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Examination of the Frequency-weighting Curve for Accelerations Measured on the Seat and at the Surface Supporting the Feet during Horizontal Whole-body Vibrations in x- and y-Directions

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Abstract: In a laboratory experiment, six male subjects were exposed to sinusoidal (0.8, 1.6, 3.15, 6.3 and 12.5 Hz) or random octave band-width white noise (mid-frequencies identical to those of the sinusoidal vibrations) whole-body vibration in x- or y-directions, at six levels of magnitude (0.4, 0.8 and 1.6 m/s^2 r.m.s. non- and frequency-weighted) with two repetitions. In order to examine time effects, additional reference stimuli were used. Each subject was exposed to these 304 exposure conditions with a duration of about one minute on four different days (76 exposures per day). The subject's sensations of vibration intensity and vibration comfort were obtained by cross modality matching (length of a line). The subjects sat with an upright posture on a hard seat without backrest, hands on the thighs. The derived equivalent sensation contours suggest an underestimation of the sensation varying in extent from 2 dB to 8 dB at 1.6, 3.15, 6.3 and 12.5 Hz in comparison with the reference frequency 0.8 Hz for both types and directions of signals by the current evaluation methods according to ISO 2631-1 with the most pronounced effects revealed at the frequencies 3.15 and 6.3 Hz and at lower intensities (overall vibration total value a_{ov} around 0.48 m/s^2 to 0.8 m/s^2 at the reference frequency 0.8 Hz).

Key words: Whole-body vibrations, Laboratory experiment, Frequency weighting, Subjective judgement

Introduction

The recently published report of the European Agency for Safety and Health at Work discovered a need for joint scientific efforts to clarify the prerequisite for an adequate risk assessment in the case of whole-body vibration (WBV). The implementation of the EC-directive 2002/44/EC[1)] intensified the discussion of the correctness of frequency-weighting curves and limit values for WBV. The evaluation methods concerning health risks, comfort and performance due to WBV, described in ISO 2631-1[2)] and used in application of the EU directive, are currently under critical discussion[3)].

ISO 2631 was first published in 1974 and later republished with new editorials and few corrections. An editorial combination of ISO 2631 (1978) and ISO 2631 AM 1 (1982b) resulted in ISO 2631-1 (1985). The version ISO 2631-1 (1997) replaced the earlier edition from 1985. The current frequency weightings in ISO 2631-1 (1997) were derived from meta-analyses of laboratory studies from the seventies of the last century. Frequency weightings obtained from equivalent discomfort contours are used for estimating the health risk as well, assuming an increase of risk with increasing vibration discomfort and pain, although this hypothesis has not been validated. However, the method is well established in practice. With an absence of information to the contrary, there seems to be no alternative method for health risk assessment.

Numerous experimental studies dealt with the effect of the frequency on discomfort caused by whole-body vibration[4–10)]. Inconsistencies in the obtained equivalent comfort contours might partially be explained by the dissimilar experimental methods (method of judging, sitting posture, seat, point of excitation etc.), but some divergences may have arisen from the different magnitudes of vibration that have been investigated.

Even in very early studies, significant major effects of acceleration and frequency and their interactions on discomfort or comfort ratings were obtained (Dempsey[11)], Oborne[12)]). These studies were limited to sinusoidal vertical vibration. Further investigations additionally included horizontal and roll, pitch and yaw vibrations. Parsons[13)] did not discover differences in levels described as "uncomfortable" between vibrations in the fore-and-aft and lateral axes. However, levels in these axes were found to be different from those obtained in the z-axis. In contrast to ISO 2631-1, mean discomfort caused by vertical acceleration showed only a small effect of frequency. Griffin[7)] concluded that the shapes of equivalent comfort contours need not normally depend on vibration level,

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possibly influenced by the choice of reference signal for magnitude estimation.

Griefahn and Bröde[6] used an intensity matching method. Applying the weighting of ISO 2631-1 they reported an underestimation of discomfort caused by sinusoidal horizontal WBV in y-direction in comparison with z-axis WBV for frequencies above 1.6 Hz. Maeda and Mansfield[8] reported a divergence of predicted and measured subjective ratings when ISO 2631-1 frequency weighting was used. Morioka[14] obtained significant interactions between vibration magnitude (0.02 to 1.25 m/s^2), frequency (2-315 Hz) and axis (x-, y- and z-axis) and concluded that probably no single linear frequency weighting can provide accurate predictions of discomfort caused by a wide range of magnitudes.

