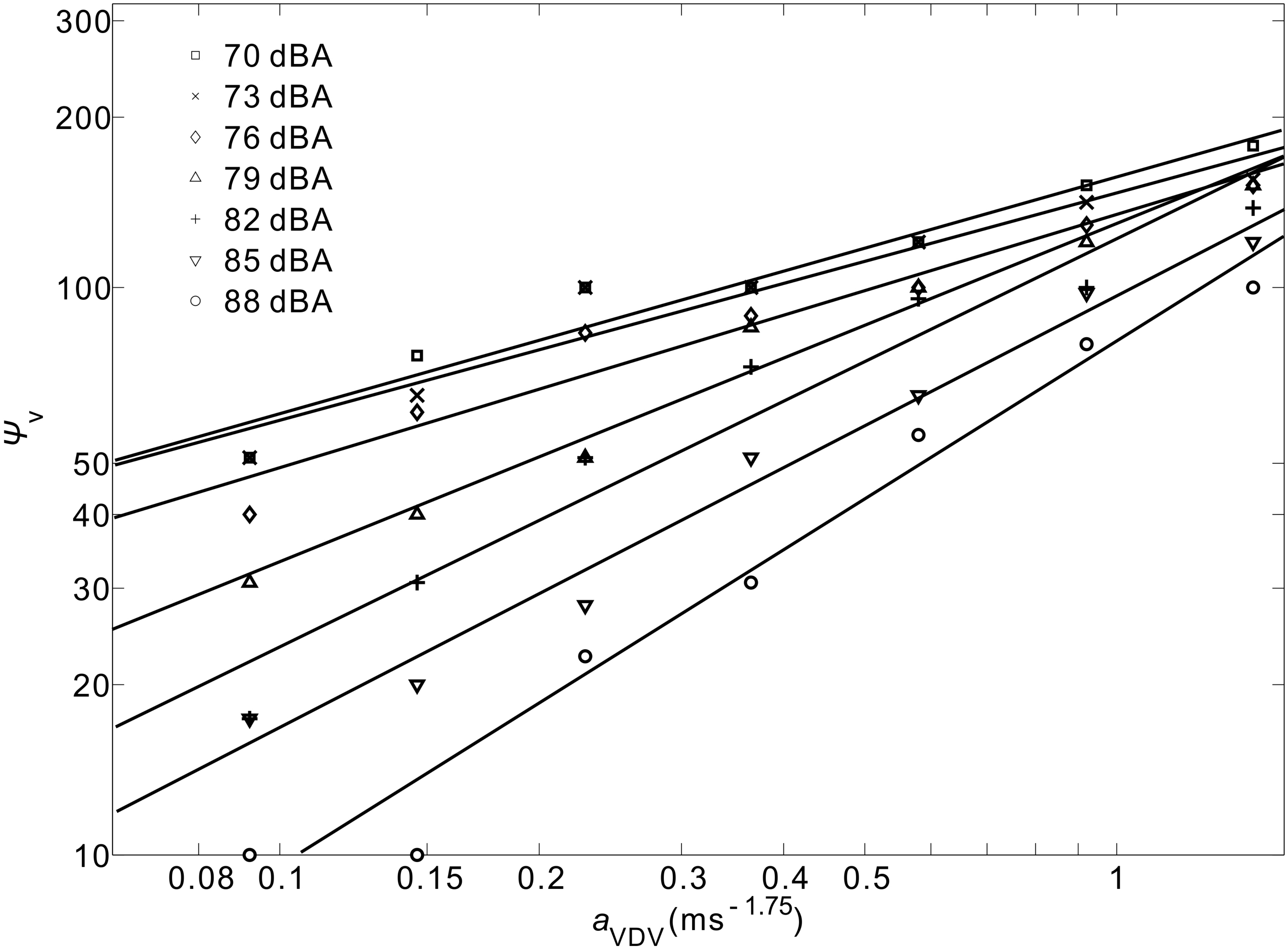

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