Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255

Number of pages: 27

Number of references: 20

Number of figures: 6

Number of tables: 4

The relative discomfort of noise and vibration: effects of stimulus duration

Yu Huang and Michael J. Griffin

Human Factors Research Unit

Institute of Sound and Vibration Research

University of Southampton, SO17 1BJ

United Kingdom

Abstract

How noise discomfort and vibration discomfort depend on duration has not previously been compared. For five durations (2, 4, 8, 16, and 32 s), the subjective equivalence of noise and vibration was investigated with all 49 combinations of seven levels of noise and seven magnitudes of whole-body vertical vibration. The rate of increase in discomfort with increasing duration was similar for noise and vibration, whereas they are currently assumed to be 3 dB per doubling of noise duration and 1.5 dB per doubling of vibration duration. The discomfort caused by low levels of noise was masked by high magnitudes of vibration, and the discomfort caused by low magnitudes of vibration was masked by high levels of noise. As stimuli durations increased from 2 to 32 s, the influence of vibration on the judgement of noise discomfort decreased, whereas the influence of noise on the judgement of vibration discomfort was unchanged.

Practitioner summary: For predicting the relative discomfort caused by steady-state noise and steady-state vibration over durations from 2 to 32 s, the combination of average measures of sound and vibration (e.g., SPL and r.m.s. acceleration) provide more accurate estimates than the combination of the principal standardised ‘dose’ measures (e.g., SEL and VDV).

Keywords: Noise; Vibration; Discomfort; Duration

1. Introduction

Noise and vibration influence the comfort experienced in land vehicles, aircraft, ships, and buildings. Some studies of the 'relative' importance of noise and vibration in causing discomfort have investigated the subjective equivalence of the sound pressure level (SPL) of noise and the root-mean-square (r.m.s.) acceleration of vibration (e.g. Fleming and Griffin 1975, Hempstock and Saunders 1976, Kjellberg *et al.* 1985). The relative importance of noise and vibration in buildings has also been investigated using the sound exposure level, SEL, and the vibration dose value, VDV, so as to account for the influence of the intensity, the duration, and the frequency of the noise and vibration on human sensations (Howarth and Griffin 1990a, 1990b, 1991). The subjective equivalence between the SEL and the VDV for the noise and vibration in cars has been compared with previous studies of the equivalence between the SPL and the r.m.s. acceleration (Huang and Griffin 2010, 2012). The discomfort caused by 'combined' noise and vibration has also been investigated using SPL and r.m.s. acceleration (Seidel *et al.* 1990, 1997) and using SEL and VDV (Howarth and Griffin 1990b, 1991).

The *A*-weighted equivalent continuous sound pressure level, SPL, is given by:

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

where $p_A(t)$ is the instantaneous *A*-weighted sound pressure starting at time t_1 and ending at time t_2, and p_0 is the reference sound pressure, 20 μPa (ISO 1996-1:2003).

The *A*-weighted sound exposure level, SEL, of a discrete noise event is:

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

where t_0 is the reference duration of 1 s.

The r.m.s. acceleration of a vibration event is given by:

$$\text{r.m.s. acceleration}\ (\text{ms}^{-2}) = a_{\text{rms}} = \left(\frac{1}{T}\int_0^T a^2(t)\mathrm{d}t\right)^{\frac{1}{2}} \tag{3}$$

and the vibration dose value, VDV, is:

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

where $a(t)$ is the frequency-weighted acceleration and T is the duration of the measurement period in seconds (BS 6841:1987, ISO 2631-1:1997).

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

$$\psi_s = k_s \varphi_s^{ns}, \tag{5}$$

and

$$\psi_v = k_v \varphi_v^{nv}, \tag{6}$$

where k_s and k_v, are constants and n_s and n_v are the rates of growth of subjective sensations produced by sound and vibration, respectively. In terms of logarithms, the power functions become:

$$\log_{10}(\psi_s) = n_s \log_{10}(\varphi_s) + \log_{10}(k_s), \tag{7}$$

and

$$\log_{10}(\psi_v) = n_v \log_{10}(\varphi_v) + \log_{10}(k_v), \tag{8}$$

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

$$\psi_s = \psi_v. \tag{9}$$

If $L_{Aeq} \propto 20 \log_{10}(\varphi_s)$ (from equation (1) assuming φ_s represents the *A*-weighted sound pressure) and $a_{rms} \propto \varphi_v$, with noise and vibration of fixed duration, it follows from equations (7) to (9) that the subjective equivalence between the stimuli may be adequately described by their r.m.s. levels, L_{Aeq} and a_{rms}, by:

$$L_{Aeq} = k' + 20\frac{n'_v}{n'_s}\log_{10}(a_{rms}), \qquad (10)$$

where *k*' is a constant (dB).

With noises and vibrations of variable duration, it seems more appropriate to express the equivalence between noise and vibration in terms of the SEL, L_{AE}, and the VDV, a_{VDV}, that reflect the expected increases in noise loudness and vibration discomfort associated with increases in the durations of noise and vibration. If $L_{AE} \propto 20 \log_{10}(\varphi_s)$ and $a_{VDV} \propto \varphi_v$, with noise and vibration of variable duration the subjective equivalence between the stimuli may be adequately described by their 'dose' values, L_{AE} and a_{VDV}, by:

$$L_{AE} = k + 20\frac{n_v}{n_s}\log_{10}(a_{VDV}) \qquad (11)$$

where *k* is a constant (dB).

These relationships imply that when presented on a graph of $\log_{10}(a_{rms})$ versus L_{Aeq}, or presented on a graph of $\log_{10}(a_{VDV})$ versus L_{AE}, the subjective equivalence between noise and vibration should have a slope of *s*' (i.e. $20(n'_v/n'_s)$ dB/(ms^{-2})) or *s* (i.e., $20(n_v/n_s)$ dB/(ms$^{-1.75}$)). However, one or both of the slopes will depend on the duration of the stimuli because the time-dependency used to express exposure to noise (in the SEL) differs from the time-dependency used to express exposure to vibration (in the VDV). With stimuli of constant magnitude, the L_{AE} increases by 3 dB (i.e., $\sqrt{2} \approx 41\%$) when the duration of noise doubles, whereas a_{VDV} increases by only 1.5 dB (i.e. $\sqrt{\sqrt{2}} \approx 19\%$) when the duration of vibration doubles. If both the SEL and the VDV have ‘correct’ time-dependencies (or the correct ratio of time-dependencies), the slope, *s*, (i.e., $20(n_v/n_s)$ in equation (11)) will not change with changes in the durations of the stimuli, but the slope, *s’*, in equation (10) will increase with increasing duration of noise and vibration, because with increasing duration, L_{AE} increases more rapidly than a_{VDV}. If the equivalence between noise and vibration is determined solely by average measures of the two stimuli (i.e., L_{Aeq} and a_{rms}), and is therefore independent of the durations of the stimuli, the slope, *s*’, (i.e., $20(n'_v/n'_s)$ in equation (10)) will not change, and the slope, *s*, in equation (11) will increase with increasing duration of noise and vibration, because with increasing duration, L_{AE} increases more rapidly than a_{VDV}.

