PREDICTING THE FEELING OF VIBRATION IN BUILDINGS

MJ Griffin Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, UK

1 INTRODUCTION

Vibration provokes sensations and responses varying from pleasure or displeasure, to interference with activities, injury, and disease. Human responses to vibration may be predicted if the vibration is 'measured', 'evaluated', and 'assessed' using understanding derived from studies of human responses vibration. Such understanding comes from both laboratory experimental exposures and from vibration exposures at work and during leisure.

The 'measurement' of vibration involves a transducer converting the movement into a representation that follows the motion with sufficient accuracy. This requires assumptions as to which parts of the motion cause the effect of interest. Measurements can be stored as tables of numbers, as waveforms on paper, as analogue recordings on magnetic tape, or in a digitised form for use by computers.

The 'evaluation' of vibration measurements with respect to human response requires knowledge of the relative importance of different qualities in the vibration exposure (e.g. frequencies, directions, and durations) so as to produce values that reflect the relative severity of different exposures. Similar to frequency weightings used in acoustics, it is common practice to 'weight' vibration according to the assumed effects different vibration frequencies, directions and durations. It is then possible to report a single 'weighted' value that represents the severity of the complex motion that was measured.

Vibration 'assessment' involves a consideration of the vibration and a judgement about it. Whereas evaluation results in a numerical value representative of the vibration severity, assessment predicts the outcome of a vibration exposure: the type, severity, or probability of a human response, or even the legal consequences. An assessment does not necessarily require measurement and evaluation of vibration: a particular type or source of vibration exposure could be labelled as unacceptable without knowledge of the vibration magnitudes.

The distinctions between 'measurement', 'evaluation', and 'assessment' are too often ignored. The ability to make an assessment without undertaking measurement and evaluation allows the possibility of judging acceptability and then merely resorting to convenient physical values to support the judgement. This happens with individual assessments and also in the process of standardisation, where the measurement and evaluation methods may be selected to reach the desired conclusion rather than being justified in their own right. The separate justification of the measurement method, the evaluation procedure, and the assessment criterion may encourage a more rigorous route to individual assessments and standards.

1.1 Approach to measuring, evaluating, and assessing building vibration

For each environment where vibration is experienced, a different approach might be taken to the measurement, the evaluation, and the assessment of vibration with respect to human response. Even when environments are similar (e.g. domestic houses and passenger cabins on ships), different approaches might be advocated – possibly stemming from pre-existing methods of measuring, evaluating, or assessing vibration with respect to other effects, such as the condition of machinery or structural responses, in those environments. The types of vibration in apparently similar environments often differ (e.g. the range of vibration frequencies) and so two methods considered appropriate in the two environments for which they have been developed may differ and be inappropriate when applied to the other environment. However, for the same response, there should be a method of measuring and evaluating vibration that is applicable in both environments.

It can be difficult or even impossible to assess the appropriateness of a means of predicting human responses to vibration solely from experience of its use in the environment for which it is intended. Human responses to vibration are highly variable (both within and between individuals) and it is not simple to conduct a useful field assessment of a means of predicting human responses to vibration. Claims that a method has been 'validated' are usually based on limited evidence of consistency with some observations or impressions in a specific situation and not evidence that the method is appropriate over the full range of conditions to which it can be applied. In contrast, it can be easy to show by laboratory experiment or demonstration that some of the assumptions in methods evolved from field studies over the years make inappropriate assumptions about human responses to vibration (e.g., inappropriate weightings for the effects of frequency, direction, or duration).

'Measurement methods' might differ between environments if, for example, vibration is measured on the floor in one environment but at the interfaces with the human body on seats in another environment. 'Evaluation methods' might differ between environments if the response of interest differs – the annoyance caused by building vibration might be dictated by whether it is above or below the absolute threshold for perception, whereas the annoyance caused by vibration on a ship might be dictated by whether it interferes with sleep. 'Assessment methods' will likely differ between environments based on the degree of undesirable effect (e.g. extent or probability of annoyance) that is considered acceptable, and this may be influenced by pragmatic considerations including the 'cost' of reducing the undesired effect.

Where vibration measurements are made at equivalent locations with respect to the person (e.g. at the point of contact with the body), and the response of interest is similar (e.g. the strength of perception of vibration), it should be possible to define an evaluation method that predicts the response of interest in a range of environments. The 'acceptable level' of vibration may then be adjusted taking into account other matters to provide a useful basis for assessing vibration in different environments.

The 'unification of methods of measuring, evaluating, and assessing human responses to vibration', based on knowledge of factors influencing human responses, has many advantages. These include the ability to use common equipment and develop a greater pool of understanding of human responses.

To illustrate the unification of procedures, this paper focuses on the measurement, evaluation, and assessment of the feeling of vibration in buildings. Building vibration can be detected by several senses – principally touch, vision, and hearing. This paper concerns situations in which the response is dictated by feeling vibration. The methods defined will not be appropriate when responses are influenced by hearing or seeing movement.

2 THE PRINCIPLES OF VIBRATION MEASUREMENT

Vibration measurement should produce the information required (e.g. acceleration signals) for the evaluation of the vibration with respect to a specific response.

The vibration magnitude, frequency, and direction can vary greatly with location in and around a building. The vibration outside a building will not provide useful indications of the vibration within a building unless the transmission from outside to inside is known. The transmission of vibration differs greatly in different buildings and is difficult to predict, so the transmission characteristics will need to be measured if outside measurements are to be used.

Where the vibration magnitude differs between rooms within a building, the acceptability of vibration will also differ between rooms. If it is desired to assess the vibration giving rise to the greatest problem, the vibration must be measured in the room with the greatest vibration severity.

The vibration felt by people in dwellings usually comes from the vibration of the floor. The vibration on walls, window sills, ceilings, etc. is therefore not normally relevant to the assessment of vibration that is felt, although it may affect the perception of vibration via hearing or vision.

The vibration may vary across a floor, and so the occupied location with the greatest severity of vibration will be the location to measure vibration. This may be near the centre of the floor. The vibration of the floor may be measured by attaching a suitable transducer to the floor. When using appropriate mounts, the carpet or other floor covering will usually have little influence unless the cover is loose or extremely thick.

When standing, the vibration on the floor will determine whether the vibration is felt, so it is reasonable to measure the vibration of the floor. Sitting on a chair or lying in a bed, the vibration can be greatly modified by the transmission of vibration through the seat or bed. Lower frequencies (usually less than 10 Hz) may be amplified by a seat or bed, while other frequencies may be attenuated. It is possible to measure at the interface between the body and the seat or bed using a SIT-pad (as used to measure vibration on car seats), but it will normally be appropriate and sufficient to measure the vibration of the floor (see below).

