Published as: The vibration discomfort of standing persons: 0.5–16-Hz fore-and-aft, lateral, and vertical vibration
Thuong, O. & Griffin, M. J. Feb 2011 In : Journal of Sound and Vibration. 330, 4, p. 816-826.

Number of pages: 27

Number of tables: 0

Number of figures: 9

Number of references: 22

The vibration discomfort of standing persons: 0.5 to 16-Hz fore-and-aft, lateral, and vertical vibration

Olivier Thuong and Michael J Griffin

Human Factors Research Unit

Institute of Sound and Vibration Research

University of Southampton, SO17 1BJ

United Kingdom

Correspondence address:

Professor Michael J Griffin
Human Factors Research Unit
Institute of Sound and Vibration Research
University of Southampton
Southampton SO17 1BJ
England
Telephone: (+44) 023 8059 2277
Facsimile: (+44) 023 8059 2927
E-mail: M.J.Griffin@soton.ac.uk

Published as: The vibration discomfort of standing persons: 0.5–16-Hz fore-and-aft, lateral, and vertical vibration
Thuong, O. & Griffin, M. J. Feb 2011 In : Journal of Sound and Vibration. 330, 4, p. 816-826.

Abstract

To minimise the discomfort of standing people caused by vibration of a floor, it is necessary to know how their sensitivity to vibration depends on the frequency of the vibration. This study was designed to determine how the discomfort of standing people exposed to horizontal and vertical vibration depends on vibration frequency over the range 0.5 to 16 Hz. Using the method of magnitude estimation, sixteen subjects judged the discomfort caused by fore-and-aft, lateral, and vertical sinusoidal vibration at each of the sixteen preferred one-third octave centre frequencies from 0.5 to 16 Hz at each of nine magnitudes. Subjects also reported the main cause of their discomfort. Equivalent comfort contours were constructed, reflecting the effect of frequency on subject sensitivity to vibration acceleration. With horizontal vibration, at frequencies between 0.5 and 3.15 Hz the discomfort was similar when the vibration velocity was similar, whereas at frequencies between 3.15 Hz and 16 Hz the discomfort was similar when the vibration acceleration was similar. At frequencies less than 3.15 Hz, the subjects experienced problems with their stability, whereas at higher frequencies vibration discomfort was mostly experienced from sensations in the legs and feet. With vertical vibration, discomfort was felt in the lower-body and upper-body at all frequencies. The frequency weightings in current standards for predicting the vibration discomfort of standing persons have been greatly influenced by the findings of studies with seated subjects: the weightings are consistent with the experimentally-determined frequency-dependence of discomfort caused by vertical vibration but inconsistent with the experimentally-determined frequency-dependence of discomfort caused by horizontal vibration. The results suggest that the responses of seated and standing people are similar for vertical vibration, but differ for horizontal vibration, partly due to greater instability in standing persons.

Keywords: vibration, discomfort, standing

1. Introduction

In public transport, passengers often stand for all or part of the journey while exposed to vibration. Standing people also experience the vibration of some fixed structures (e.g. buildings and walkways). Such vibration can cause discomfort and inconvenience. Procedures are needed to predict how the discomfort of standing people is related to the characteristics of the vibration so that human discomfort and inconvenience can be minimised.

Due to the complexity of the mechanisms involved in the perception of vibration, the discomfort caused by vibration depends on the frequency of vibration – discomfort cannot be predicted accurately by a simple quantity such as acceleration, velocity, or displacement. This has led to the use of equivalent sensation contours determined in laboratory experiments to develop frequency weightings that reflect the frequency-dependence of sensitivity to vibration acceleration.

Methods are advocated in British Standard 6841 (1987) [1], European prestandard ENV 12299 [2] and International Standard 2631 (1997) [3] for evaluating vibration with respect to the discomfort of standing people. To reflect the assumed frequency-dependence of discomfort, the standards employ frequency weightings, but the dearth of relevant experimental studies resulted in the use of weightings for standing people derived from equivalent-sensation contours obtained with seated subjects. It is reasonable to suppose that there will be some differences between seated and standing people, and that the weightings for seated people may not be ideal for predicting the discomfort of standing people.

Various methods can be used to construct equivalent comfort contours, including magnitude production and magnitude estimation. When magnitude production is used, subjects must adjust the magnitude of a vibration stimulus in order to match a given level of discomfort, generally defined by a reference motion or semantic labels. When magnitude estimation is used, subjects are exposed to motion stimuli and asked to report the magnitude of discomfort associated with them, generally using numbers (sometimes, relative to the discomfort of a reference motion) or semantic labels. For the vertical vibration of standing people, equivalent comfort contours have been constructed from experimental studies employing a variety of experimental methods over various frequency ranges: magnitude production with a semantic scale, 1-27 Hz [4]; magnitude production using a reference motion, 4-80 Hz [5]; method of adjustment with a random reference motion, 0.7-20 Hz [6]; magnitude estimation using numbers without a reference motion, 3-80 Hz [7]; magnitude production using a reference motion, 0.5-300 Hz [8]. Using a similar method and frequency range, Miwa [8] also constructed equivalent comfort contours for standing people exposed to horizontal vibration. Some of the above methods have been found to lack consistency, most notably methods relying on semantic labels where the interpretation can be highly dependent on the subject. The distortion of the motions used in previous studies was often unreported, but sometimes high. A more accurate reproduction of motion is now possible, the methods have been improved, and equivalent comfort contours can be determined for both vertical and horizontal vibration at the lower frequencies seldom investigated previously. There are significant motions in transport at low frequencies [e.g. 9], and increased understanding of the relative discomfort caused by low and high frequencies has important practical applications.

To understand the discomfort caused by vibration it is necessary to know the causes of discomfort. Landström and Lundström [10] found that over the frequency range 2 to 16 Hz, the localization of discomfort and the type of sensation (e.g. trembling, swinging) caused by the vertical excitation of standing people depended on the frequency of vibration. A variation in response with the frequency of vibration may also be expected with horizontal excitation, especially because loss of balance may be produced by low frequency motions but not by high frequency motions. With subjects exposed to narrow-band random motions of the same r.m.s. velocity in either the fore-and-aft or lateral direction at frequencies in the range 0.125 to 2 Hz, all subjective and objective indicators of loss of balance (displacement of the centre of pressure, loss of balance, and estimates of the probability of losing balance) peaked around 0.5 Hz [11].

This study was designed to improve understanding of the discomfort of standing people exposed to vibration of the floor and determine how their discomfort depends on the frequency of fore-and-aft, lateral, and vertical excitation. It was hypothesized that, with each direction of excitation, both the sensitivity to vibration acceleration and the cause of discomfort would depend on the frequency of the vibration.

2. Method

2.1 Motions

All vibration stimuli were sinusoidal and 6 seconds in duration, including a 1-second cosine-tapered start and a 1-second cosine-tapered end. Subjects were exposed to pairs of motions: a ‘reference vibration’ followed by a ‘test vibration’ in the same direction (i.e. either fore-and-aft, lateral, or vertical).