The subjective equivalence between noise and vibration obtained by Howarth and Griffin (1990a) with 24-s stimuli is given by either $L_{Aeq} = 88.1 + 25.1 \log_{10}(a_{rms})$ or $L_{AE} = 89.2 + 29.3 \log_{10}(a_{VDV})$ (i.e., a slope of 25.1 (dB/ms^{-2}) when using average measures and a slope of 29.3 (dB/ms$^{-1.75}$) when using dose measures). With shorter duration stimuli, such as 10-s stimuli used by Fleming and Griffin (1975) and 4-s stimuli used by Huang and Griffin (2010), similar slopes are obtained when using average measures (i.e., SPL and r.m.s. acceleration) or dose measures (i.e., SEL and VDV). With 1-s stimuli, the same slope is obtained irrespective of whether the average measures or the dose measures are used. The slopes obtained in different studies cannot be used to determine whether the slope *s*’ or the slope *s* increases with the increasing duration because they have been obtained with different experimental conditions (different stimuli with differing physical magnitudes and frequencies, and different psychophysical methods, subjects, etc.).

A previous study has found that the subjective equivalence between noise and vibration appears to depend on whether noise is judged relative to vibration or vibration is judged relative to noise (Huang and Griffin 2012). The dependence of the subjective equivalence of noise and vibration on the durations of the stimuli, as reflected in the slopes *s*' and *s*, may therefore also depend on whether the discomfort produced by noise is judged relative to the discomfort produced by vibration or the discomfort produced by vibration is judged relative to the discomfort produced by noise. When judging noise, higher magnitude vibrations appeared to mask the discomfort caused by low levels of noise and, when judging vibration, higher levels of noise appeared to mask the discomfort caused by low magnitudes of vibration (Huang and Griffin 2012). Since noise and vibration are mostly sensed by different mechanisms in the body, the masking of vibration discomfort by noise and the masking of noise discomfort by vibration might be regarded as 'informational masking' (i.e., masking that cannot be explained by 'energetic masking' in the sensory epithelium; Shinn-Cunningham 2008).

This study was designed to investigate how the subjective equivalence of noise and vibration depends on the durations of the stimuli, and whether this dependence differs between judging noise relative to vibration and judging vibration relative to noise. Assuming r.m.s. measures of noise and vibration indicate the subjective equivalence between noise and vibration over a range of durations, it was hypothesised that if the subjective equivalence between noise and vibration is expressed in terms of the 'dose' of noise and the 'dose' of vibration (i.e., $L_{AE} = k + 20(n_v/n_s)\log_{10}(a_{VDV})$), the slope, s (i.e., $20(n_v/n_s)$ dB/(ms$^{-1.75}$)), will increase as the durations of the stimuli increase.

2. Method

2.1. *Subjects*

Fifteen healthy male subjects with median age 24 years (range 20 to 29 years), stature 174 cm (range 165 to 196 cm), and weight 72 kg (range 52 to 115 kg) volunteered to take part in the experiment. The subjects were all students at 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 steel-framed seat with a vertical flat backrest mounted on the Human Factors Research Unit 1-m vertical vibrator (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*

The sound and vibration stimuli simulated the sound and vibration in a road vehicle. Seven levels of steady-state random sound band-pass filtered between 50 and 500 Hz were generated with L_{Aeq} levels ranging from 64 to 82 dBA in 3 dB steps (ISO 1996-1:2003). Seven magnitudes of steady-state random vibration band-pass filtered between 5 and 10 Hz were generated with 0.05, 0.079, 0.126, 0.199, 0.315, 0.50, and 0.792 ms^{-2} r.m.s. acceleration, using frequency weighting W_b (BS 6841:1987). The exposure durations of the vibration and the sound stimuli used in the experiment were 2, 4, 8, 16, and 32 s, with a 0.2-s cosine taper at the start and end.

The SEL for the five durations of the sound stimulus and the VDV for the five durations of vertical vibration are listed in Tables I and II. The background noise was caused by the hydraulic vibrator, which produced a level of 50 dBA measured at the ear when wearing the headphones. Intermittently, the noise reached 53 dBA when an underground pump operated automatically. The background vibration was not perceptible.

TABLES I and II ABOUT HERE

2.4. *Procedure*

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 of the same durations were presented simultaneously in pairs with one of the two stimuli identified as the reference stimulus.

The experiment was undertaken in two sessions on separate days. On each day there were five parts to the study, corresponding to the five stimulus durations: 2, 4, 8, 16, or 32 s. In each part, subjects provided magnitude estimates of the discomfort caused by each of the seven levels of one of the stimuli (noise or vibration) relative to the discomfort caused by each of the seven levels of the other stimulus (vibration or noise). On one day, subjects rated the discomfort of noise, assuming the discomfort caused by the vibration was 100. On the other day, subjects rated the discomfort of vibration, assuming the discomfort caused by the noise was 100. Subjects experienced the two sessions in a balanced order.

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

3. Results

3.1. *Discomfort of test noises judged relative to reference vibrations*

For each of the five stimulus durations, and each magnitude of the reference vibration, linear regression was performed between the median values of the dependent variable, $\log_{10}(\psi_s)$, and the independent variable, L_{AE}. The slopes, $n_s/20$, the intercepts, $\log_{10}(k_s)$, and the correlation coefficients are shown in Table III. From these linear relationships, the SELs that produced discomfort equivalent to the reference vibration (i.e., a subjective magnitude of 100) were obtained and are shown in the L_{AE} column of Table III. Similarly, the SPLs that produced discomfort equivalent to the reference vibration are shown in the L_{Aeq} column of Table III.

TABLE III ABOUT HERE

Linear regression between the values of L_{AE} and $\log_{10}(a_{VDV})$ in Table III (in accord with equation (11)) provided contours showing the subjective equivalence of simultaneous noise and vibration for each duration (Figure 2). The corresponding contours from linear regression between L_{Aeq} and $\log_{10}(a_{rms})$ are shown in Figure 3 (in accord with equation (10)).

FIGURES 2 and 3 ABOUT HERE

The same procedures were applied to the magnitude estimates provided by each subject. These showed significant increases in the slopes, s (i.e., $20(n_v/n_s)$), and the intercepts, k, in the linear regression between L_{AE} and $\log_{10}(a_{VDV})$ (p<0.01, Friedman), and showed significant increases in the slopes, s' (i.e., $20(n'_v/n'_s)$), and the intercepts, k', in the linear regression between L_{Aeq} and $\log_{10}(a_{rms})$ (p<0.01, Friedman) as the durations of the stimuli increased from 2 to 32 s.