It is current practice to use instrumentation conforming to standards for the measurement and evaluation of vibration with respect to human responses (see ISO 8041, 2005). This is intended for vibration over the range 0.5 to 80 Hz and has high-pass filters at 0.4 Hz and low pass filters at 100 Hz. The vibration felt in buildings is usually at a frequency greater than 0.5 Hz and less than 80 Hz.

3 THE PRINCIPLES OF VIBRATION EVALUATION

Vibration evaluation should produce numerical values from which it can be predicted which of two or more vibrations are ‘greatest’ with respect to a specific human response.

The human response of interest in a building may be whether the vibration can be felt. In their dwelling, most people do not normally feel vibration coming from external sources, so some of those who feel vibration consider it excessive. Alternatively, the vibration may be tolerated when it is just perceptible but becomes intolerable as it becomes more intrusive at only slightly greater magnitudes. In consequence, the main interest in feeling vibration in buildings arises with vibration magnitudes at, and slightly above, absolute thresholds for perception. Human perception of these magnitudes can be predicted from experimentally determined thresholds and from equivalent comfort contours obtained with low magnitude vibration.

3.1 Frequency weightings for evaluating vertical vibration in buildings

The biodynamic responses of the human body and the characteristics of the tactile sensory systems result in people being more sensitive to some frequencies of vibration than others.

3.1.1 Thresholds

Examples of median absolute thresholds for the perception of vertical vibration by seated persons are illustrated in Figure 1a. At the level of the median threshold, vibration will be felt by some people (about half of the fit adult population) but not by others. A seated person may also be in contact with vibration at the feet or the hands, but thresholds at these locations are similar to, or greater than, those at the seat for frequencies less than about 100 Hz so, if the vibration magnitude is the same

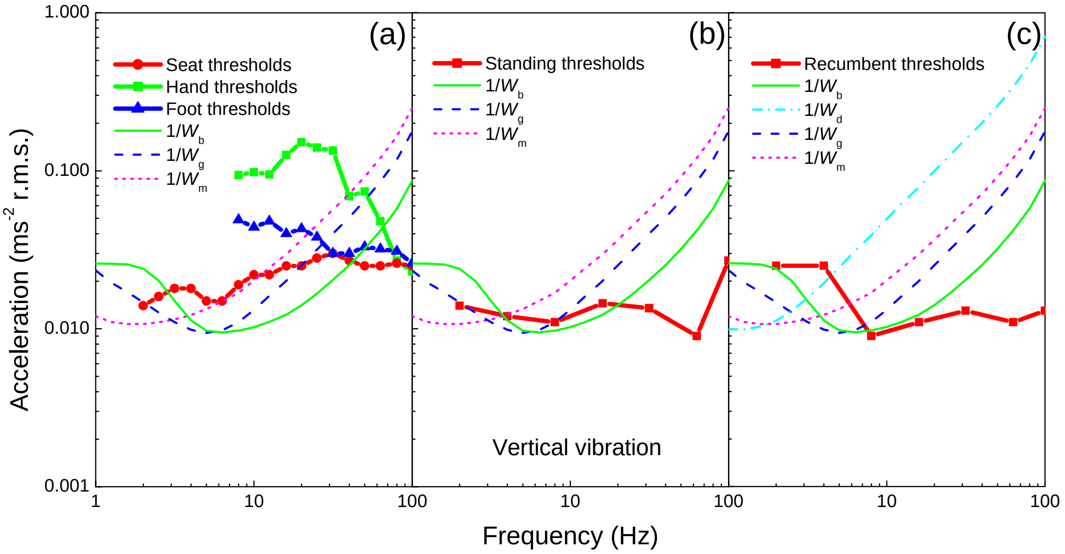

Figure 1 Absolute thresholds for the perception of vertical vibration when (a) seated on a rigid seat with no backrest and a stationary footrest (Morioka and Griffin, 2006), (b) standing (Parsons and Griffin, 1988), and (c) recumbent (Miwa *et al.*, 1984), compared with reciprocals of frequency weightings W_b, W_d, W_g and W_m defined in standards. Weightings drawn to have minima of 0.01 ms^{-2} r.m.s.

at all three locations, vertical vibration at the seat can be used to predict whether vibration will be felt.

Absolute thresholds for the perception of vertical vibration by standing persons are illustrated in Figure 1b. Thresholds for standing persons exposed to vertical vibration tend to be similar to, or slightly lower than, thresholds for seated persons.

Absolute thresholds for the perception of vertical vibration by supine recumbent persons are shown in Figure 1c and indicate a similar sensitivity to standing subjects, except with reduced sensitivity at the lowest frequencies.

3.1.2 Influence of seats and beds

It is common current practice to measure vibration on the floor of a building without any specific allowance for the amplification or attenuation provided by seats and beds.

Seats can attenuate the vertical vibration in buildings (which is often at frequencies greater than 10 Hz) but it may be inappropriate to allow for attenuation of such frequencies by seats because, as shown in Figure 1a, floor vibration can be felt in the feet of a seated person even if it is not felt through the seat. The greatest influence of seats may therefore be amplification of low frequencies, increasing the probability of perceiving vibration at these frequencies. The greatest influence of beds may also be amplification of low frequencies. The amplification will vary between seats and beds and cannot easily be taken into account when evaluating the vibration in a building.

The influence of seat dynamics and bed dynamics on the perception of vertical vibration can be greater than the difference in sensitivity between being seated, standing, or recumbent. This encourages the use of the same frequency weighting when evaluating vertical floor vibration, irrespective of whether the occupants of the room are seated, standing, or recumbent.

3.1.3 Frequency weightings and standards

Absolute thresholds for the perception of vibration (and equivalent comfort contours at greater magnitudes of vibration) are lowest where the body is most sensitive – where the greatest 'weight'