With all three directions of motion, the ‘test stimuli’ were presented at the sixteen preferred one-third octave centre frequencies between 0.5 and 16 Hz. At each frequency, the test stimuli were presented at nine magnitudes, in steps of 2 dB (Fig. 1). The magnitudes of the stimuli were chosen in the expectation that they would cause approximately similar discomfort at each frequency, based on the findings of Thuong and Griffin [12] and preliminary studies.

FIGURE 1 ABOUT HERE

2.2 Equipment

The motions were produced using two hydraulic vibrators capable of 1-metre displacement, one in the horizontal direction, and the other in the vertical direction. Fore-and-aft or lateral vibration was obtained by orientating subjects relative to the axis of motion (Fig. 2). The motion stimuli were generated using *HVLab* software (version 3.81) with a sampling rate of 1000 samples per second. The acceleration of the platform was monitored using piezoresistive accelerometers (Entran Model EGCSY-240D*-10) and an *HVLab* data acquisition system. The acceleration was sampled at 1000 samples per second, after low-pass filtering at 40 Hz.

For each frequency, magnitude, and direction of motion, the importance of the distortion in the motion waveforms was determined by taking account of the frequency-dependence of human sensitivity to vibration in each direction. Based on the results from the current study, the horizontal acceleration measured on the table of the vibrator was frequency-weighted using a weighting corresponding to constant velocity at frequencies between 0.5 and 3.15 Hz and constant acceleration at frequencies greater than 3.15 Hz (Section 4.2). The vertical acceleration of the vibrator table was frequency-weighted using the weighting curve W_b advocated in standards. The distortion was calculated from the square root of the ratio of the acceleration power spectral density outside an octave band centred on the frequency of the motion to the acceleration power spectral density inside the octave band. For motions at frequencies greater than 1 Hz, the weighted distortion was always less than 10%. At lower frequencies, the distortion was mostly less than 20% but greater with low magnitudes of motion and reached 38% at the lowest frequency and the lowest magnitude.

2.3 Subjects

Sixteen healthy male university students and staff with median age 25 years (range 20 to 29 y), stature 179 cm (164 to 193 cm), weight 77 kg (48 to 133 kg) participated in the studies with horizontal vibration. They attended two sessions, one for each direction of motion (i.e. fore-and-aft and lateral), each lasting approximately 60 minutes.

Sixteen healthy male university students and staff with median age 26 years (range 20 to 30 y), stature 176 cm (164 to 187 cm), weight 73 kg (48 to 92 kg) participated in the study using vertical vibration, including 10 subjects who participated in the studies with horizontal vibration. They attended one session lasting 60 minutes.

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.

2.4 Conditions and posture

The subjects wore socks but not shoes and wore a loose harness in case they should fall. The harness did not provide support or restrict movement when subjects stood as instructed. It was attached to an extruded aluminium frame secured to the 120 cm by 90 cm table of the vibrator. Wooden boards were attached to the aluminium frame, so that the visual field was closed and moved with the subjects who could not see outside the moving cabin (Fig. 2).

FIGURE 2 ABOUT HERE

The subjects maintained an upright posture, with their knees locked, and looked straight ahead. Their feet were parallel and separated so that their lateral ‘base of support’ (distance between the outer edges of their feet) was 275 mm, the median shoulder width for adult males [13].

The subjects wore headphones delivering broadband noise at 65 dB(A). The headphones also provided some acoustic isolation from external noises, and this was found sufficient to mask noises produced by the simulator when generating motions (the level of the noise generated by the simulator when producing the motions was about 57 dB(A)).

2.5 Procedure

The method of magnitude estimation, as used previously by Morioka and Griffin [14] and Thuong and Griffin [12], was employed to determine the discomfort caused by each of the test motions relative to the discomfort caused by a reference motion presented in the same axis as the test motion.

The subjects for the 'horizontal' experiment attended two sessions in which they were exposed to either fore-and-aft or lateral vibration: half of the subjects were first exposed to fore-and-aft vibration and half of the subjects began with lateral vibration. The subjects for the 'vertical' experiment attended one session.

Subjects were exposed to the reference motion (2.5 Hz at 0.35 $m.s^{-2}$ r.m.s. for horizontal vibration, 2.5 Hz at 0.56 $m.s^{-2}$ r.m.s. for vertical vibration), followed by a test motion at a randomly chosen frequency and magnitude from the range shown in Fig. 1. After the presentation of the test motion, subjects were asked to provide a number reflecting the discomfort it caused, assuming the discomfort caused by the reference motion was 100. The subjects could ask for the pair of motions to be repeated if they were not sure of their judgement. Prior to commencing the experiment, subjects practiced magnitude estimation by judging the lengths of lines drawn on paper and by judging a few selected vibration stimuli. This provided an opportunity to check that they understood the procedure and also familiarised them with the type of vibration stimuli.

After the magnitude estimation of all stimuli, subjects were presented with additional vibration stimuli and asked to state where in the body they experienced most discomfort, or if discomfort arose due to postural instability (when exposed to horizontal vibration) or a different cause (when exposed to vertical vibration). If most discomfort arose from sensations in the body, they reported the location using a body map. These stimuli were identical to stimuli used in the first part of the experiment (two stimuli at each frequency, at the third and seventh magnitudes in the ranges shown in Fig. 1) and were presented in random order.

2.6 Analysis

Stevens' power law [15] was used to relate the magnitude estimates of subject discomfort, ψ, to the physical magnitudes of the motions, φ:

$$\psi = k\,\varphi^{n} \tag{1}$$

where k (the 'constant' in Stevens' power law) and n (the 'exponent') are assumed to be constant at any frequency. With whole-body vibration of seated persons the exponent depends on the frequency of vibration [14].

Values of the exponent, n, at each frequency were determined by linear regression between the logarithms of the magnitude estimates and the vibration acceleration using bisquare weights to reduce bias from outlier values [16]:

$$\log \psi = \log k + n \log \varphi \tag{2}$$

For each subject, equivalent comfort contours were obtained for different subjective magnitudes, ψ, using individual values of k and n (which depend on frequency):

$$\varphi(f) = \left(\frac{\psi}{k(f)}\right)^{\frac{1}{n(f)}} \tag{3}$$

This equation gives the acceleration, φ, needed at each frequency to achieve a given level of discomfort, ψ. For horizontal vibration, equivalent comfort contours were constructed for magnitude estimates of 100 (i.e. equivalent to the reference motion in the same direction), and for magnitude estimates of 130 and 160. For vertical vibration, contours were constructed for magnitude estimates of 120, 150 and 180. These levels were chosen so that the equivalent comfort contours were within the range of stimuli presented to the subjects, as shown in Fig. 3. Values outside this range would be based on extrapolation.

The equivalent comfort contours corresponding to the magnitude estimates in the middle of the range (130 for horizontal vibration, and 150 for vertical vibration) were used to derive frequency weightings. For each axis, the equivalent comfort contour was inverted, and then multiplied by an arbitrary constant to assist comparison with the frequency weightings advocated in the standards.