In different studies, various terms were used for judging the sensation caused by vibration. Griffin[15], Wyllie[16], Morioka[14] and Jang[17] asked the subjects to judge the "vibration discomfort". In ISO 2631-1, 1991, the phrase "effect of vibration on the comfort" is used. Jönsson[18] requested the subjects to rate the vibration on a scale from "uncomfortable" to "comfortable". In Europe, the use of these terms is linked with linguistic and semantic difficulties. For example, the word "discomfort" does not exist in German. The authors of the present study decided to ask for judgements of "vibration comfort" and additionally for the "vibration intensity" assuming that this phrase is less uncertain at least for German speaking subjects. Presumably, because of the same reasons, Griefahn[6] determined the "equal comfort contours" by asking the German speaking subjects to alter a vibration signal until they judged it to be equal in "magnitude" to a reference signal.

The theory of cross-modality matching used in the present study is based on investigations carried out by Stevens[19]. The authors found, that the association between the magnitude of the physical stimulus Φ and the sensation Ψ can be described by a power function.

(1) $\Psi = \Phi^m$

The power function can be logarithmised in order to get a linear association between lg Ψ and lg Φ:

(2) $\lg\Psi = m \times \lg\Phi$

The factor m is the so called "Stevens' exponent". Stevens determined these exponents for different types of stimuli. The subjects were asked to assign a number to a stimulus representing its sensation. This judging method is called "magnitude estimation". As a result of these experiments, the exponent can be assumed to be only dependent on the type of stimulus and nearly constant, provided the task is identical for all subjects and conditions when external influences on the judgements are absent or constant.

In contrast, cross-modality matching is based on the subjects' ability to judge their sensation according to the sensation caused by another stimulus. For example, the subjects could be requested to adjust the length of a line (response modality) according to a sensation caused by a simultaneous vibration (stimulus). This equilibrium of stimuli (exposed stimulus and scalable stimulus adjustable by the subject e.g. the brightness of an area, length of a line, force of a hand grip) can be influenced by other conditions (additional stimuli).

This procedure can be mathematically described as follows:

(3) $\Psi_1 = \Phi_1^{m1}$
power function of the stimulus which has to be judged (e.g. vibration)

(4) $\Psi_2 = \Phi_2^{m2}$
power function of the response modality (e.g. length of a line)

Provided that the sensation concerning stimulus and response modality are equalised with respect to the question which has to be answered (e.g. intensity or discomfort or annoyance):

(5) $\Psi_1 = \Psi_2$, therefore follows

(6) $\Phi_1^{m1} = \Phi_2^{m2}$

Logarithmised in order to get linear associations:

(7) $m_1 \times \lg \Phi_1 = m_2 \times \lg \Phi_2$ and finally

(8) $\lg \Phi_2 = m_1 / m_2 \times \lg \Phi_1$

In the present study, the vibration stimuli were judged by adjusting the length of a line presented on a screen simultaneously with the vibrations, in accordance with the sensations. The Stevens' exponent is m_2=1 for a length of a line[19]. Therefore, the determined exponents could be directly compared with those obtained by magnitude estimation in previous studies[9, 14, 20].

Exposure to whole-body vibration shall be assessed on the basis of frequency-weighted accelerations and multiplying factors in accordance with ISO 2631-1. For the evaluation of the effect of vibration on comfort, the weighted root mean square acceleration shall be determined for each axis of translational vibration at the surface which supports the person. For seated persons and horizontal seat surface vibration, the frequency weighting W_d should be applied with the multiplying factor k=1. The point vibration total value a_v shall than be calculated by a root-sum-of-squares summation. Alternatively, where the comfort is affected by vibrations at more than one point an overall vibration total value a_{ov} can be determined from the root-sum-of-squares of the point vibration total values. In this case, vibration at the feet is recommended to be assessed using the frequency weighting W_k and the multiplying factor k=0.25.