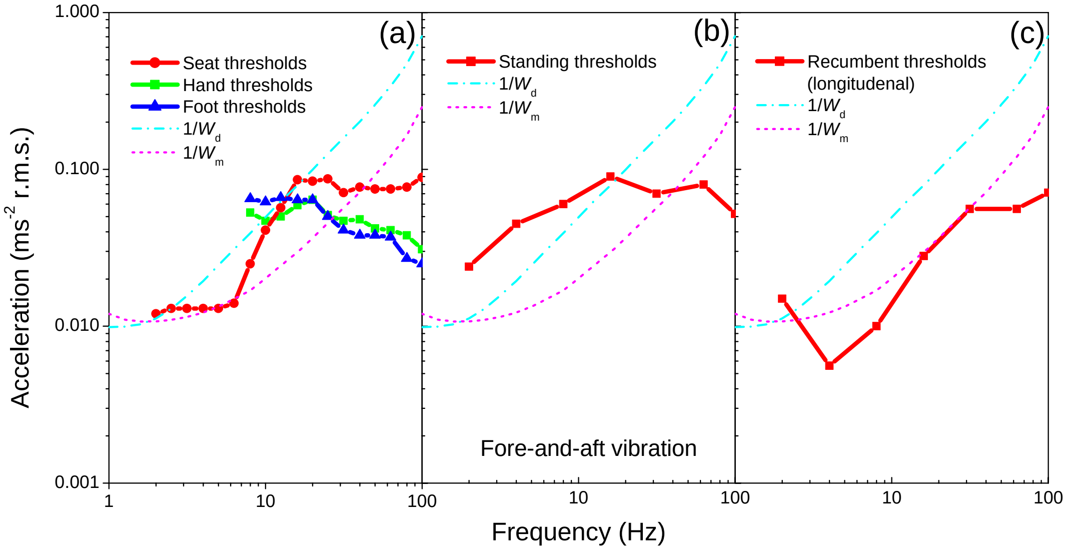

Figure 2 Absolute thresholds for the perception of fore-and-aft vibration when (a) seated on a rigid seat with no backrest and a stationary footrest (Morioka and Griffin, 2006), (b) standing (Parsons and Griffin, 1988), and (c) recumbent (Miwa *et al.*, 1984), compared with reciprocals of frequency weightings W_d and W_m defined in standards. Weightings drawn to have minima of 0.01 ms^{-2} r.m.s.

should be given when evaluating the vibration. Frequency weightings may therefore be based, precisely or approximately, on the inverse of either thresholds or equivalent comfort contours: the weighting is greatest where the lowest vibration magnitude causes perception or discomfort.

Old standards for the evaluation of vibration in buildings used a frequency weighting (now called weighting W_g) for vibration along the ‘long axis’ of the body – vertical when seated or standing but horizontal when recumbent. The weighting had no clear origin but was influenced by studies of very severe discomfort conducted at magnitudes sufficiently high to be a possible cause of injury (about a thousand times greater than the absolute threshold of perception). Equivalent comfort contours change their shape with increasing vibration magnitude (Morioka and Griffin, 2006) and so the frequency-dependence of human response in studies at high magnitudes provides a poor indication of the frequency-dependence at magnitudes close to the threshold of perception. Weighting W_g became known internationally from its inclusion in ISO 2631 in 1974 and subsequent reappearance in many other standards, including BS 6472 (1992) for the evaluation of human exposure to vibration in buildings.

A frequency weighting for human response is best obtained from knowledge of how the response of interest depends on the frequency of vibration at relevant vibration magnitudes. Figure 1a shows that perception thresholds for vertical vibration differ greatly from the shape of frequency-weighting W_g – most notably, the weighting underestimates sensitivity to high frequencies relative to low frequencies. Thresholds are also poorly reflected by the characteristics of weighting W_m, now advocated for the evaluation of fore-and-aft, lateral or vertical vibration in buildings in ISO 2631-2 (2003), see below. It has been suggested that reduced sensitivity to high frequency vibration in W_g allows for the vibration attenuation of seats and beds, but this ignores perception of vibration in standing people or at the feet of seated people.

No weighting can be precise for all situations or all magnitudes of interest. It can be argued that thresholds (for the perception of vertical vibration by seated, standing, and recumbent persons) are better approximated by the same acceleration at all frequencies (very approximately 0.01 or 0.02 ms^{-2} r.m.s. from 1 to 100 Hz) than by a weighting with an attenuation of 6 dB/octave that implies sensitivity depends on vibration velocity (as in W_g and W_m at frequencies greater than about 8 Hz). Of the alternative weightings defined in current standards, weightings W_j and W_b are closest to the

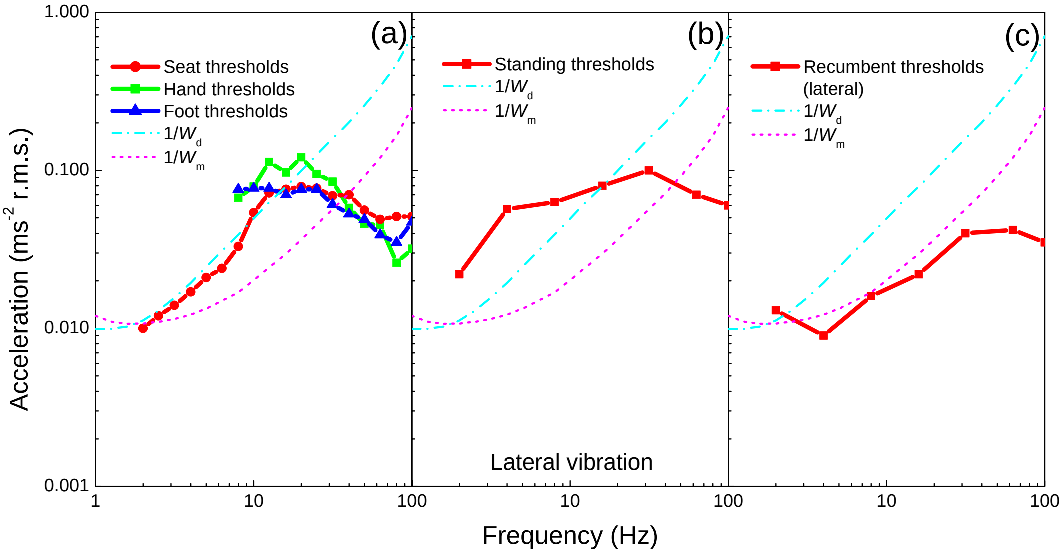

Figure 3 Absolute thresholds for the perception of lateral vibration when (a) seated on a rigid seat with no backrest and a stationary footrest (Morioka and Griffin, 2006), (b) standing (Parsons and Griffin, 1988), and (c) recumbent (Miwa *et al.*, 1984), compared with reciprocals of frequency weightings W_d and W_m defined in standards. Weightings drawn to have minima of 0.01 ms^{-2} r.m.s.

frequency-dependence of the perception of low magnitude vertical vibration. The little-used weighting W_j has a nominal unity gain from 5 to 80 Hz, whereas W_b has greatest sensitivity from about 4 to 16 Hz. The vibration in buildings is generally disturbing at levels in excess of the threshold, and sensitivity to high frequencies decreases relative to low frequencies as the magnitude increases. The weighting W_b, derived for predicting the discomfort of vertical vibration and widely used for evaluating ride comfort (see BS 6841; 1987), provides a reasonable general-purpose approximation to equivalent comfort contours and seems more appropriate for predicting subjective responses than either weighting W_g or weighting W_m (see also Figure 4 below).

3.2 Frequency weightings for evaluating non-vertical vibration in buildings

3.2.1 Thresholds

Absolute thresholds for the perception of fore-and-aft and lateral vibration of seated persons are illustrated in Figures 2a and 3a. Thresholds for the fore-and-aft and lateral vibration of standing persons are shown in Figures 2b and 3b. Thresholds for the horizontal vibration of recumbent persons are shown in Figure 2b (for *y*-axis, lateral, vibration) and Figure 3b (for *z*-axis, longitudinal vibration). There is little difference between thresholds in the two horizontal directions (assuming vibration is not perceived via the backrest of a seat). There are some differences between standing and seated persons, but this is mainly restricted to the range 2 to 16 Hz where standing persons have slightly higher thresholds for the perception of horizontal vibration.