2.7 Statistical tests

Non-parametric tests (the Friedman two-way analysis of variance by ranks, the Wilcoxon matched-pairs signed ranks test, the Spearman rank-order correlation coefficient, the McNemar change test and the Cochran Q test) were employed in the statistical analysis.

3. Results

3.1 Rate of growth of discomfort, n

The rate of growth of discomfort, also called the 'exponent' in Stevens' power law, is shown for all three directions of vibration in Fig. 4, together with inter-quartile ranges.

FIGURE 3 ABOUT HERE

FIGURE 4 ABOUT HERE

With fore-and-aft vibration, over the range 0.5 to 16 Hz the exponent was highly dependent on the frequency of vibration ($p<0.001$, Friedman). The exponent was least from 5 to 8 Hz, and over the range 0.5 to 4 Hz the exponent was not significantly dependent on the frequency of vibration ($p=0.079$).

With lateral vibration, the exponent was independent of frequency ($p=0.085$, Friedman).

With vertical vibration, over the range 0.5 to 16 Hz the exponent was highly dependent on the frequency of vibration ($p<0.001$, Friedman). Multiple comparisons showed that the exponent at any frequency in the range 0.5 to 4 Hz was greater than that at any frequency in the range 5 to 16 Hz ($p<0.05$, Wilcoxon). Over the range 5 to 16 Hz, the exponent did not depend on frequency ($p=0.220$, Friedman). As shown in Fig. 4, the median exponent tends to decrease from 0.5 to 4 Hz but is relatively constant from 5 to 16 Hz.

3.2 Equivalent comfort contours

Equivalent sensation contours corresponding to magnitude estimates of 100, 130, and 160 for horizontal vibration, and 120, 150 and 180 for vertical vibration, are shown in Fig. 3, together with the range of magnitudes used in the experiment. In all three directions, the acceleration on each contour depended on frequency ($p<0.05$, Friedman), so sensitivity to acceleration depended on the frequency of vibration with each direction of vibration.

With both fore-and-aft and lateral vibration, when each of the three equivalent comfort contours were expressed in terms of vibration velocity they were independent of the frequency of vibration over the range 0.5 to 2.5 Hz (Friedman, $p > 0.16$), suggesting the contours have constant velocity in this range.

With vertical vibration, the equivalent contours suggest sensitivity is greatest in the range 5 to 16 Hz. The shapes of the contours depend on the magnitude of vibration, consistent with the dependence of the exponent, n, on the frequency of vibration (Section 3.1).

3.3 Frequency weightings

For all three axes of vibration, frequency weightings were derived from the equivalent comfort contours (as explained in Section 2.5) and are shown in Fig. 5, with the weightings W_b and W_d, advocated in the standards, and a curve corresponding to constant velocity at low frequencies and constant acceleration at high frequencies, with a transition at 3.15 Hz.

FIGURE 5 ABOUT HERE

3.4 Cause of discomfort

The main causes of discomfort reported by the subjects for the three axes of motion are reported in Fig. 6. At each frequency of horizontal vibration and at both magnitudes of vibration, the proportions of subjects reporting the main cause of discomfort as vibration in the legs and feet, vibration in the upper-body, or balance disturbance are shown.

FIGURE 6 ABOUT HERE

With both axes of horizontal vibration, and at both magnitudes, the proportions of subjects reporting balance as the main cause of discomfort and the proportion of subjects reporting vibration in the lower body as the main cause of discomfort were dependent on the frequency of vibration ($p < 0.05$, Cochran). As the frequency of vibration increased, the discomfort caused by vibration in the legs and feet tended to increase, and the discomfort caused by loss of balance tended to decrease.

With vertical vibration, the proportions of subjects reporting vibration in the legs and feet, vibration in the upper-body, or a different cause of discomfort, are shown in Fig. 6. The ‘different’ causes of discomfort were not specified explicitly but may have included vestibular excitation as they occurred at low frequencies but not in a specific part of the body. At both magnitudes, the importance of vertical vibration in the legs was independent of the frequency of vibration ($p>0.14$, Cochran).

4. Discussion

4.1 Equivalent comfort contours

Equivalent sensation contours for standing people exposed to fore-and-aft and lateral vibration have been obtained previously for the octave centre frequencies in the range 0.5 to 16 Hz using the same method employed here but with a different range of magnitudes, a different reference motion, and different subjects [12]. The contours corresponding to a magnitude estimate of '100' in the previous study and '140' in the present study are compared in Fig. 7 (these are approximately equivalent subjective magnitudes because different reference motions were employed: 2 Hz at 0.5 $m.s^{-2}$ r.m.s. in the previous study and 2.5 Hz at 0.35 $m.s^{-2}$ r.m.s. in the current study). The contours are similar, except at lower frequencies: the present results show a higher sensitivity to low-frequency vibration (0.5 to 2.5 Hz) in both axes of motion. In the previous study, the subjects could see outside the moving cabin, whereas this was not possible in the present study. The restricted view may have increased the difficulty of maintaining balance, thus increasing discomfort at low frequencies.

FIGURE 7 ABOUT HERE

Equivalent-sensation contours have previously been constructed for standing people exposed to vertical vibration by Chaney [4], Jones and Saunders [5]), Ashley [6], Oborne and Clarke [7] and Miwa [8], and are compared with the equivalent comfort contours from the present study in Fig. 8. The studies used different psychophysical methods and different environmental conditions, so differences can be expected. However, all contours suggest greatest sensitivity to vertical acceleration between 5 and 8 Hz.

FIGURE 8 ABOUT HERE

In the present study the rate of growth of sensation was least, and sensitivity to low magnitude acceleration was greatest, at 6.3 Hz, within the range of greatest sensitivity found in previous studies. Investigating the apparent masses of standing subjects exposed to random vertical vibration over the range 2 to 20 Hz, Subashi *et al.* [18] found the first resonance frequency at 6.39 Hz, 6.01 Hz, and 5.63 Hz when using vibration magnitudes of 0.125, 0.25, and 0.5 $m.s^{-2}$ r.m.s., respectively. It seems reasonable to assume that the increased sensitivity to vertical vibration at 6.3 Hz found in the present study may be associated with body resonance around this frequency.

4.2 Frequency weightings

British Standard 6841 (1987) [1], European prestandard ENV 12299 (1999) [2], and International standard ISO 2631-1 (1997) [3] provide frequency weightings for evaluating vibration with respect to the discomfort of standing persons. For lateral and fore-and-aft vibration, all three standards advocate frequency weighting W_d for predicting the vibration discomfort of both seated and standing people. For vertical vibration, British Standard 6841 (1987) [1] and European prestandard ENV 12299 (1999) [2] advocate weighting W_b, whereas International standard ISO 2631-1 (1997) [3] promotes weighting W_k, which is similar to W_b, although an annex to ISO 2631-1 states that in some environments, including railway vehicles, W_b is considered the appropriate weighting.