The study aimed to examine the effects of sinusoidal and random whole-body vibration in x- and y-axis on the perceived intensity and comfort. The equivalent intensity and comfort contours predicted on the basis of the overall vibration total value a_{ov} at different vibration magnitudes were compared to the current evaluation methods according to ISO 2631-1.

Subjects and Methods

Subjects and posture

In a laboratory experiment, six male subjects were exposed to whole-body vibrations of different magnitudes, frequencies and types of vibration signal. In order to determine the optimal sample size, information about the variance of the dependent variables is necessary. The authors have already performed similar investigations using cross-modality matching for the subjective judgements, but the vibration signals and seats were not comparable with those in the current study. However, the authors understood from their previous experience[21, 26]) that six subjects should be sufficient for discovering significant differences in the mean values of intensity or comfort judgements due to different vibration magnitude levels. There were no available data obtained by the authors concerning the effects of different frequencies, directions and types of vibration signals, using the same method in previous studies. Data analyses of the present study discovered that the number of subjects was sufficient for observing the expected differences due to vibration magnitude and frequency, but the current paper does not focus on this topic. A publication on this issue is in preparation.

The subjects were selected from a then available 36-person subgroup of a larger dataset consisting of 100 subjects with fixed subject numbers (the numbers did not change after the selection). Therefore, a subject with number 37 appears in Fig. 1. In order to guarantee the subjects' suitability and to equalize the physical prerequisites, the results of medical and anthropometric examinations including a list of contraindications were used. The ages varied from 24 to 46 yr (mean value 31 yr), the heights from 177.7 cm to 188.5 cm (mean value 183.9 cm), the body masses from 72 kg to 94.3 kg (mean value 84.5 kg) and the body mass indices from 20.7 to 27.8 (mean value 25.0). The individual values are shown in Fig. 1. Previous studies indicated that a similar understanding of semantic nuances is favourable for the comparability of subjective judgements. Therefore, subjects with comparable educational level were chosen. Moreover, comprehensive experience in driving might influence the subjective judgements (Seidel *et al.*[29])). For that reason, professional drivers were excluded. It could be of interest to investigate differences in subgroups of different professions, but a study design of that kind would be very time-consuming and expensive.

The subjects sat with an upright posture on a hard seat without backrest, with hands on the thighs.

The Ethics Committee of the Berlin General Medical Council approved the experiments. Informed consent was obtained from all subjects.

Vibration exposure and measurements

The experiment was conducted with a six-degree-of-freedom (DOF) servo-hydraulic simulator with a control system by FCS Control Systems B.V. (The Netherlands) in the vibration laboratory of the Federal Institute for Occupational Safety and Health, Berlin, Germany, considering the guidelines for human experiments with WBV (ISO 13090-1, 1998). Drive files were generated and optimised to realize the desired accelerations. The translational accelerations were measured on the platform and on the seat in three axes (accelerometer Type Endevco 7290A-10) with a sampling frequency of 1 kHz.

The subjects were exposed to sinusoidal (five frequencies 0.8, 1.6, 3.15, 6.3 and 12.5 Hz) or random octave band-width white noise (mid-frequencies identical with those of sinusoidal vibration) whole-body vibration in x- or y-directions, at six levels of magnitude (0.41, 0.82 and 1.65 m/s^2 desired overall vibration total value non-weighted $a_{des,ov(n.w.)}$ (n.w. - M1, M2 and M3) and frequency weighted $a_{des,ov}$ (w. - M4, M5 and M6)) with two repetitions. Table 1 shows the desired – not the measured - accelerations in the main axes. Magnitudes M4, M5 and M6 with desired overall vibration total values $a_{des,ov}$ weighted according to ISO 2631-1, were chosen to be numerically equal to the modified non-weighted desired overall vibration total values $a_{des,ov(n.w.)}$ M1-M3 (grey lines in Table 1).