3.2.2 Frequency weightings and standards

In current standards for evaluating whole-body vibration with respect to comfort and health, the frequency weighting for evaluating vibration in the fore-and-aft and lateral directions of the body when seated or standing is W_d. Compared with absolute thresholds for the perception of vibration by seated and standing people, if weighting W_d is approximately correct at lower frequencies, it underestimates sensitivity to high frequencies (at frequencies greater than about 20 Hz). The dominant horizontal vibration in buildings often occurs at the lower frequencies and so the underestimation of higher frequencies may not often be a concern.

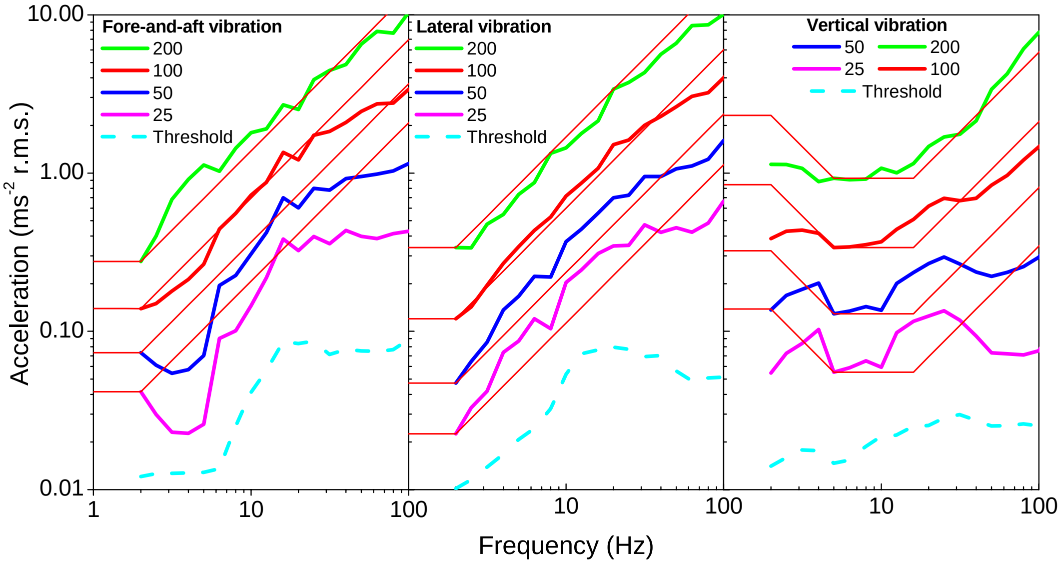

Figure 4 Equivalent comfort contours for vertical vibration when seated (adapted from Morioka and Griffin, 2006). The four experimentally determined contours correspond to magnitude estimates of 25, 50, 100, and 200, where a doubling corresponds to doubling discomfort. The frequency weightings are represented by the reciprocal of W_d for fore-and-aft and lateral vibration and the reciprocal of W_b for vertical vibration, drawn to coincide with the experimental contours at 2 and 5 Hz, respectively.

Figure 4 compares experimentally determined equivalent comfort contours with frequency weightings W_d and W_b. It can be seen that at some supra-threshold magnitudes the frequency weighting W_d is remarkably good at predicting the frequency-dependence of the discomfort of seated persons exposed to fore-aft and lateral vibration. Similarly, frequency weighting W_b is a better fit at supra-threshold magnitudes than at threshold.

With uncertainty whether the occupants of a building are sitting, standing, or recumbent, some felt it appropriate to combine the old weighting W_g (for vibration along the long axis of the body – the *z*-axis) and weighting W_d (for vibration along the other two axes – the *x*- and *y*-axes) to form a new weighting, with a weight at least as great as W_g and W_d at every frequency, resulting in a new weighting (originally called $WB_{combined}$ but now identified as W_m in ISO 2631-2; 2003). With differences as great as 4.0 between W_g and W_d, the combined weighting increased the importance of vibration in the *x*- and *y*-axes at frequencies greater than 2 Hz. There is no scientific justification for W_m, but in the politics of standardisation it allowed the demise of W_g while appearing to acknowledge the importance of W_g by its influence on the combined weighting. The outcome is a weighting that does not provide a better fit than W_d to thresholds and equivalent comfort contours for horizontal vibration of seated or standing persons at frequencies less than about 20 Hz where horizontal vibration is often dominant (see Figures 2 and 3). Weighting W_m is also a poorer fit to thresholds for vertical vibration than weighting W_b (see Figure 1). A small consolation is that W_m fits thresholds for the horizontal vibration of recumbent persons and should allow the prediction of the perception of horizontal vibration by people lying on the floor, although probably not those lying in a bed.

In ISO 2631 (1974) for the general evaluation of whole-body vibration, frequency weightings were associated with the axes of the body. So, for example, the W_g weighting was applied to vibration along the long axis of the body – vertical when seated or standing but horizontal when recumbent. The thresholds for recumbent persons show that this is inappropriate for predicting the perception of vibration. A better prediction can be obtained by using the same weighting (such as W_b) for vertical vibration irrespective of whether it is perceived when sitting, standing, or recumbent (see Figure 1c).

Similarly, it seems reasonable to use the same weighting, such as W_d, for horizontal vibration irrespective of the orientation of the body.

3.3 Weighting for duration

Traditionally, the r.m.s. value of time-varying quantities has been determined. So, for evaluating the frequency-weighted acceleration, $a_w(t)$, some vibration meters have incorporated:

$$\text{root-mean-square (r.m.s.)} = \left[\frac{1}{T} \int_{t=0}^{t=T} a_w^{\,2}(t)\, \mathrm{d}t \right]^{\frac{1}{2}}$$

If a vibration is steady-state (continuous with no shocks), the r.m.s. value may provide a useful indication of the average severity of the vibration. However, building vibration is often not steady-state and human reaction to building vibration depends on the duration over which vibration is felt (e.g. Howarth and Griffin, 1988).