For standing people exposed to horizontal vibration, whereas the standards advocate weighting W_d (corresponding to constant acceleration from 0.5 to 2.0 Hz and constant velocity from 2.0 to 16 Hz), the weightings obtained in this experiment correspond to constant velocity from 0.5 Hz to 3.15 Hz and constant acceleration from 3.15 Hz to 16 Hz, as shown by the similarity between the weightings and the dotted line in Fig. 5. There is therefore little agreement between the present data and the recommendation in the standards for standing people exposed to horizontal vibration. This also implies that seated and standing persons have different responses to horizontal vibration, since the standard weighting was based on findings from studies with seated subjects.

For standing people exposed to vertical vibration at frequencies greater than 1.6 Hz, the weighting curve derived from the current results is consistent with the weighting W_b advocated in the standards (Fig. 5). This suggests that the responses of standing and seated people to vertical vibration are similar. However at lower frequencies, W_b seems to underestimate the sensitivity of standing passengers, although this might be due to the absence of an external visual field in this study, as suggested in Section 4.1 with horizontal vibration.

The comfort contours presented here were obtained with 6-second motion stimuli, and should be appropriate for evaluating vibration when the duration of exposure is short. The frequency-dependence of vibration discomfort may depend on the duration of exposure, and so the appropriate comfort contours for long duration exposures may differ.

4.3 Cause of discomfort

Standing people can resist the destabilizing influence of gravity if their centre of mass is positioned above their base of support. Otherwise, a step or the help of a support is needed to avoid loss of balance [19]. Horizontal motion of a floor will therefore not be expected to cause loss of balance if the displacement of the centre of mass is not sufficient for it to approach the limits of the base of support. Although the transmissibility between the floor and the centre of mass of the body is not known, the transmissibility to the head has been measured, and it may be reasonable to assume that the motion of the head is related to the motion of the centre of mass. The transmissibility from the floor to the heads of standing subjects exposed to vibration in all three axes of translational vibration has been reported by Paddan and Griffin [20], with full data provided in Reference [21]. The transmissibility of standing subjects exposed to fore-and-aft, lateral, and vertical vibration in conditions similar to those of the present experiment are shown in Fig. 9.

FIGURE 9 ABOUT HERE

The fore-and-aft and lateral transmissibilities are greatest at frequencies between about 0.5 and 0.8 Hz, and decrease as the frequency increases from 0.8 Hz to 10 Hz, similar to the trend in the importance of balance disturbance as a source of discomfort (Fig. 6). The importance of vibration in the legs increases with increasing frequency, consistent with the decrease in the transmission of vibration to the upper-body with increasing frequency. With vertical vibration, the importance of vibration in the legs as a source of vibration discomfort did not change with frequency (Fig. 6), consistent with vertical transmissibility being independent of frequency over this range (Fig. 9). This is consistent with the results of Landström and Lundström [10], who found that even at frequencies as high as 8 and 16 Hz, standing people experienced discomfort in upper-body areas, such as the lumbar region, abdominal region, shoulders, and face.

4.4 The frequency-dependence of discomfort of standing people

From the frequency-dependence of both sensitivity to vibration and causes of discomfort, it appears that the responses of the subjects were different at lower and higher frequencies.

With fore-and-aft and lateral vibration, subject sensitivity seems to depend on vibration velocity at frequencies less than about 3.15 Hz, and vibration acceleration at frequencies greater than about 3.15 Hz, as shown by the equivalent comfort contours and the frequency weightings (Figs. 4 and 5). Over the range 0.5 to 3.15 Hz, at least some of the discomfort was caused by balance disturbance (Fig. 6), suggesting that the disturbance of the stability of standing people may depend on vibration velocity, consistent with the loss of balance in walking subjects exposed to transient lateral motions at frequencies between 0.5 and 2 Hz depending on the velocity of the motion (Sari and Griffin [22]).

With vertical vibration, the rate of growth of discomfort was different at low and high frequencies (Fig. 4): at frequencies less than 4 Hz, the exponent decreased steadily as frequency increased, whereas at frequencies greater than 4 Hz it remained approximately constant. The analysis of the causes of discomfort show that in the range 0.5 Hz to 4 Hz, some subjects did not feel discomfort in a specific part of the body. These findings suggest that, as with horizontal vibration, the principal mechanisms for the perception of vibration differ between frequencies less than 4 Hz and frequencies greater than 4 Hz.

The equivalent comfort contours presented in this paper were derived from the responses of male subjects. Studies with seated subjects suggest there may be differences in the frequency-dependence of vibration discomfort between groups of males and females [23]. However, the extent to which any differences are due to gender, or due to other factors that depend on gender (e.g. body size), is not yet clear.

5. Conclusion

At frequencies between 0.5 and 16 Hz, the rates of growth of sensation, the shapes of equivalent comfort contours, and the causes of discomfort in standing persons are similar for fore-and-aft and lateral vibration. For both axes, the frequency weightings correspond to constant velocity at lower frequencies (where loss of balance is a cause of discomfort) and constant acceleration at higher frequencies (where loss of balance is not a cause of discomfort), with a transition at about 3.15 Hz. This is not consistent with the frequency weighting advocated in current standards (i.e. W_d) that was based on studies with seated subjects.

The equivalent comfort contours for vertical vibration are consistent with the weighting advocated in standards (i.e. W_b) except at frequencies less than 1.6 Hz. Subjects were particularly sensitive to vibration at frequencies in the range 4 to 16 Hz, with greatest sensitivity to low magnitude acceleration around 6.3 Hz, possibly due to a resonance of the body.

Comparisons with the weightings advocated in the standards suggest that the responses of standing and seated people are similar when exposed to vertical vibration but different when exposed to horizontal vibration. For all three axes of excitation, different mechanisms are responsible for discomfort caused by low frequency and high frequency vibration (i.e. less than or greater than 3 or 4 Hz).

6. Acknowledgements

This study was conducted with the support of Société Nationale des Chemins de fer Français (SNCF), Paris, France. The assistance of Cedric Gallais is gratefully acknowledged.

7. References

[1] British Standards Institution BS 6841, Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock, 1987.

[2] European Committee for Standardisation Prestandard ENV 12299:1999, Railway applications – Ride comfort for passengers – Measurement and evaluation, 1999.

[3] International Organization for Standardization ISO 2631-1, Mechanical vibration and shock - evaluation of human exposure to whole-body vibration - part 1: general requirements, 1997.

[4] R.E. Chaney, Whole-body vibration of standing subjects, Boeing Co., Human Factors Technical Report D3-6474, 1965.

[5] A.J. Jones, D. J. Saunders, Effects of postural and methodological changes on equal comfort contours for whole-body, vertical, sinusoidal vibration. *Applied Acoustics* 5 (1972) 279-299.

[6] C. Ashley, Equal annoyance contours for the effect of sinusoidal vibration on man. *Shock and Vibration Bulletin* 41 (1970) 12-20.

[7] D.J. Oborne, M.J. Clarke, The determination of equal comfort zones for whole-body vibration. *Ergonomics* 17 (1974) 769-782.

[8] T. Miwa, Evaluation methods for vibration effect. Part 1. measurements of the threshold and equal sensation contours of whole body for vertical and fore and aft vibrations. *Industrial Health* 5 (1967) 183-205.