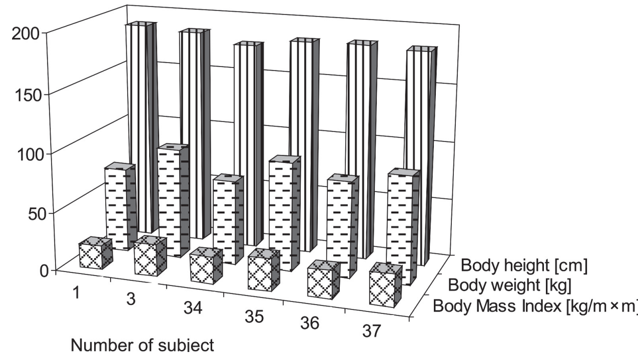

Fig. 1. Body Mass Index, weight and height of the six selected volunteers.

Table 1. Levels of the root mean square (r.m.s.) values of the desired non-weighted acceleration in the axes of excitation on the seat and at the feet $a_{des,ex,seat,\ feet}$ and calculated desired overall vibration total values $a_{des,ov}$, weighted according to ISO 2631-1 (Eq. (9)) and modified without frequency weighting $a_{des,ov(n.w.)}$ (Eq. (10)), sinusoidal (F) or random octave band-width white noise (B) in m/s^{-2} with magnitudes M).

	Frequency [Hz]	0.8	1.6	3.15	6.3	12.5
Magnitude [m/s^2]		F1/ B1	F2/ B2	F3/ B3	F4/ B4	F5/ B5
M1	$a_{des,ex,seat,\ feet}$	0.40	0.40	0.40	0.40	0.40
	$a_{des,ov(n.w.)}$	0.41	0.41	0.41	0.41	0.41
	$a_{des,ov}$	0.40	0.39	0.27	0.17	0.11
M2	$a_{des,ex,seat,\ feet}$	0.80	0.80	0.80	0.80	0.80
	$a_{des,ov(n.w.)}$	0.82	0.82	0.82	0.82	0.82
	$a_{des,ov}$	0.80	0.78	0.54	0.33	0.22
M3	$a_{des,ex,seat,\ feet}$	1.60	1.60	1.60	1.60	1.60
	$a_{des,ov(n.w.)}$	1.65	1.65	1.65	1.65	1.65
	$a_{des,ov}$	1.60	1.56	1.08	0.67	0.44
M4	$a_{des,ex,seat,\ feet}$	0.41	0.42	0.61	0.99	1.47
	$a_{des,ov(n.w.)}$	0.42	0.43	0.63	1.02	1.52
	$a_{des,ov}$	0.41	0.41	0.41	0.41	0.41
M5	$a_{des,ex,seat,\ feet}$	0.82	0.84	1.22	1.97	2.96
	$a_{des,ov(n.w.)}$	0.85	0.87	1.26	2.03	3.05
	$a_{des,ov}$	0.82	0.82	0.82	0.82	0.82
M6	$a_{des,ex,seat,\ feet}$	1.65	1.69	2.46	3.95	5.96
	$a_{des,ov(n.w.)}$	1.70	1.74	2.54	4.07	6.14
	$a_{des,ov}$	1.65	1.65	1.65	1.65	1.65

The idea behind this study design was to perform the investigation twice, with both non-weighted and weighted values. Assuming that the frequency-weighting curves recommended in ISO 2631-1 correctly reflect the sensations, the shape of the frequency-weighting curves derived from the sensations due to the non-weighted magnitude levels M1 to M3 should coincidence with the current weighting curves. The equivalent sensation contours and frequency-weighting curves derived from

Table 2. Experimental design

Day of experiment	Direction of exposure	Repetition	Reference stimuli
1	Y	1	M2F3X and Z
2	Y	2	M2B3X and Z
3	X	1	M2B3Y and Z
4	X	2	M2F3Y and Z

X, Y and Z=axes of excitation, M=magnitude, F=sinusoidal vibration, B=random octave band-width white noise.