Absolute thresholds for the perception of vibration decrease slightly with increasing duration, but only up to a few seconds, with longer exposures having similar thresholds (Parsons and Griffin, 1988). In contrast, it is intuitive that a vibration is more likely to cause annoyance the longer it lasts, so the acceptability of supra-threshold vibration is assumed to be dependent on the total duration. For that purpose, the relation between acceleration and time in r.m.s. averaging (i.e. a^2t) is not reasonable – if 0.01 ms^{-2} r.m.s. (about the absolute threshold) were considered a reasonable exposure for 24 hrs, the a^2t relationship implies that 0.38 ms^{-2} r.m.s. would be acceptable for 1 minute and 2.94 ms^{-2} r.m.s. would be acceptable for 1 second (see Figure 5). When using the a^2t (i.e. r.m.s.) time-dependency, the vibration magnitudes for short durations are not reasonably consistent with experiencing threshold vibration for 24 hours. They are also inconsistent with the current guidance for human response to building vibration as in BS 6472 (1992) (see below). A magnitude of 0.38 ms^{-2} r.m.s. is similar to that often experienced in public transport, and a magnitude of 2.94 ms^{-2} r.m.s. is unrealistic for any habitable building.

Experimental studies have found that when subjects are asked to state their preferences for motions of varying magnitude and duration, a doubling of vibration magnitude requires, very approximately, a sixteen-fold reduction in duration to maintain equivalence (Griffin and Whitham, 1980a, b). This led to fourth-power relationships between the acceleration magnitude and the duration. The root-mean-quad is identical to the r.m.s. except the square and square-root are replaced by a fourth power and a fourth root:

$$\text{root-mean-quad (r.m.q.)} = \left[\frac{1}{T} \int_{t=0}^{t=T} a_w^{\,4}(t)\, \mathrm{d}t \right]^{\frac{1}{4}}$$

The r.m.q. gives greater relative weight to occasional higher vibration magnitudes than the r.m.s., and seems to more appropriately reflect the greater sensitivity to shocks and other motions having occasional peaks (e.g., Griffin, 1990; Howarth and Griffin, 1991; Ahn and Griffin, 2007). In contrast, the r.m.s. value of a time-varying motion with occasional peaks can suggest that an annoying vibration is imperceptible.

Both r.m.s. and r.m.q. values are averages – they do not increase with increases in the duration of steady-state signals and they tend to decrease with increasing measurement duration if the signal is non-stationary. Building vibration tends to be more unacceptable the longer it lasts. Building vibration is often not statistically stationary (e.g. when vibration is caused by a passing vehicle) and it is difficult to define the moment to start and end the r.m.s. or r.m.q. evaluation of events that vary

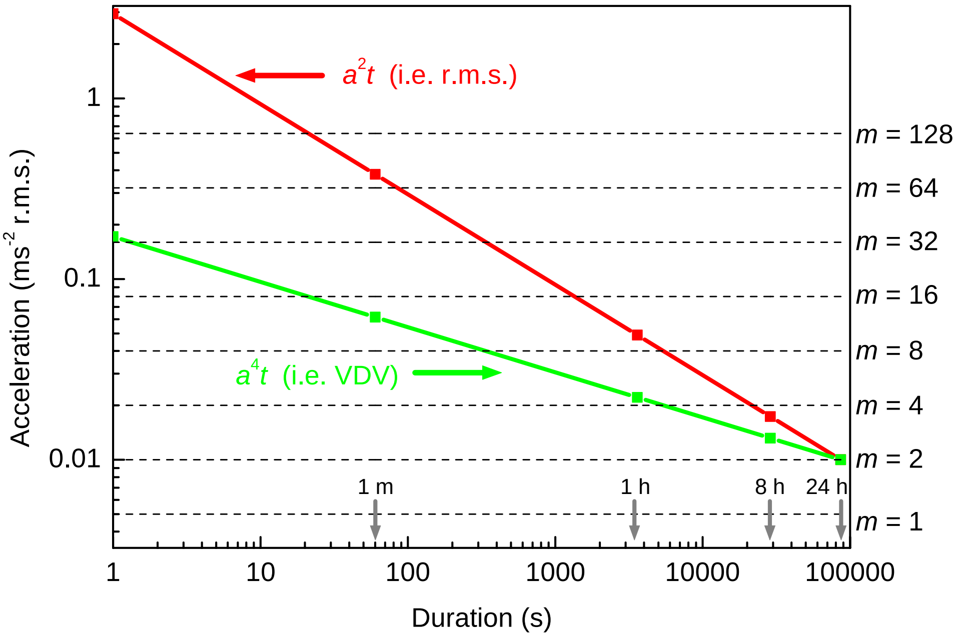

Figure 5 Time-dependencies corresponding to a^2t (r.m.s. averaging) and a^4t (r.m.q. averaging, VDV and eVDV) compared with the multiplying factors, *m*, from 1 to 128 as suggested in BS 6472 (1992) (see Table 1).

in magnitude and duration. These problems can be overcome by the use of a measure that accumulates, rather than averages, the measured vibration.

The fourth-power relationship is therefore mostly used as a dose (as in the vibration dose value, VDV) that increases with duration, rather than as an average (as in the r.m.q.). The vibration dose value comes from the r.m.q. without dividing by the exposure duration:

$$\text{vibration dose value (VDV)} = \left[\int_{t=0}^{t=T} a_w^{\,4}(t)\,dt \right]^{\frac{1}{4}}$$

where $a_w(t)$ is the frequency-weighted acceleration and T is the period during which a person is exposed to vibration.

The VDV can be used to quantify vibration events of any type. It is robust and not sensitive to variations in the time of starting or ending the period of measurement. It is sensitive to peaks in the vibration, because people are sensitive to peaks, so it is susceptible to instrumentation faults that lead to false peaks.

Vibration dose values obtained from different events (e.g. the passage of different vehicles past a building) can be compared to predict the main contributor to human response. Vibration dose values can be added (from the fourth root of the sum of the fourth powers of the VDVs) to obtain an overall value from a series of events. It is only necessary to measure one of each type of event and count the number of events to be able to calculate to total VDV for a day.

The vibration dose value can be estimated from the r.m.s. value and the exposure duration if the vibration is statistically stationary. For exposure duration, t (in seconds), and frequency-weighted r.m.s. acceleration, a_{rms} (in ms^{-2} r.m.s.) the 'estimated vibration dose value' is given by:

$$\text{estimated vibration dose value (eVDV)} = 1.4\ a_{rms}\ t^{1/4}$$

The eVDV is a simple way of showing the fourth-power time-dependency in terms of r.m.s. acceleration. If a vibration magnitude of 0.01 ms^{-2} r.m.s. (about the absolute threshold) is considered an acceptable exposure for 24 hrs, the a^4t relationship implies that 0.06 ms^{-2} r.m.s. would be acceptable for 1 minute and 0.17 ms^{-2} r.m.s. would be acceptable for 1 second (Figure 5). These magnitudes seem more consistent with a threshold level of exposure for 24 hours than those obtained using the a^2t time-dependency in r.m.s. averaging (see Figure 5). However, whereas a vibration magnitude of 0.01 ms^{-2} r.m.s. is about the absolute threshold for vibration perception, a VDV based on this magnitude for 24 hrs will correspond to a vibration that is increasingly perceptible as the exposure duration reduces.