With stimuli having durations of 2 and 4 s, the slopes, $n_s/20$, in the linear relation between $\log_{10}(\psi_s)$ and L_{AE} increased when the magnitude of reference vibration increased (p=0.02 for 2 s, and p=0.07 for 4 s; Friedman). For the longer duration stimuli (i.e., 8, 16 and 32 s), the slopes did not change when the magnitude of the reference vibration increased (p>0.25; Friedman).

3.2. *Discomfort of test vibrations judged relative to reference noises*

For each of the five stimulus durations, and each level of the reference noise, linear regression was performed between all median values of the dependent variable, $\log_{10}(\psi_v)$, and the independent variable, $\log_{10}(a_{VDV})$. The slopes, the intercepts, and the correlation coefficients are shown in Table IV. From these linear relationships, the VDVs that produced discomfort equivalent to the reference noise (i.e., a subjective magnitude of 100) were obtained and are shown in the a_{VDV} column of Table IV.

Similarly, the vibration r.m.s. acceleration that produced discomfort equivalent to the reference sound are shown in the a_{rms} column of Table IV.

TABLE IV ABOUT HERE

Using equations (10) and (11), the equivalence between the discomfort caused by simultaneous noise and vibration was determined for every duration. The equivalence is shown in Figure 4 (from linear regressions between L_{AE} and $\log_{10}(a_{VDV})$) and in Figure 5 (from linear regression between L_{Aeq} and $\log_{10}(a_{rms})$).

FIGURES 4 and 5 ABOUT HERE

The same procedures were applied to the magnitude estimates provided by each subject. As the durations of the stimuli increased from 2 to 32 s, there were no significant differences in the slopes, s (p=0.33, Friedman), but significant increases in the intercepts, k (p<0.01, Friedman) in the regressions between L_{AE} and $\log_{10}(a_{VDV})$. Similarly, as the durations of the stimuli increased there were no significant differences in the slopes, s' (p=0.45, Friedman), but significant increases in the intercepts, k' (p=0.03, Friedman) in the regressions between L_{Aeq} and $\log_{10}(a_{rms})$, as the durations of the stimuli increased from 2 to 32 s.

With stimuli of all durations from 2 to 32 s, the slopes, n_v, in the linear relation between $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$ increased when the level of the reference noise increased (p<0.01, Friedman)

3.3. *Contours of equivalence between sound and vibration*

Contours showing the noise and vibration that produced equivalent discomfort for every duration were obtained when judging noise relative to vibration and when judging vibration relative to noise (Figures 2 to 5).

At each duration, the slopes, s and s', were greater when judging vibration relative to noise than when judging noise relative to vibration (p<0.01 for 2, 4, 8, 16 s, and

p=0.012 for 32 s; Wilcoxon). The intercepts, k, in the regressions between L_{AE} and $\log_{10}(a_{VDV})$ were greater when judging vibration relative to noise than when judging noise relative to vibration at the durations of 2 and 8 s (p<0.01, Wilcoxon) but did not differ at the other durations (p=0.08 for 4 s, p=0.28 for 16 s, and p=0.43 for 32 s). The intercepts, k', in the regressions between L_{Aeq} and $\log_{10}(a_{rms})$ were greater when judging vibration relative to noise than when judging noise relative to vibration at the durations of 2, 4, 8 and 16 s (p<0.01, Wilcoxon) but were less at the duration of 32 s (p<0.01, Wilcoxon).

4. Discussion

4.1. *Equivalence when judging noise relative to vibration or vibration relative to noise*

With all five durations (i.e., 2, 4, 8, 16, and 32 s), when judging noise relative to vibration the five slopes of the equivalent comfort contours (12.5, 13.6, 15.4, 13.3, and 17.4 dB/(ms$^{-1.75}$)) were significantly less than when judging vibration relative to noise (22.0, 21.1, 24.7, 26.1, and 23.5 dB/(ms$^{-1.75}$)). However, both sets are considered consistent with the findings of previous studies. When judging noise relative to vibration, Huang and Griffin (2010, 2012) and the present study have found values in the range of 12.4 to 17.4 dB/(ms$^{-1.75}$), and when asking subjects to indicate the subjective intensity of noise on a 9-point-scale, Paulsen and Kastka (1995) found a value of 13.7 dB/(ms$^{-1.75}$) (with tram noise) and 14.4 dB/(ms$^{-1.75}$) (with hammermill noise). When adjusting the level of noise to match vibration, Hempstock and Saunders (1976) found slopes in the range 16.2 to 29.1 dB/(ms$^{-1.75}$). In these studies, the discomfort caused by noise was the principal dependent variable (i.e., noise was judged relative to a reference vibration).

When judging vibration relative to noise, Huang and Griffin (2012) found slopes of 30.4 or 32.6 dB/(ms$^{-1.75}$) and when adjusting vibration to match noise Hempstock and Saunders (1976) found slopes from 37.0 to 47.6 dB/(ms$^{-1.75}$), both broadly consistent with the present study. In these studies, the discomfort caused by the vibration was the principal dependent variable.

When asking subjects to state the noise or the vibration they would prefer to reduce, Fleming and Griffin (1975) and Howarth and Griffin (1990a) obtained similar slopes of 33 and 29.3 dB/(ms$^{-1.75}$), respectively. Their slopes are similar to those obtained when judging vibration relative to noise in a previous study (Huang and Griffin 2012), implying their subjects may have focused more on the vibration than on the noise, possibly because the vibration was less familiar to subjects and so demanded their attention.

As suggested by Huang and Griffin (2012), if asked to evaluate noise, subjects may focus on the modality 'noise', whereas if 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'.

4.2. *Influence of duration on the exponents for noise and vibration*

When judging noise relative to vibration, for short durations of 2 and 4 s, the exponent n_s in equation (5) (i.e., the slope $n_s/20$ in the relation between $\log_{10}(\psi_s)$ and L_{AE}) increased as the magnitude of the simultaneous reference vibration increased. The discomfort produced by low levels of noise may be considered to have been underestimated due to 'masking' from the discomfort produced by high magnitudes of vibration. This is consistent with a previous study in which the exponent n_s increased when judging the discomfort of noise relative to 4-s reference vibrations of increasing magnitude (Huang and Griffin 2012). When the duration was

Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255

increased to 8 s or longer in the present experiment, the exponent n_s did not vary with the magnitude of the simultaneous vibration, possibly because the influence of vibration decreased as the durations of both stimuli increased.

When judging vibration relative to noise, for all durations from 2 to 32 s, the exponent n_v in equation (6) (i.e., the slopes, n_v, in the linear relation between $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$) increased when the levels of the simultaneous reference noise increased. This is also consistent with Huang and Griffin (2012), who found the exponent n_v increased as the level of a reference noise increased when judging vibration discomfort relative to noise discomfort with 4-s stimuli, and concluded that the discomfort produced by low magnitudes of vibration were underestimated due to ‘masking’ by high levels of noise. It seems that this influence of noise on judgements of vibration discomfort is independent of stimulus duration (up to 32 s).