[9] International Organization for Standardization ISO 2631-4, Mechanical vibration and shock - evaluation of human exposure to whole-body vibration - part 4: guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems, 1997.

[10] U. Landström, R. Lundström, Sensations, perception thresholds and temporary threshold shifts of whole body vibrations in sitting and standing posture. *Journal of Low Frequency Noise and Vibration* 5 (1986) 68-77.

[11] N. Nawayseh, M.J. Griffin, Effect of frequency, magnitude and direction of translational and rotational oscillation on the postural stability of standing people. *Journal of Sound and Vibration* 298 (2006) 725-754.

[12] O. Thuong, M.J. Griffin, The vibration discomfort of standing persons: effect of body supports. *Journal of Rail and Rapid Transit* (Accepted, awaiting publication).

[13] S. Pheasant, *Bodyspace: anthropometry, ergonomics and design*. Taylor & Francis, London, 1988.

[14] M. Morioka, M.J. Griffin, Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical whole-body vibration. *Journal of Sound and Vibration* 298 (2006) 755-772.

[15] S.S. Stevens, *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*, John Wiley & Sons inc., New York, 1975, re-issued by Transaction Books, New Brunswick, 1986.

[16] J. Fox, *An R and S-Plus Companion to Applied Regression* (Appendix). Sage, Thousand Oaks, California, 2002.

[17] T. Miwa, Evaluation methods for vibration effect. Part 6. Measurements of unpleasant and tolerance limit levels for sinusoidal vibrations. *Industrial Health* 6 (1968) 18-27.

[18] G. Subashi, Y. Matsumoto, M.J. Griffin, Apparent mass and cross-axis apparent mass of standing subjects during exposure to vertical whole-body vibration. *Journal of Sound and Vibration* 293 (2006) 78-95.

[19] L.M. Nashner, Practical Biomechanics and Physiology of Balance, in: G.P. Jacobson, C.W. Newman, J.M. Kartush, *Handbook of Balance Function Testing*, Singular, San Diego, 1997.

[20] G.S. Paddan, M.J. Griffin, The transmission of translational floor vibration to the head of standing subjects. *Journal of Sound and Vibration* 160 (1993) 503-521.

[21] G.S. Paddan, M.J. Griffin, Transmission of vibration through the human body to the head: A summary of experimental data, University of Southampton, Institute of Sound and Vibration Research Technical Report No. 218, 1993.

[22] M. Sari, M.J. Griffin, Subjective assessment of the postural stability of walking subjects exposed to lateral vibration. Presented at the 44th UK Conference on Human Response to Vibration, Loughborough, United Kingdom, 7-9 September 2009.

[23] C. Corbridge, M. J. Griffin, Vibration and comfort: vertical and lateral motion in the range 0·5 to 5·0 Hz. Ergonomics 29(2) (1986) 249-272.

Figure captions

Fig. 1. Frequencies and magnitudes of the vibration stimuli used in the experiment. ●:horizontal stimulus; ○:vertical stimulus.

Fig. 2. Models of the experimental setups used to expose subjects to fore-and-aft, lateral and vertical vibration respectively.

Fig. 3. Equivalent sensation contours constructed for all three axes of motion, corresponding to different magnitude estimates:
Horizontal: —▼— 100; —■— 130; —▲— 160; – – Range of stimuli;
Vertical: —◄— 120; —●— 150; —►— 180; – – Range of stimuli.

Fig. 4. Rates of growths of sensation at each frequency and in each axis of motion, and interquartile ranges.

Fig. 5. Comparison of the frequency weightings with the weightings advocated in standards.
—●—:Fore-and-aft; —▼—:Lateral; —▲—: Vertical. ——: W_b; – –: W_d;
- - -: Constant velocity / constant acceleration (transition at 3.15 Hz).

Fig. 6. Proportion of subjects reporting different factors as the main cause of discomfort:
☐: vibration in the legs and feet; ▨: vibration in the upper body; ■: postural stability; ☰: different cause.

Fig. 7. Comparison of results on horizontal vibration with previous work:
—— Equivalent sensation contour corresponding to magnitude estimate ‘140’ in the present experiment ; - - - Equivalent sensation contour corresponding to magnitude estimate ‘100’ in Thuong and Griffin [12].

Fig. 8. Comfort contours obtained with vertical vibration in the present study for the magnitude estimates ‘100’, ‘140’ and ‘200’, and by previous researchers:
——: Present study (120); – –: Present study (150); - - -: Present study (180); —▼—: Miwa [8] ; —►—: Miwa [8]; —▲—: Miwa [17]; —◆—: Oborne and Clarke [7]; —■—: Ashley [6]; —●—: Jones and Saunders [5]; —✱—: Jones and Saunders [5]; —+—: Chaney [4] (“perceptible”).

Fig. 9. Floor-to-head transmissibility of standing people measured by Paddan and Griffin [20]:
——: Fore-and-aft, light grip; – –: Lateral, feet 30 cm apart; - - -: Vertical, knees locked.

Published as: The vibration discomfort of standing persons: 0.5–16-Hz fore-and-aft, lateral, and vertical vibration
Thuong, O. & Griffin, M. J. Feb 2011 In : Journal of Sound and Vibration. 330, 4, p. 816-826.

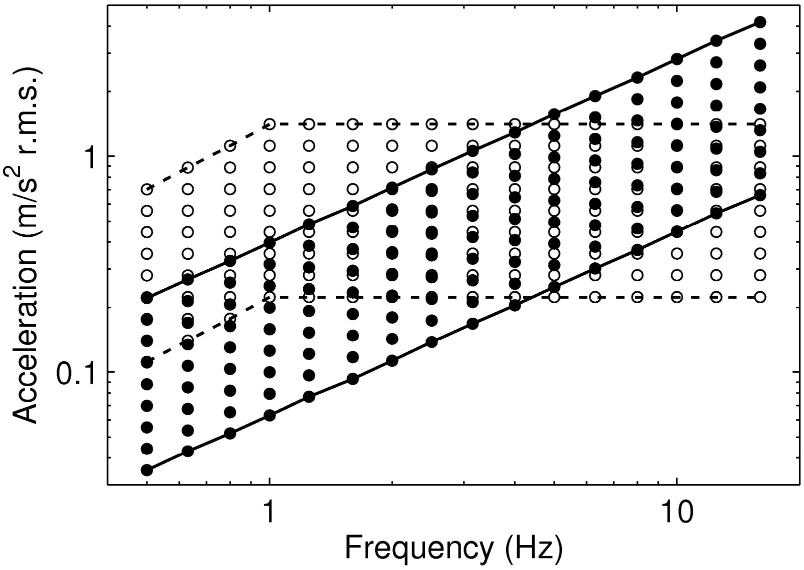

Fig. 1.