The eVDV is not applicable to transients, shocks, and repeated shock motions. For these motions, the true vibration dose value is required.

The vibration dose value is rugged, easy to use, and seems more appropriate than overall r.m.s. values (that may rise or fall with increasing duration) or a 1-s peak r.m.s. value (which is uninfluenced by vibration other than during the worst 1-s period). The fourth-power time-dependency seems to be useful over short durations (including single events such as shocks and transients including vehicle-induced building vibration) and also reasonable over periods as long as a full day. However, the vibration dose value (both the VDV and the eVDV) is best seen as a pragmatic solution to a complex problem rather than a reflection of an underlying mechanism in human perception of vibration.

3.4 Complex motions

The perception of vibration is more complex than suggested by the vibration dose value and simple frequency-weighted measures of r.m.s. acceleration. These measures sum and average vibration over frequencies and durations in conveniently simple ways. They make assumptions as to how multiple-frequency, random, transient and multi-axis vibrations are perceived. Although the simple assumptions may often be sufficient, the perception of vibration is actually more interesting and more complex, with masking and other phenomena. The simple methods are based on some understanding of vibration perception but they do not precisely reflect current understanding – and it is clear that understanding is not yet complete.

3.5 Practical methods of evaluation

A simple practical means of evaluating the vibration in buildings is required today. There are several possibilities, but it seems reasonable to suggest the use of frequency weighting W_b to evaluate vertical floor vibration and frequency weighting W_d to evaluate horizontal floor vibration. The vibration dose value seems practical and helpful when quantifying transients and the vibration dose value (or estimated vibration dose value) gives a convenient and reasonable trade-off to allow for variations in the durations of events from single shocks to continuous exposures. Evaluations in the form of frequency-weighted vibration dose values may provide a useful pragmatic basis for assessing the acceptability of building vibration.

There is no ‘right method’ of evaluating vibration to predict the feeling of vibration by the occupants of buildings. The use of more than two frequency weightings (e.g., more than W_d and W_b) and more understanding of the time-dependency of human responses to vibration may allow greater precision, but with large variability within and between people, and uncertainties associated with the measurement of vibration, high precision cannot be expected.

4 THE PRINCIPLES OF VIBRATION ASSESSMENT

Assessment requires decisions on the type, severity, and probability of the human response of interest. The 'assessment' of vibration in a building may involve a judgement on what responses are acceptable and what responses are unacceptable.

A judgement might be possible solely from the measurement and evaluation of vibration and knowledge of what vibration is perceptible. Other judgements require information that varies according to the situation, including other aspects of the environment, information about the people exposed to vibration, and the consequences of requiring reductions in vibration. So, whereas the perceptibility of vibration can be predicted, the acceptability of vibration depends on factors other than the vibration (see Figure 6).

Where the measurement and evaluation method are based on knowledge of absolute thresholds for vibration perception, it seems reasonable to standardise a scale for assessment based on perception. However, the level on the perception scale above which the vibration is to be considered 'unacceptable' may depend on information specific to the environment being assessed, including local factors.

In BS 6472 (1992), "*satisfactory magnitudes of building vibration with respect to human response*" are given by multiplying factors (see Table 1). For continuous vibration, the multiplying factors vary from 1 to 8, corresponding to frequency-weighted acceleration magnitudes from 0.005 to 0.04 ms^{-2} r.m.s. for vertical vibration (using weighting W_g) and from 0.0036 to 0.0286 ms^{-2} r.m.s. for horizontal vibration (using weighting W_d). Doubling these vibration magnitudes is said to result in "*adverse comment*" that may "*increase significantly*" if the magnitudes are quadrupled. As seen from the thresholds in Figures 1, 2 and 3, the weighting W_g is not a good representation of the frequency-dependence of thresholds for vertical vibration, and vibration corresponding to a multiplying factor of 1 is below the absolute threshold in the range where weighting W_g has greatest sensitivity. The use of weighting W_b with a baseline of 0.01 ms^{-2} r.m.s. seems more consistent with the absolute thresholds for the perception of vertical vibration. Similarly, the use of weighting W_d with a baseline of 0.01 ms^{-2} r.m.s. seems roughly consistent with absolute thresholds for the perception of horizontal vibration.

Irrespective of whether seated, standing, or recumbent, a frequency-weighted acceleration of 0.01 ms^{-2} r.m.s. corresponds, very approximately, to the perception threshold (assuming use of weighting W_b for vertical vibration and weighting W_d for horizontal vibration). In BS 6472 (1992), the lowest multiplying factor for continuous vibration in residential properties during the day is 2, corresponding to 0.01 ms^{-2} r.m.s. at the frequencies of greatest sensitivity. If this is assumed to apply to the 16-hour period from 07.00 hrs to 23.00 hrs, the corresponding eVDV is approximately 0.2 $ms^{-1.75}$. This eVDV (or VDV) can then be used to judge vibrations occurring during a 16-hour period irrespective of whether they arise from continuous or intermittent vibration, a series of shocks, a single shock, or some combination of these events. The guidance for residential properties can then be expressed in terms of vibration dose values: 0.2 to 0.4 ("*low probability of adverse comments*"), 0.4 ("*adverse comments possible*"), and 0.8 ("*adverse comments probable*"), as shown in Figure 7. Half these magnitudes are given for 'critical working areas', double the values are given for 'offices', and four times the values are given for 'workshops'. Other values will be considered appropriate in some situations.

5 DISCUSSION

This paper has summarised background information that may assist the evolution and interpretation of standards for the measurement, evaluation, and perception of vibration in buildings where this is based on absolute thresholds for the perception of vibration. Further research could usefully define the thresholds more precisely and, especially, quantify variations in the probability of perceiving vibration as the vibration magnitude varies.