4.3. *Influence of duration on the relative importance of noise and vibration*

From Figures 2 and ~~3~~ 4 it may be concluded that the combination of SEL and VDV does not provide a good basis for expressing the relative discomfort caused by noise and whole-body vibration over durations from 2 to 32 s. In contrast, Figures ~~4~~ 3 and 5 suggest the SPL and the r.m.s. acceleration may provide a useful indication of the equivalence between the stimuli, at least from 2 to 32 s. Over this range of durations, with VDV varying from 0.073 to 2.396 $ms^{-1.75}$ (Table I), using SEL and VDV the range of median SEL varied from 4.2 to 11.3 dB when judging noise relative to vibration (Table ~~IV~~III) or, with SEL varying from 67 to 97 dBA (Table II), using SEL and VDV the range of median VDV varied from 1.7:1 to 2.1:1 when judging vibration relative to noise (Table ~~V~~IV). The ranges are far less when using the SPL and r.m.s. acceleration, with the range of median SPL from 3.0 to 3.0 dB when judging noise relative to vibration (over the range of 0.050 to 0.792 ms^{-2} r.m.s.) and the range of median r.m.s. acceleration from 1.2:1 to 1.3:1 when judging vibration relative to noise (over the range of 64 to 82 dBA SPL).

This study does not indicate that both SEL and VDV have incorrect time-dependencies, but it does indicate that, at least, either SEL has an inappropriate time-dependency in respect of the discomfort caused by noise or VDV has an inappropriate time-dependency in respect of the discomfort caused by vibration. The similarity in the equivalence between SPL and r.m.s. acceleration over the range 2 to 32 s suggests the time-dependency for noise and vibration should be similar, yet SEL increases by 3 dB when the duration of noise doubles and VDV increases by only 1.5 dB when the duration of vibration doubles. Studies of the duration-dependence of vibration discomfort have found slopes around, or slightly greater than, 1.5 dB per doubling of vibration duration (Griffin 1990). Studies with noise have used loudness or annoyance rather than 'discomfort' as the dependent variable. Loudness increases by about 10 phon (in loudness level) for each 10-fold increase in duration up to about 0.1 s, and is almost independent of duration in the range 0.1 to 1.0 s (e.g. Zwicker and Fastl 1999). Studies have found wide variations in the slope of the duration-dependence of noise annoyance. For example, slopes from 0.6 to 3.1 dB with a median slope of 2.0 dB per doubling of duration from 1 to 34 s (Little and Mabry 1968), and 3.4 dB per doubling of duration from 0.03 to 90 s (Hiramatsu *et al*. 1978). The convenient slope of 3 dB per doubling of duration, as embodied in the standardized measurement of SEL (e.g. ISO 1996-1:2003) may overestimate the effect of duration on the discomfort caused by noise.

4.4. *Time-dependence of the slope in the equivalent comfort contour between noise and vibration*

The study does not reveal how the exponents (n_s and n_v) depend on the durations of the stimuli (noise and vibration) but it shows how their ratio (i.e., n_v/n_s) varies with stimulus duration. The slope, s' (i.e., $20(n'_v/n'_s)$ in equation (10)), is similar to the slope, s (i.e., $20(n_v/n_s)$ in equation (11)), over durations from 2 to 32 s. The slope, s (or s') in the regressions between L_{AE} and $\log_{10}(a_{vdv})$ (or between L_{Aeq} and $\log_{10}(a_{rms})$) depended on the stimulus duration when noise was judged relative to vibration but not when judging vibration relative to noise. The slope, s, is plotted as a function of duration in Figure 6.

FIGURE 6 ABOUT HERE

When judging noise relative to vibration, in accord with Stevens' power law (Stevens 1986), an exponential relationship is assumed between the slope, s (i.e., $20(n_v/n_s)$) and the duration, t:

$$s = s_0 (t / t_0)^{n_t} \tag{12}$$

where s_0 is a constant in dB/(ms$^{-1.75}$), t_0 = 1 s, and n_t is the exponent. From Table IV and Figure 6, the dependence of s on the duration t is obtained by linear regression in logarithmic form as:

$$\log_{10}(s) = 1.07 + 0.092 \log_{10}(t/t_0) \tag{13}$$

with a correlation coefficient of 0.70 (p<0.01, Spearman). So:

$$s = 11.75 \, (t/t_0)^{0.092}. \tag{14}$$

When judging vibration relative to noise, the slope, s, did not change significantly with the durations of the stimuli when their magnitudes were expressed in terms of L_{AE} and a_{VDV}, and the median value of 23.5 dB/(ms$^{-1.75}$) for the slopes seems to be appropriate.

The increases in the slopes s (i.e., $20(n_V/n_S)$) and s' (i.e., $20(n'_V/n'_S)$) with increasing duration when noise was judged relative to vibration but not when vibration was judged relative to noise might be explained by judgements of noise relative to vibration being affected by the simultaneous vibration, with the influence of vibration (similar to 'masking') decreasing as the duration increased. The judgement of vibration may have been affected by the simultaneous noise but with the influence of the noise (i.e., 'masking') independent of the duration, so the slope did not change.

The effects observed in this study may depend on the characteristics of the noise and the vibration stimuli, especially their 'meaning' to the person making judgements. The effect of one stimulus on the judgement of the other stimulus may not be a physiological phenomenon but 'information masking' (Shinn-Cunningham 2008). Further systematic study is needed to understand 'masking effects' over long time periods and with stimuli having different characteristics.

It might be expected that with long duration stimuli the slope would be the same when judging noise relative to vibration and when judging vibration relative to noise. From equation (14), when judging noise relative to vibration, the slope s will become 23.5 dB/(ms$^{-1.75}$), the median value when judging vibration relative to noise, at about 33 minutes. Possibly, after long exposures to simultaneous noise and vibration, if a noise is considered to cause similar discomfort to a vibration, the vibration may be considered to cause similar discomfort to the noise.

5. Conclusions

For predicting the relative discomfort of steady-state noise and steady-state vibration over durations from 2 to 32 s, the combination of 'dose' measures of sound and vibration (i.e., SEL and VDV) provide less accurate estimates than the combination of the principal standardised 'average' measures (i.e., SPL and r.m.s.

acceleration). The findings suggest the rate of increase in discomfort with increasing duration should be similar for noise and vibration, whereas they are currently assumed to be 3 dB per doubling of noise duration and 1.5 dB per doubling of vibration duration. This conclusion should be applicable to the noise and vibration in transport and in other living and working environments.

The discomfort caused by low levels of noise may be masked by high magnitudes of vibration, and the discomfort caused by low magnitudes of vibration may be masked by high levels of noise. As the durations of the stimuli increase from 2 to 32 s, the influence of vibration on the judgement of noise discomfort decreased, whereas the influence of noise on the judgement of vibration discomfort did not change.