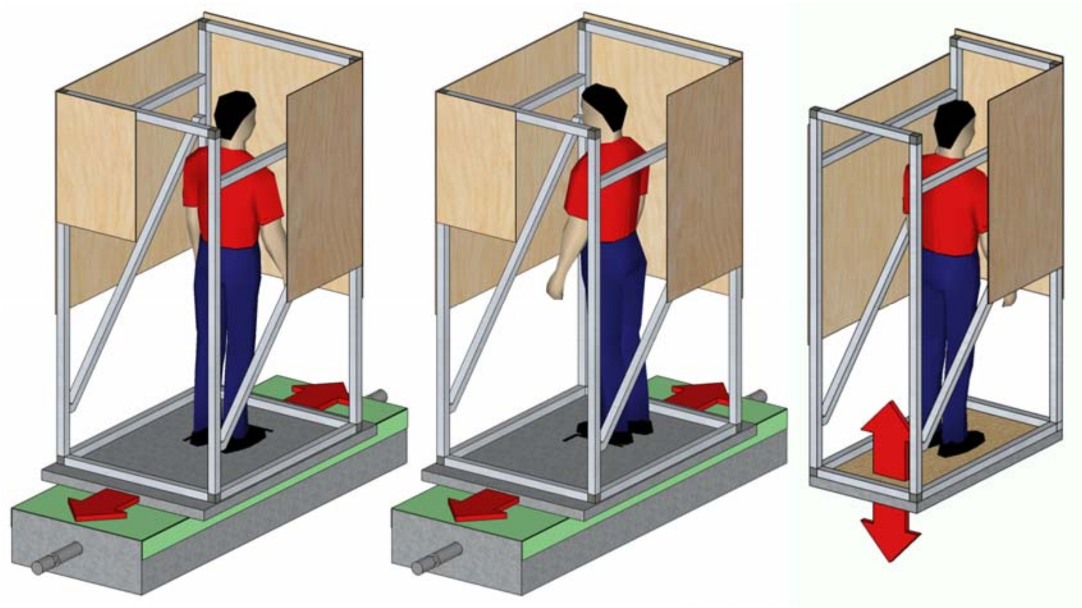

Fig. 2.

Published as: The vibration discomfort of standing persons: 0.5–16-Hz fore-and-aft, lateral, and vertical vibration
Thuong, O. & Griffin, M. J. Feb 2011 In : Journal of Sound and Vibration. 330, 4, p. 816-826.

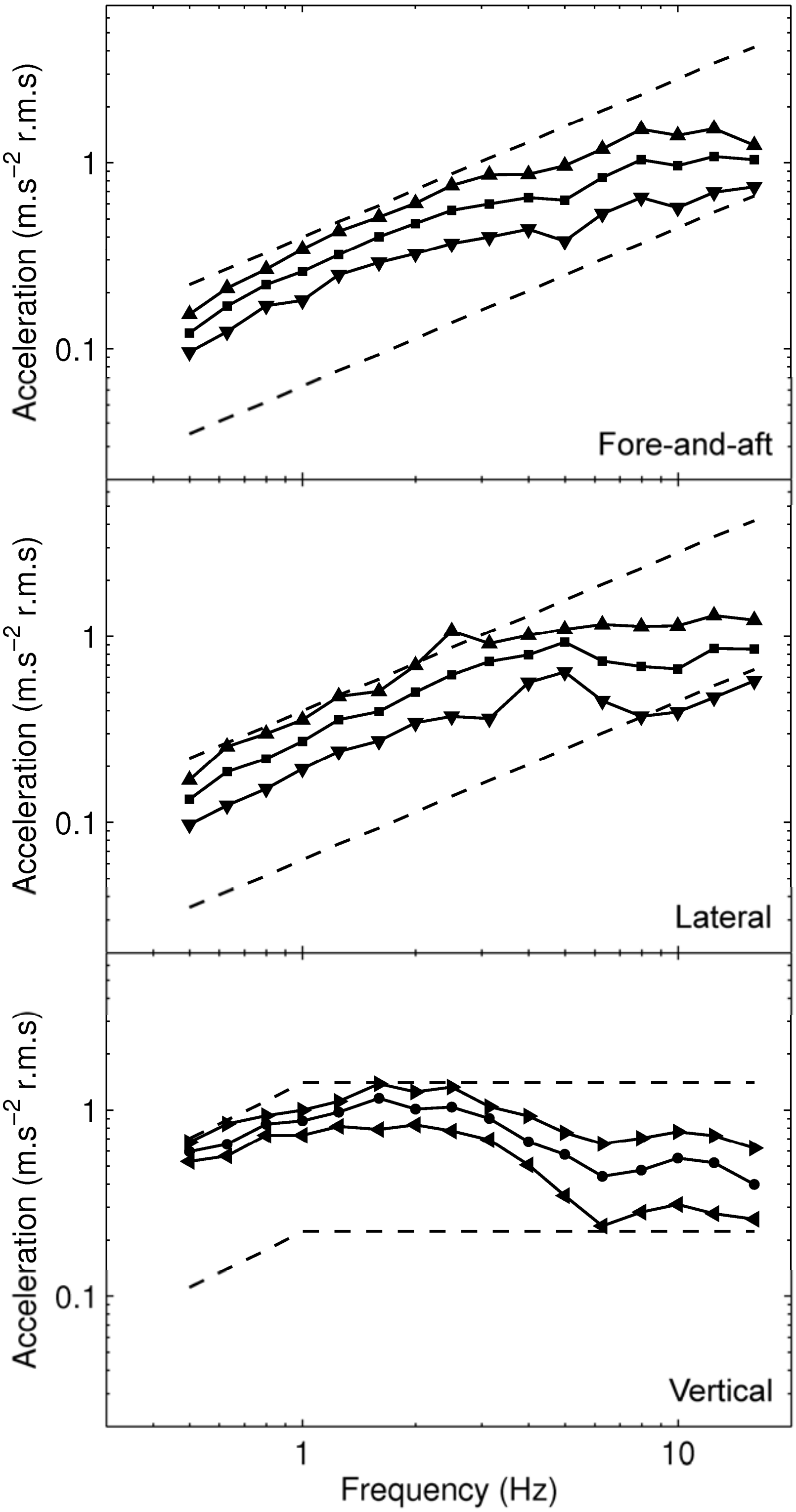

Fig. 3.