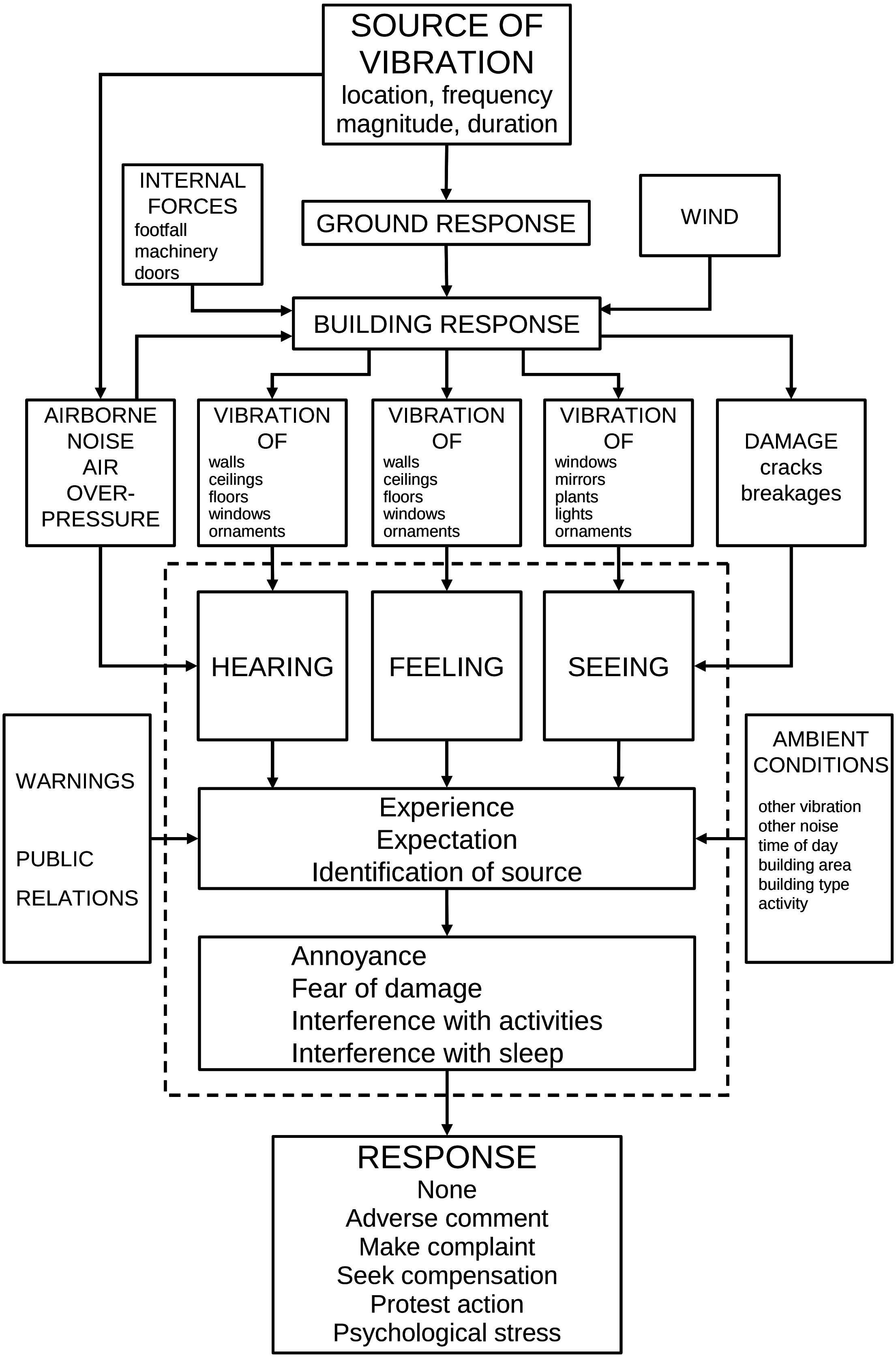

Figure 6 Factors affecting the acceptability of building vibration (from Griffin, 1990).

Table 1 Multiplying factors, *m*, used to specify 'satisfactory magnitudes' of building vibration with respect to human response in BS 6472 (1992) (see Figures 5 and 7).

<table>
<tr><th rowspan="2">Place</th><th rowspan="2">Time</th><th colspan="2">Multiplying factors, m</th></tr>
<tr><th>Exposure to continuous vibration* (16-h day, 8-h night)</th><th>Impulsive vibration excitation with up to 3 occurrences</th></tr>
<tr><td rowspan="2">Critical working areas (e.g. hospital operating theatres, precision laboratories</td><td>Day</td><td>1</td><td>1</td></tr>
<tr><td>Night</td><td>1</td><td>1</td></tr>
<tr><td rowspan="2">Residential</td><td>Day</td><td>2 to 4</td><td>60 to 90</td></tr>
<tr><td>Night</td><td>1.4</td><td>20</td></tr>
<tr><td rowspan="2">Office</td><td>Day</td><td>4</td><td>128</td></tr>
<tr><td>Night</td><td>4</td><td>128</td></tr>
<tr><td rowspan="2">Workshops</td><td>Day</td><td>8</td><td>128</td></tr>
<tr><td>Night</td><td>8</td><td>128</td></tr>
<tr><td colspan="4">* Doubling of the suggested vibration magnitudes may result in 'adverse comment' and this may increase significantly if the magnitudes are quadrupled</td></tr>
</table>

Standards are often promulgated without information on the basis on which they have been prepared. This is not helpful or responsible – it presents the user of a standard with difficulty in knowing whether the guidance offered is appropriate to their application. It unfairly places responsibility on the user to disprove the unproven standard. In some cases the absence of evidence conceals absence of understanding among the writers of standards – understanding that may not be absent from the user of the standard. In other cases, the user may wrongly assume their knowledge to be greater than that of those involved in preparing the standard. It is to be hoped that standards in this area will, like scientific publications, include the basis on which guidance and claims are made.

Standards are sometimes questioned because they require a change, rather than because they are known to be wrong. In such circumstances, declaring the reasons for change is helpful. Standards for building vibration can also be questioned when a change to the measurement or evaluation method inconveniently alters judgements of acceptability. However, disagreement with any proposed 'assessment' should not be confused with doubts about the method of 'measuring' or 'evaluating' vibration. There will always be some disagreement with guideline 'assessments' of building vibration because, for the same vibration exposure, different assessments will be appropriate for different environments.

There are large variations within and between people in their perception of vibration and their judgement of the acceptability of vibration in an environment. It should not be expected that all persons will begin to feel vibration at the same magnitude, or that when all people feel vibration they will form similar judgements on whether it is acceptable. Even when they decide that vibration is not pleasant, different people form different decisions on whether they will take any action. The most vociferous complainer may, or may not, be the most sensitive person or the most disturbed person. A scale of the strength perception should be helpful when considering whether individual responses reflect a widespread problem or a heightened sensitivity in an individual.