The slopes in dB/(ms^{-2}) or dB/($ms^{-1.75}$) expressing the levels of noise judged equivalent to various magnitudes of vibration are less when judging noise discomfort relative to vibration discomfort than when judging vibration discomfort relative to noise discomfort. Over durations from 2 to 32 s, the slopes increased with increasing duration when judging noise relative to vibration, but were independent of duration when judging vibration relative to noise.

References

British Standards Institution, 1987. BS 6841 1987. *Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Repeated Shock.* London: British Standards Institution.

British Standards Institution, 2004. BS EN ISO 11904-2 2004. *Acoustics-Determination of Sound Emission from Sound Sources Placed Close to the Ear-Part 2: Technique Using a Manikin.* London: British Standards Institution.

Fleming, D.B., and Griffin, M.J., 1975. "A study of the subjective equivalence of noise and whole-body vibration." *Journal of Sound and Vibration*, 42 (4), 453-561.

Griffin, M.J., 1990. *Handbook of Human Vibration.* London: Academic Press. Chaps. 3 and 10.

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

Hiramatsu, K., Takagi, K., and Yamamoto T., 1978. "The effect of sound duration on annoyance." *Journal of Sound and Vibration*, 59 (4), 511-520.

Howarth, H.V.C., and Griffin, M.J., 1990a. "The relative importance of noise and vibration from railways." *Applied Ergonomics*, 21 (2), 129-134.

Howarth, H.V.C., and Griffin, M.J., 1990b. "Subjective response to combined noise and vibration: summation and interaction effects." *Journal of Sound and Vibration*, 143 (3), 443-454.

Howarth, H.V.C., and Griffin, M.J., 1991. "The annoyance caused by simultaneous noise and vibration." *Journal of the Acoustical Society of America*, 89 (5), 2317-2323.

Huang, Y., and Griffin, M.J., 2010. "The relative importance of noise and vibration to the sensation of comfort in vehicles." *45th UK Conference on Human Response to Vibration*, Institute of Naval Medicine, Gosport, UK.

Huang, Y., and Griffin, M.J., 2012. "The effects of sound level and vibration magnitude on the relative discomfort of noise and vibration." *Journal of the Acoustical Society of America*,131 (6), 4558-4569.

International Organization for Standardization, 1997. ISO 2631-1 1997. *Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration-Part 1:General Requirements.* Geneva: International Organization for Standardization.

International Organization for Standardization, 2003. ISO 1996-1 2003. *Acoustics-Description, Measurement and Assessment of Environmental Noise-Part 1: Basic Quantities and Assessment Procedures.* Geneva: International Organization for Standardization.

Kjellberg, A., Wikström, B.O., and Dimberg, U., 1985. "Whole-body vibration: exposure time and acute effects-experimental assessment of discomfort." *Ergonomics*, 28 (3), 545-554.

Little, J.W., and Mabry, J.E., 1968. "Sound duration and its effect on judged annoyance." *Journal of Sound and Vibration*, 9 (2), 247-262.

Paulsen, R., and Kastka, J., 1995. "Effects of combined noise and vibration on annoyance." *Journal of Sound and Vibration*, 181 (2), 295-314.

Seidel, H., Erdmann, U., Blüthner, R., Hinz, B., Bräuer, D., Arias, J. F., and Rothe, H.J., 1990. "Evaluation of simultaneous exposures to noise and whole body vibration by magnitude estimation and cross-modality matching – an experimental study with professional drivers." *Archives of Complex Environmental Studies*, 2 (3), 17-24.

Seidel, H., Schust, M., Seidel, H., Blüthner, R., and Rothe, H.J., 1997. "Subjective evaluation of the effects of noise with a different tonality combined with random low-frequency whole-body vibration." *32th UK Conference on Human Response to Vibration*, University of Southampton, Southampton, UK.

Shinn-Cunningham, B.G., 2008. "Objective-based auditory and visual attention," *Trends in Cognitive Science*, 12 (5), 182-186.

Stevens, S.S., 1986. *Psychophysics: Introduction to its perceptual, neural, and social prospects.* New Brunswick: Transaction Books. Chap. 1.

Zwicker, E., and Fastl, H., 1999. *Psychoacoustics: Facts and Models*. (Berlin: Springer – Verlag. Chap. 8, pp. 216-218.

Table I The VDVs ($ms^{-1.75}$) of the vibration stimuli of different magnitudes and durations.

Duration (s)	a_{rms} (ms^{-2})						
	0.050	0.079	0.126	0.199	0.315	0.500	0.792
2	0.073	0.122	0.193	0.305	0.482	0.762	1.203
4	0.092	0.145	0.230	0.363	0.573	0.906	1.431
8	0.109	0.172	0.271	0.429	0.677	1.070	1.691
16	0.129	0.204	0.322	0.509	0.805	1.271	2.009
32	0.154	0.243	0.384	0.607	0.960	1.516	2.396

Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255

Table II The SELs (dBA) of the sound stimuli of different levels and durations.

Duration (s)	L_{Aeq} (dBA)						
	64	67	70	73	76	79	82
2	67	70	73	76	79	82	85
4	70	73	76	79	82	85	88
8	73	76	79	82	85	88	91
16	76	79	82	85	88	91	94
32	79	82	85	88	91	94	97

Table III Discomfort of noise judged relative to the discomfort of simultaneous vibration. Linear regression analysis showing the SEL, L_{AE}, equivalent to each reference VDV, a_{VDV}, for each stimulus duration.

Duration (s)	Slope (n_s/20)	Intercept ($\log_{10}(k_s)$) (dB)	Correlation (r_s^2)	a_{VDV} ($ms^{-1.75}$)	L_{AE} (dBA)	L_{Aeq} (dBA)
2	0.019	0.735	0.940**	0.073	66.58	63.63
	0.020	0.650	0.937**	0.122	67.50	64.60
	0.016	0.838	0.941**	0.193	72.63	69.56
	0.018	0.691	0.877**	0.305	72.72	69.67
	0.017	0.711	0.795**	0.482	75.82	72.76
	0.014	0.913	0.834**	0.762	77.64	74.64
	0.031	-0.551	0.952**	1.203	82.29	79.26
4	0.020	0.572	0.949**	0.092	71.40	65.40
	0.017	0.776	0.945**	0.145	72.00	66.06
	0.016	0.809	0.956**	0.230	74.44	68.38
	0.017	0.752	0.876**	0.363	73.41	67.53
	0.017	0.663	0.943**	0.573	78.65	72.65
	0.019	0.443	0.864**	0.906	81.95	75.95
	0.021	0.138	0.951**	1.431	88.67	82.57
8	0.019	0.600	0.961**	0.109	73.68	64.68
	0.018	0.680	0.905**	0.172	73.33	64.56
	0.016	0.821	0.891**	0.271	73.69	64.94
	0.016	0.714	0.971**	0.429	80.38	71.19
	0.014	0.811	0.902**	0.677	84.93	75.64
	0.017	0.513	0.893**	1.070	87.47	78.41
	0.024	-0.138	0.872**	1.691	89.08	80.04
16	0.015	0.878	0.983**	0.129	74.80	62.67
	0.018	0.637	0.932**	0.204	75.72	63.94
	0.019	0.438	0.956**	0.322	82.21	70.00
	0.017	0.621	0.920**	0.509	81.12	69.06
	0.021	0.225	0.847**	0.805	84.52	72.52
	0.020	0.292	0.951**	1.271	85.40	73.70
	0.026	-0.399	0.972**	2.009	92.27	80.12
32	0.014	0.954	0.941**	0.154	74.71	59.64
	0.014	0.887	0.896**	0.243	79.50	64.07
	0.016	0.699	0.906**	0.384	81.31	66.44
	0.017	0.519	0.916**	0.607	87.12	71.82
	0.017	0.489	0.915**	0.960	88.88	73.76
	0.019	0.233	0.969**	1.516	93.00	78.00
	0.029	-0.769	0.989**	2.396	95.48	80.59