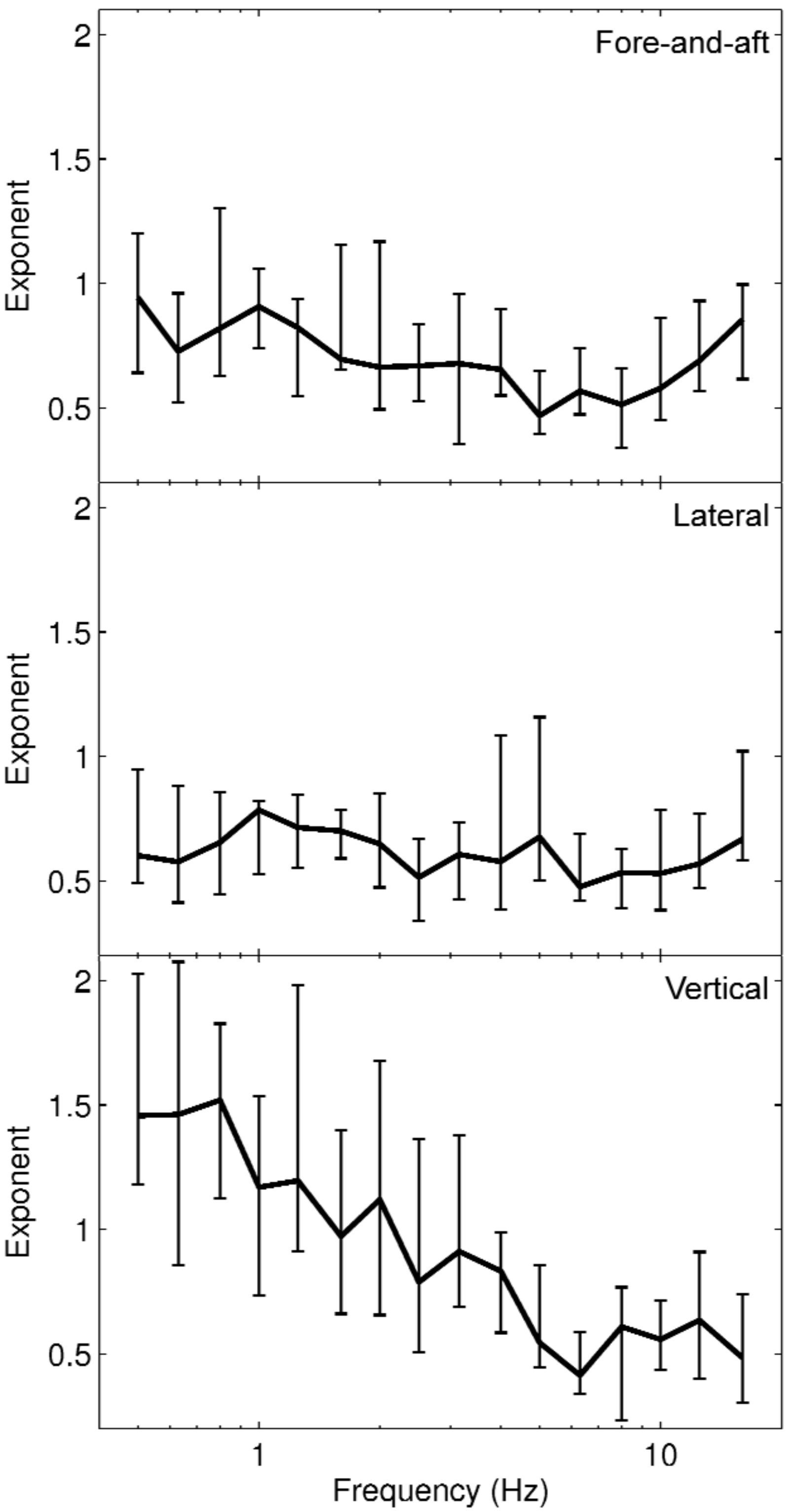
Fore-and-aft
Lateral
Vertical
Exponent
Exponent
Exponent
2
1.5
1
0.5
1
10
Frequency (Hz)

Fig. 4.

Published as: The vibration discomfort of standing persons: 0.5–16-Hz fore-and-aft, lateral, and vertical vibration
Thuong, O. & Griffin, M. J. Feb 2011 In : Journal of Sound and Vibration. 330, 4, p. 816-826.

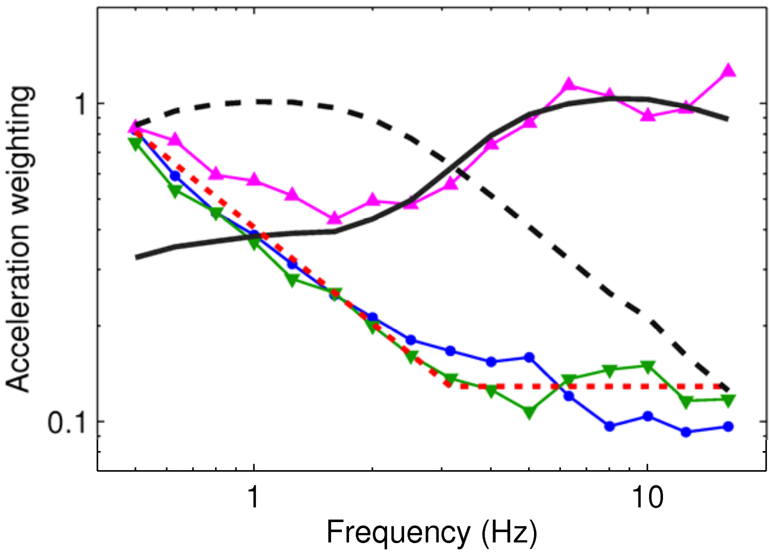

Fig. 5.

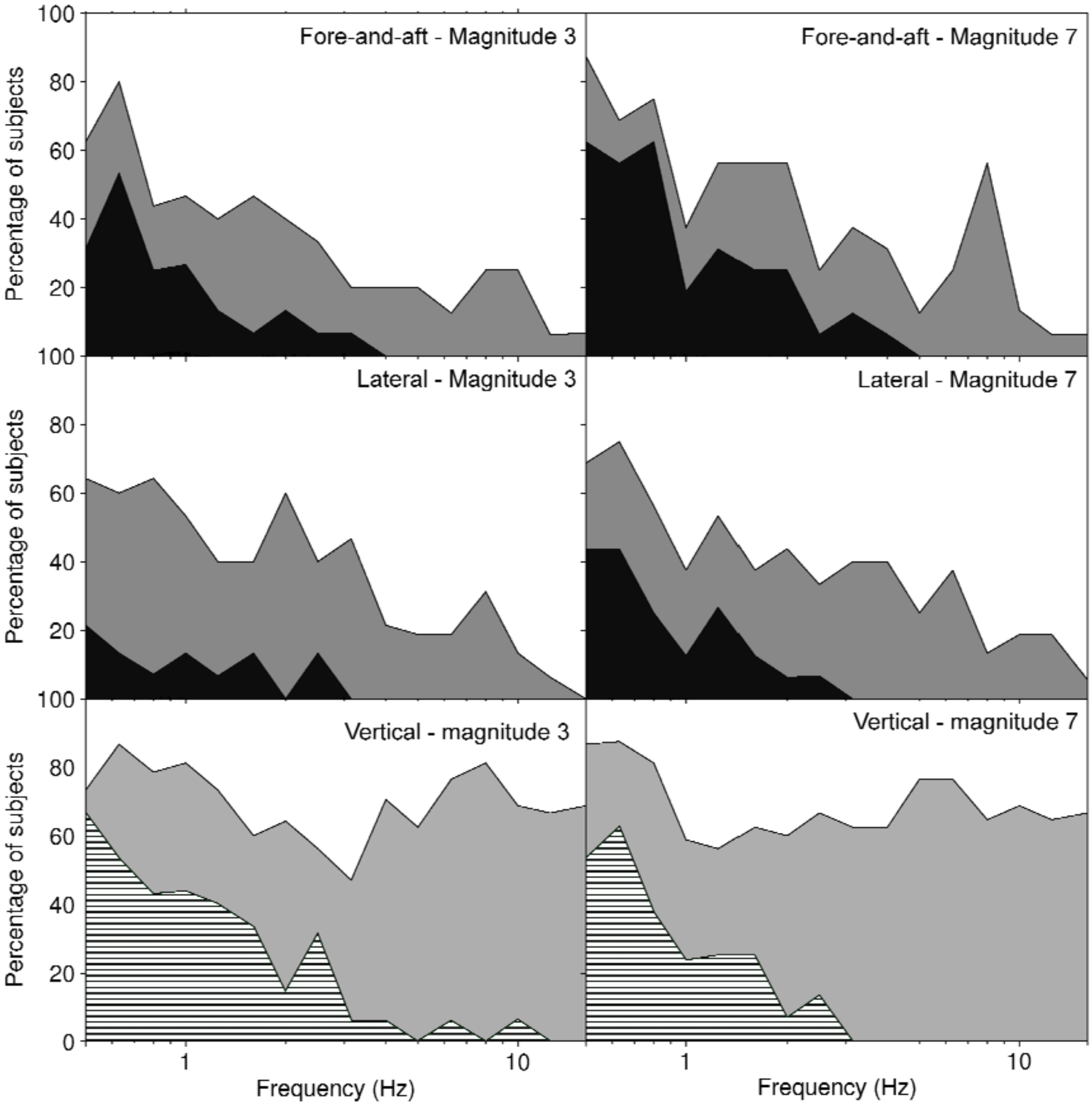
Fore-and-aft - Magnitude 3
Fore-and-aft - Magnitude 7
Lateral - Magnitude 3
Lateral - Magnitude 7
Vertical - magnitude 3
Vertical - magnitude 7
Percentage of subjects
Percentage of subjects
Percentage of subjects
100
80
60
40
20
100
80
60
40
20
100
80
60
40
20
0
1
10
1
10
Frequency (Hz)
Frequency (Hz)