The principles of the evaluation method outlined above have traceable origins and a clear scope. It is therefore clear what it should be capable of predicting and also clear what it cannot predict. It should give a useful indication of whether vibration is perceptible and, if so, how much it is in excess of the threshold of perception. If annoyance or acceptability is dictated by feeling vibration it should give useful predictions. It will not predict responses influenced in any way by hearing or seeing vibration (e.g. Howarth and Griffin, 1990a, b, 1991). The evaluation method is not sufficient to

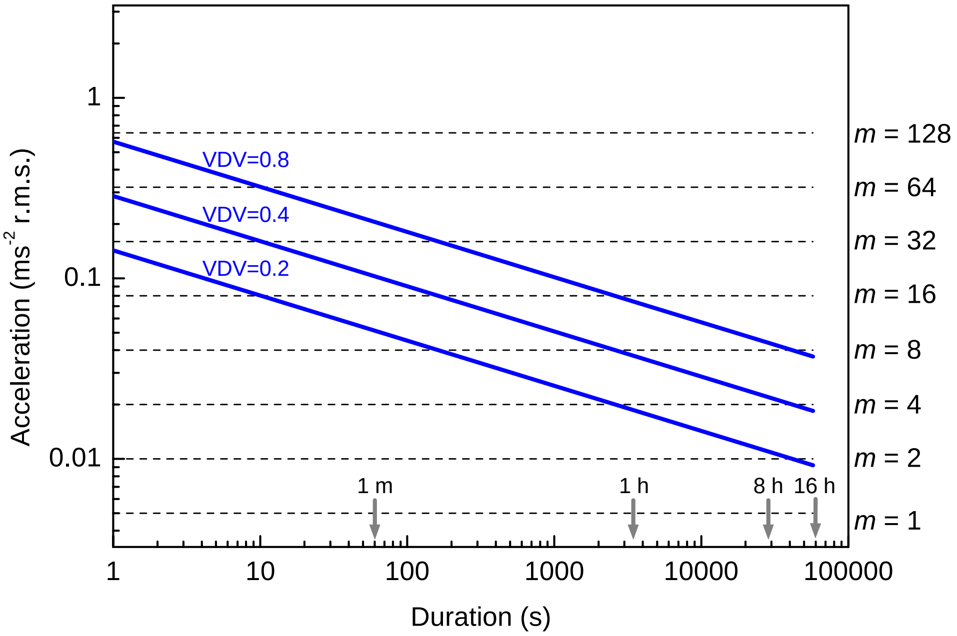

Figure 7 Time-dependencies corresponding to a VDV of 0.2 ("*low probability of adverse comments*"), a VDV of 0.4 ("*adverse comments possible*"), and a VDV of 0.8 ("*adverse comments probable*") compared with the multiplying factors, *m*, from 1 to 128, as suggested in BS 6472 (1992) (see Table 1).

predict whether vibration is acceptable but, together with other information, can be used to predict the relative acceptability of alternatives where acceptability is determined by the strength of feeling of vibration.

The method outlined here is defined within existing standards (e.g., BS 6841, 1987 and ISO 2631-1, 1997), and instrumentation is available to undertake the measurement and evaluation of the vibration (see ISO 8041, 2005). There may be reasons for developing additional methods for the measurement and evaluation of building vibration where the method outlined for predicting the strength of perception is not sufficient (e.g. where vibration is heard or seen). The need for such methods will become clearer as a method based on the strength of perception is applied uniformly. Similarly, situations in which it is appropriate to adjust the scale for judging the acceptability of vibration will become apparent as more experience is gained.

Irrespective of the merits, changes to standards can be difficult to accept when they alter the numerical value of the assessed vibration, or the judgement of acceptability. For vertical vibration, a change to the frequency weighting from, say, W_g to W_b, increases vibration severity by a factor of 2 at frequencies greater than 16 Hz. For non-vertical vertical vibration, even if the frequency-weighting is retained as W_d, the multiplying factor of 1.4 previously increased sensitivity to vibration in these directions and its removal will reduce the vibration severity of horizontal vibration by a factor of 1.4. The consequence of both changes is that vertical vibration is more likely to be judged the dominant vibration in buildings and it will be given a higher evaluation than previously. The changes may give better predictions of whether vibration will be perceived and better predictions of the strength of perception when it is felt. However, people do not overnight change their feelings when weightings are changed, so assessment methods must take such changes into account.

The method of assessing building vibration is more fickle than the method of measuring and evaluating building vibration. While a basis for measuring and evaluating vibration may be agreed, the assessment of building vibration requires sensitive consideration for each environment.

6 CONCLUSION

From suitable measurements it is possible to predict whether people will feel vibration when seated, standing or recumbent. For practical convenience, methods of evaluating vibration use simple weightings that approximately reflect human sensitivity to different frequencies, directions, and durations of vibration. The assessment of vibration so as to decide whether it is acceptable to the occupants of a building may be informed by suitable measurements and evaluations, but the criteria for deciding on the acceptability of building vibration will vary from situation to situation.

7 REFERENCES

1. Ahn,S-J and Griffin,M.J. (2007) Effects of frequency, magnitude, damping, and direction on the discomfort of vertical whole-body mechanical shocks. (Awaiting publication).
2. British Standards Institution (1987). Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. British Standard, BS 6841.
3. British Standards Institution (1992). Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz). British Standard, BS 6472.
4. Griffin,M.J. (1990). Handbook of human vibration. Published: Academic Press, London, ISBN: 0-12-303040-4.
5. Griffin,M.J., Whitham,E.M. (1980). Time dependency of whole-body vibration discomfort. The Journal of the Acoustical Society of America, 68, (5), 1522-1523.
6. Griffin,M.J., Whitham,E.M., (1980). Discomfort produced by impulsive whole-body vibration. The Journal of the Acoustical Society of America, 68, (5), 1277-1284.
7. Howarth,H.V.C., Griffin,M.J. (1988). Human response to simulated intermittent railway-induced building vibration. Journal of Sound and Vibration, 120, (2), 413-420.
8. Howarth,H.V.C., Griffin,M.J. (1990). Subjective response to combined noise and vibration: summation and interaction effects. Journal of Sound and Vibration, 143, (3), 443-454.
9. Howarth,H.V.C., Griffin,M.J. (1990). The relative importance of noise and vibration from railways. Applied Ergonomics, 21, (2), 129-134.
10. Howarth,H.V.C., Griffin,M.J. (1991). Subjective reaction to vertical mechanical shocks of various waveforms. Journal of Sound and Vibration, 147, (3), 395-408.
11. Howarth,H.V.C., Griffin,M.J. (1991). The annoyance caused by simultaneous noise and vibration from railways. The Journal of the Acoustical Society of America, 89, (5), 2317-2323.
12. International Organization for Standardization (1974). Guide for the evaluation of human exposure to whole-body vibration. International Standard, ISO 2631 (E).
13. International Organization for Standardization (1997). Mechanical vibration and shock - evaluation of human exposure - to whole-body vibration. Part 1: general requirements. International Standard, ISO 2631-1, Second edition 1997-05-01, Corrected and reprinted 1997-07-15.
14. International Organization for Standardization (2003). Mechanical vibration and shock - evaluation of human exposure to whole-body vibration - Part 2: Vibration in buildings (1Hz to 80 Hz).
15. International Organization for Standardization (2005). Human response to vibration - measuring instrumentation. International Standard, ISO 8041.
16. Miwa,T., Yonekawa,Y., Kanada,K. (1984). Thresholds of perception of vibration in recumbent men. The Journal of the Acoustical Society of America, 75, (3), 849-854.
17. Morioka,M., Griffin,M.J. (2006) 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.
18. Parsons,K.C., Griffin,M.J. (1988). Whole-body vibration perception thresholds. Journal of Sound and Vibration, 121, (2), 237-258.