** $p < 0.01$

Table IV Discomfort of vibration judged relative to the discomfort of simultaneous noise. Linear regression analysis showing the VDV, a_{VDV}, equivalent to each reference SEL, L_{AE}, for each stimulus duration.

Duration (s)	Slope (n_v) (1/(ms$^{-1.75}$))	Intercept ($\log_{10}(k_v)$)	Correlation (r_v^2)	a_{VDV} (ms$^{-1.75}$)	L_{AE} (dBA)	L_{Aeq} (dBA)
2	0.187	2.153	0.932**	67.0	0.152	0.101
	0.265	2.142	0.883**	70.0	0.291	0.192
	0.282	2.139	0.902**	73.0	0.321	0.211
	0.378	2.138	0.986**	76.0	0.432	0.284
	0.516	2.096	0.974**	79.0	0.652	0.427
	0.505	2.063	0.908**	82.0	0.750	0.490
	0.613	1.973	0.983**	85.0	1.107	0.721
4	0.190	2.145	0.932**	70.0	0.173	0.094
	0.236	2.131	0.941**	73.0	0.279	0.152
	0.306	2.130	0.974**	76.0	0.376	0.207
	0.381	2.106	0.872**	79.0	0.527	0.291
	0.477	2.084	0.882**	82.0	0.667	0.367
	0.554	2.031	0.958**	85.0	0.879	0.485
	0.550	1.926	0.958**	88.0	1.365	0.755
8	0.268	2.169	0.948**	73.0	0.234	0.108
	0.302	2.152	0.960**	76.0	0.314	0.146
	0.345	2.114	0.904**	79.0	0.468	0.217
	0.393	2.103	0.853**	82.0	0.547	0.254
	0.382	2.054	0.946**	85.0	0.723	0.337
	0.514	2.001	0.972**	88.0	0.995	0.465
	0.643	1.937	0.957**	91.0	1.253	0.586
16	0.225	2.109	0.981**	76.0	0.328	0.128
	0.291	2.122	0.960**	79.0	0.381	0.149
	0.364	2.095	0.930**	82.0	0.548	0.215
	0.381	2.073	0.943**	85.0	0.643	0.252
	0.408	2.036	0.924**	88.0	0.817	0.321
	0.514	1.959	0.982**	91.0	1.202	0.473
	0.603	1.888	0.976**	94.0	1.535	0.603
32	0.252	2.134	0.960**	79.0	0.294	0.095
	0.304	2.112	0.968**	82.0	0.429	0.140
	0.385	2.063	0.961**	85.0	0.685	0.224
	0.505	2.035	0.860**	88.0	0.853	0.279
	0.528	1.999	0.934**	91.0	1.005	0.330
	0.609	1.938	0.972**	94.0	1.265	0.417
	0.649	1.829	0.921**	97.0	1.832	0.605

** $p < 0.01$

FIGURE CAPTIONS

Figure 1 Subject on the test rig.

Figure 2 The subjective equivalence between noise (L_{AE}) and vibration (a_{VDV}) with stimuli durations from 2 to 32 s when judging noise relative to vibration. Medians and inter-quartile ranges of 15 subjects.

Figure 3 The subjective equivalence between noise (L_{Aeq}) and vibration (a_{rms}) with stimuli durations from 2 to 32 s when judging noise relative to vibration. Medians and inter-quartile ranges of 15 subjects.

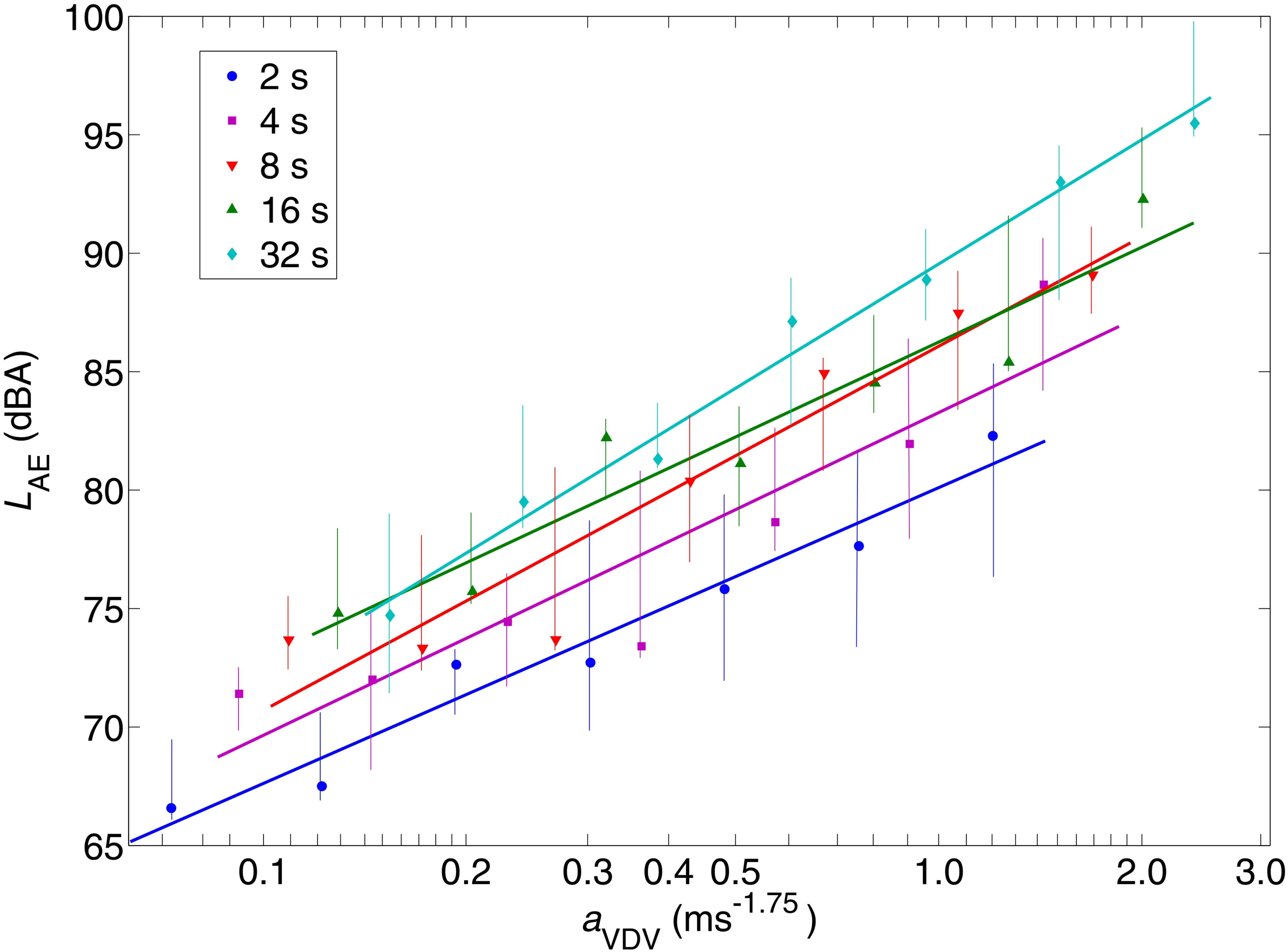
Figure 4 The subjective equivalence between noise (L_{AE}) and vibration (a_{VDV}) with stimuli durations from 2 to 32 s when judging vibration relative to noise. Medians and inter-quartile ranges of 15 subjects.