Fig. 6.

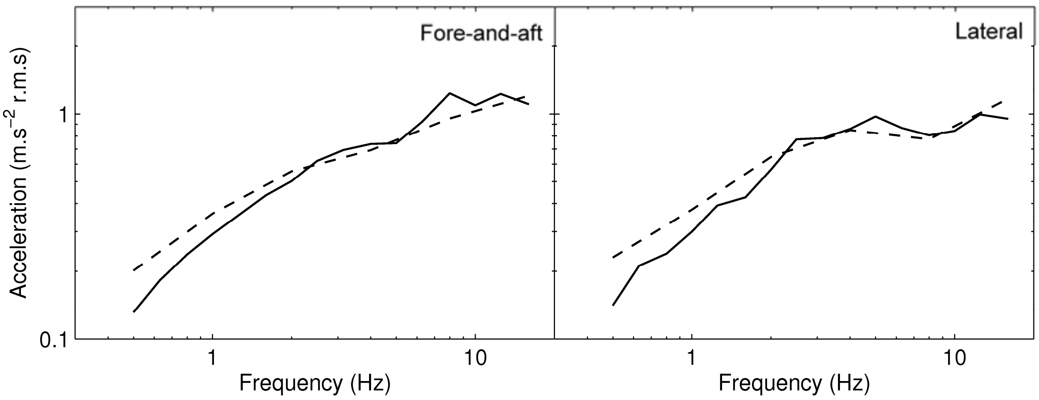
Fore-and-aft
Lateral
Acceleration (m.s^{-2} r.m.s)
1
0.1
1
10
Frequency (Hz)
1
10
Frequency (Hz)

Fig. 7.

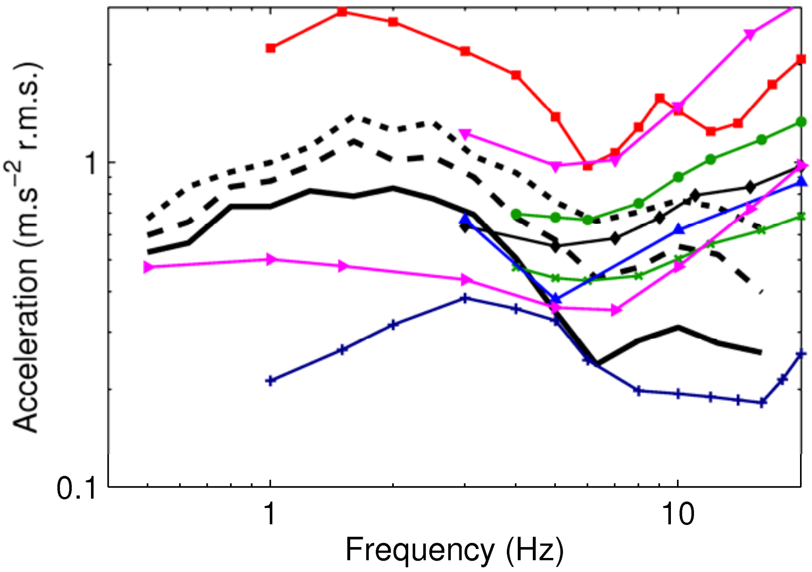

Fig. 8.

Published as: The vibration discomfort of standing persons: 0.5–16-Hz fore-and-aft, lateral, and vertical vibration
Thuong, O. & Griffin, M. J. Feb 2011 In : Journal of Sound and Vibration. 330, 4, p. 816-826.

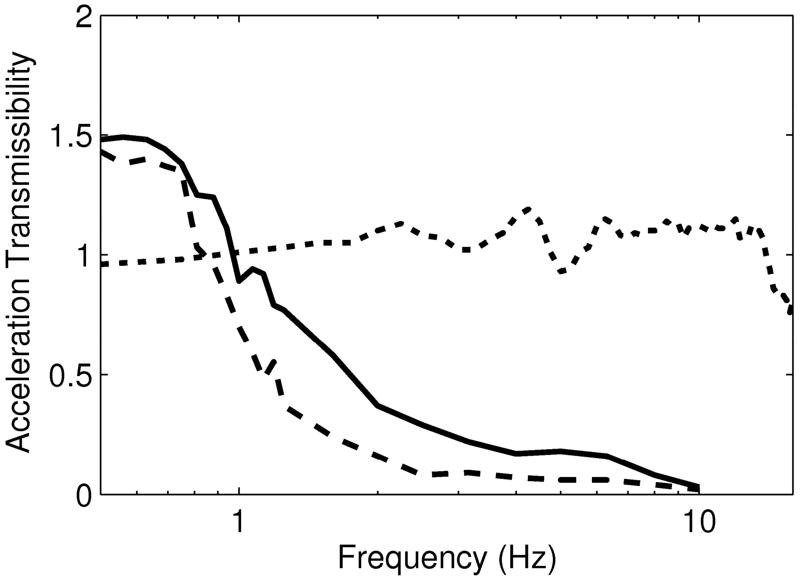

Fig. 9.