Table 3. Exposure conditions used for subject 1 at experimental day number one

Trial 1	Trial 2	Trial 3	Trial 4
M2F3X	**M2F3X**	**M2F3X**	**M2F3X**
M2F3Z	**M2F3Z**	**M2F3Z**	**M2F3Z**
M6F1Y	M4F2Y	M4B5Y	M5B3Y
M6B1Y	M2F1Y	M2F3Y	M6B4Y
M5B1Y	M4B2Y	M4F5Y	M6F3Y
M1F2Y	M1B1Y	M2B3Y	M6F4Y
M5F1Y	M5F2Y	M3B5Y	M6B3Y
M1B2Y	M1F1Y	M3F3Y	M5B4Y
M4B1Y	M5B2Y	M3F5Y	M1F4Y
M2F2Y	M6B5Y	M3B3Y	M5F4Y
M4F1Y	M6F2Y	M2B5Y	M1B4Y
M2B2Y	M6F5Y	M4F3Y	M4B4Y
M3B1Y	M6B2Y	M2F5Y	M2F4Y
M3F2Y	M5B5Y	M4B3Y	M4F4Y
M3F1Y	M1F3Y	M1B5Y	M2B4Y
M3B2Y	M5F5Y	M5F3Y	M3B4Y
M2B1Y	M1B3Y	M1F5Y	M3F4Y
M2F3X	**M2F3X**	**M2F3X**	**M2F3X**
M2F3Z	**M2F3Z**	**M2F3Z**	**M2F3Z**

bold letters – reference stimuli.

the weighted magnitude levels M4 to M6 should be horizontal lines.

In Table 1, the desired overall vibration total values were calculated in accordance with equation (9) and equation (10), assuming the accelerations in the cross axes were zero.

To examine the time effects, 16 additional reference stimuli were used per day. Every subject was exposed to these 304 exposure conditions on four different days, 76 single exposures per day, randomized and divided into 4 trials of 19 single exposures (Table 2 and Table 3). Each single exposure had a duration of about one minute (Fig. 2). There were short pauses between the single exposures. Therefore, one trial lasted approximately 25–30 min. The subjects were asked to walk or stand during the 10 min pause between the trials. Altogether, it took roughly two hours to two and a half hours to realize the 76 single exposures per day. Day 2 and day 4 were complete repetitions of day 1 and day 3, respectively, but the exposure conditions were presented in a different order. No sequence of exposure conditions was used twice. The experimental design was described in more detail in Kreisel *et al*[28].

(9)

$$a_{des,ov(n.w.)} = \sqrt{a^2_{des,ex,seat} + 0.25^2 \times a^2_{des,ex,feet}}$$ modified

with

$a_{des,ex,seat}$ = desired non-weighted acceleration (r.m.s.) on the seat in the axis of excitation and

$a_{des,ex,feet}$ = desired non-weighted acceleration (r.m.s.) at the feet (platform) in the axis of excitation

(10)

$$a_{des,ov} = \sqrt{a^2_{des,Wd,ex,seat} + 0.25^2 \times a^2_{des,Wk,ex,feet}}$$

according to ISO 2631-1

with

$a_{des,Wd,ex,seat}$ = desired weighted acceleration (r.m.s.) on the seat in the axis of excitation and

$a_{des,Wk,ex,feet}$ = desired weighted acceleration (r.m.s.) at the feet (platform) in the axis of excitation

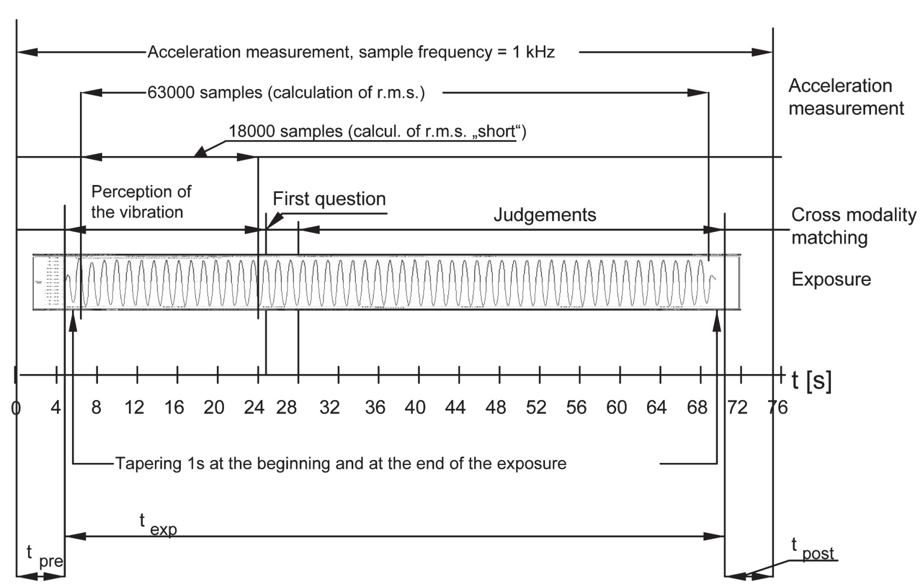

Fig. 2. Measurement of acceleration and subjective judgements during one single exposure.