Figure 5 The subjective equivalence between noise (L_{Aeq}) and vibration (a_{rms}) with stimuli durations from 2 to 32 s when judging vibration relative to noise. Medians and inter-quartile ranges of 15 subjects.

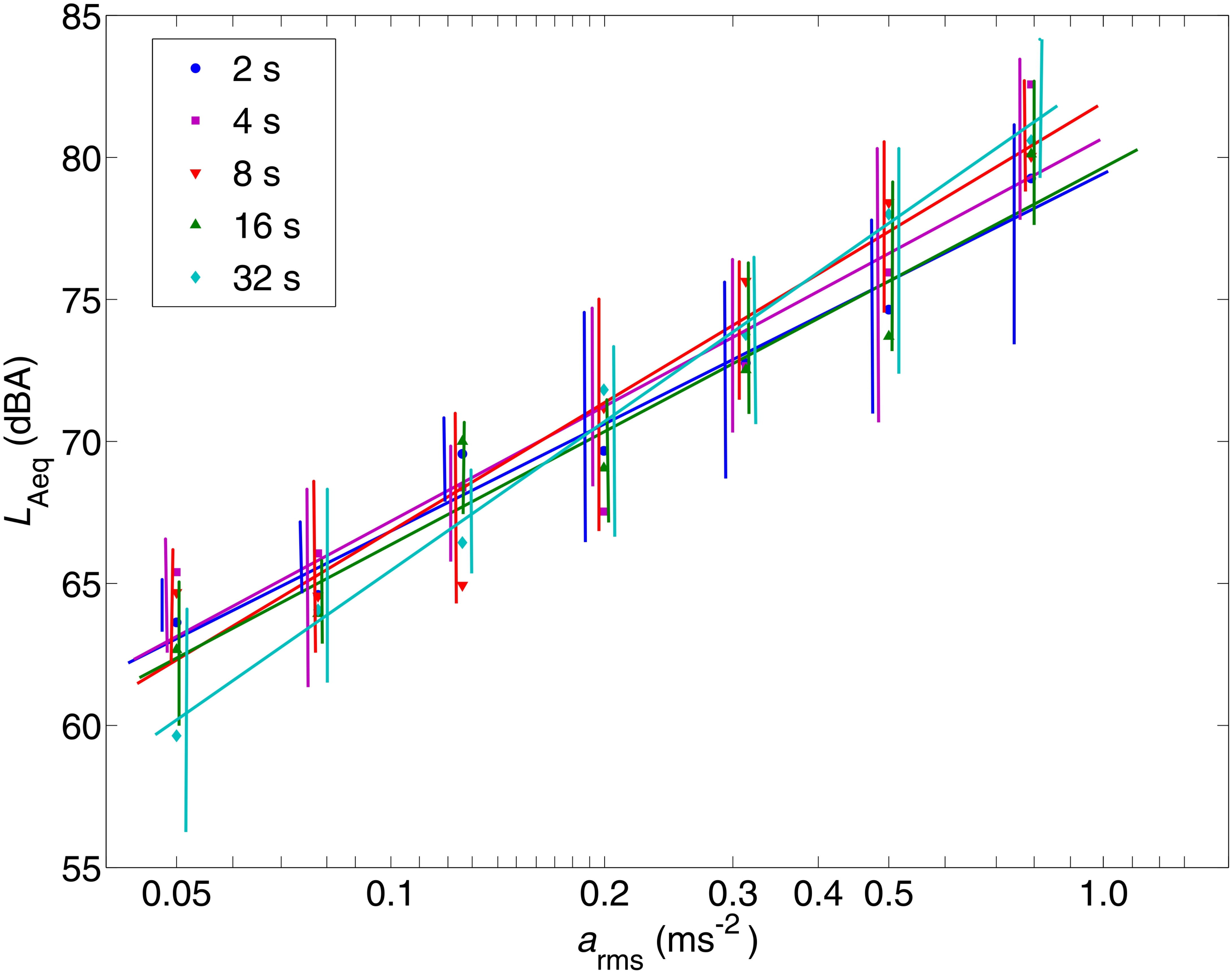
Figure 6 The slopes of subjective equivalence between noise and vibration for durations from 2 to 32 s. Medians of individual and inter-quartile ranges from 15 subjects. ■ judging noise relative to vibration, ● judging vibration relative to noise.

Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255

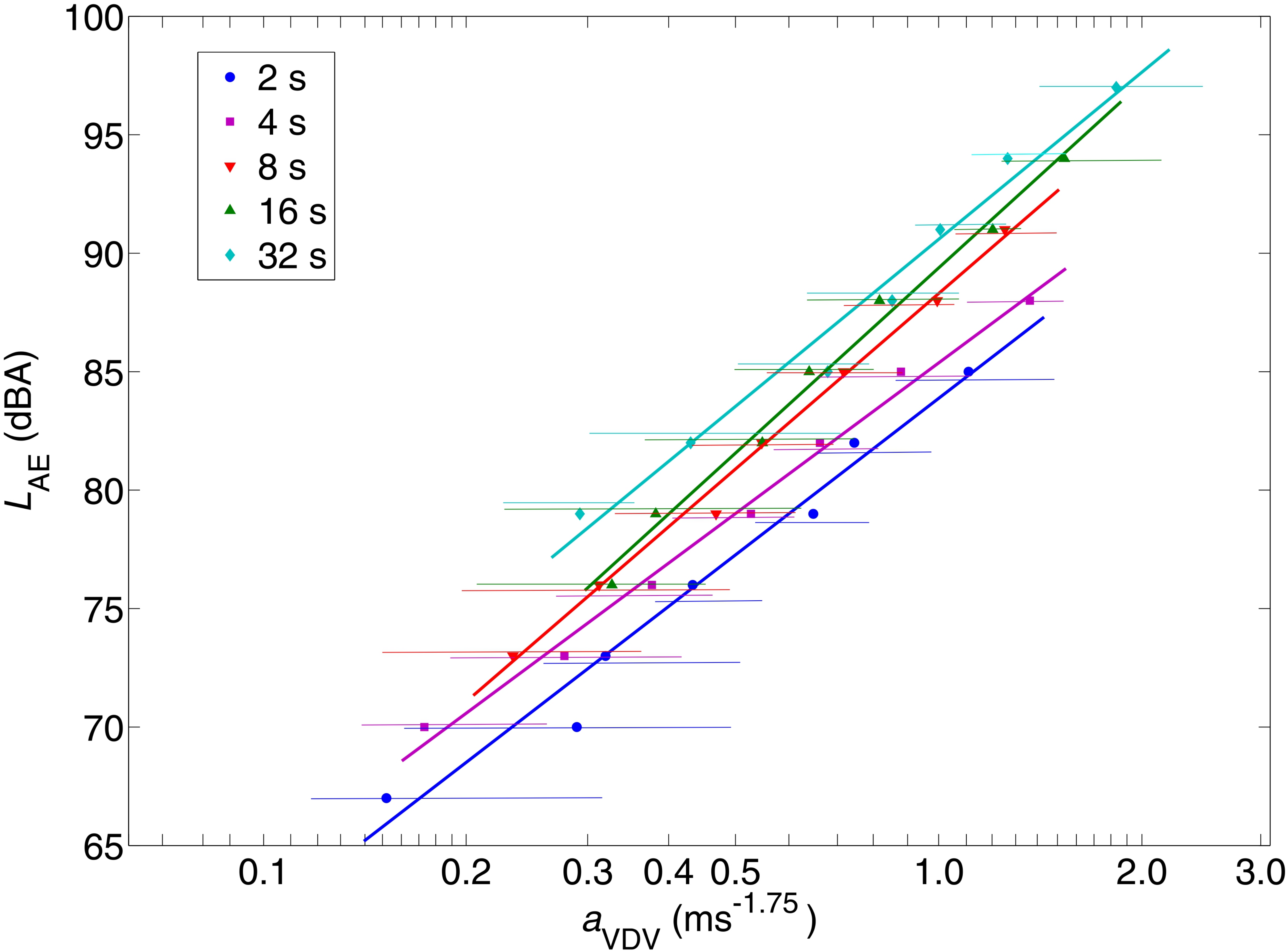
Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255



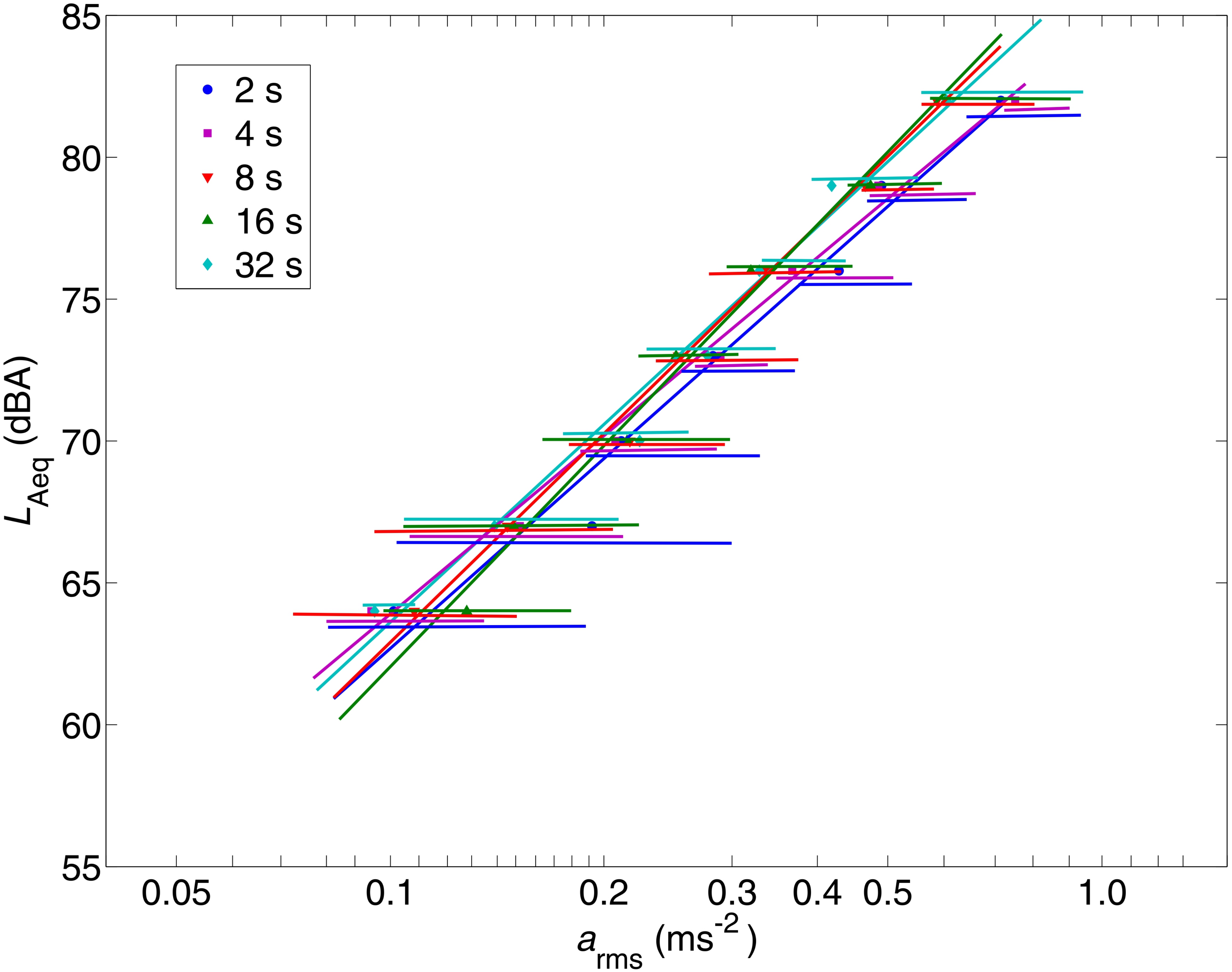
Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255



Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255



Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255



Published as:
The relative discomfort of noise and vibration: effects of stimulus duration
Huang, Y. & Griffin, M. J. Aug 2014 In : Ergonomics. 57, 8, p. 1244-1255