and assumption: accelerations in the cross axes equal zero in both equations

The combination of the frequency-weighting curves W_d and W_k and the multiplying factors k=1 (seat) and k=0.25 (feet) is defined as $W_d \wedge W_k$ in this paper for convenience, using the Boolean operator for conjunction (^). It is valid for the calculation of the desired overall vibration total value in this experiment. Supposing identical exposure on the seat and the platform due to the mechanical stiffness between seat and platform and assuming that the accelerations in the cross axes were zero, equation (11) was derived from equation (10).

(11)

$$a_{ov} = a_{ex} \times \sqrt{1.0^2 \times W_d^2 + 0.25^2 \times W_k^2} = a_{ex} \times (W_d \wedge W_k)$$

with

W_d and W_k = weighting factors according to ISO 2631-1, Table 3 and

a_{ex} = non-weighted acceleration (r.m.s.) on the seat and at the feet (platform) in the axis of excitation

The sensations of vibration intensity and vibration comfort were obtained by cross-modality matching (length of a line). The subjects responded by adjusting the length of a line presented on a screen in front of them. They were instructed to adjust the length of the line in accordance with their sensations, i.e., the stronger the sensation the longer the line had to be. The subjects used a mouse which was fixed on the vibration simulator to be easily gripped with their right hand (Fig. 3). The cross-modality matching included answers on the following questions:

How intensive do you perceive the vibration to be?

How comfortable do you perceive the vibration to be?

Day 1 started with a training session with at least 10 different representative exposures to allow the subjects to reach a similar level of experience. No subject expressed having been restricted due to the maximum length of the presented line (1,481 mm) on a screen at a distance of 2,600 mm from the subject's eyes, neither during the training session nor during the main study. At the beginning of each experimental day, the subjects had to read a written instruction (Appendix B). The insructions were repeated by the operator at certain time points during the trials.

Data analyses

Data were examined with the statistical program SPSS 15.0.1. The order of successive steps in the data analyses is illustrated in Fig. 4.

The overall vibration total values calculated from the measured accelerations $a_{ov(n.w.)}$ and a_{ov} (Eq. (12) and Eq. (13)) differed from the desired overall vibration total values $a_{des,ov(n.w.)}$ and $a_{des,ov}$ according to Table 1 in about 10% of the cases by 1 dB or more. Therefore, these excitations and the corresponding responses (length of lines) were treated as missing values when differences of mean values between the responses caused by different exposure levels or time points had to be examined (*t*-Tests and Variance Analyses). The excitations in the higher frequencies were most frequently concerned. The cross-axis vibration reached a maximum of 31.7% (y-axis during excitation in x-axis) and 26.6% (x-axis during excitation in y-axis) for sinusoidal excitation at 12.5 Hz, calculated on the basis of the mean values of the r.m.s. of the measured accelerations in main and cross axes. Information about the background vibration is given in Appendix A.

(12)

$$a_{ov(n.w.)} = (a_{x,seat}^2 + a_{y,seat}^2 + a_{z,seat}^2 + 0.25^2 \times a_{x,feet}^2 + 0.25^2 \times a_{y,feet}^2 + 0.4^2 \times a_{z,feet}^2)^{1/2}$$

modified

with

$a_{x,seat}$, $a_{y,seat}$, $a_{z,seat}$ = measured non-weighted acceleration (r.m.s.) on the seat in the x-, y- and z-axis and

$a_{x,feet}$, $a_{y,feet}$, $a_{z,feet}$ = measured non-weighted acceleration (r.m.s.) at the feet (platform) in the x-, y- and z-axis

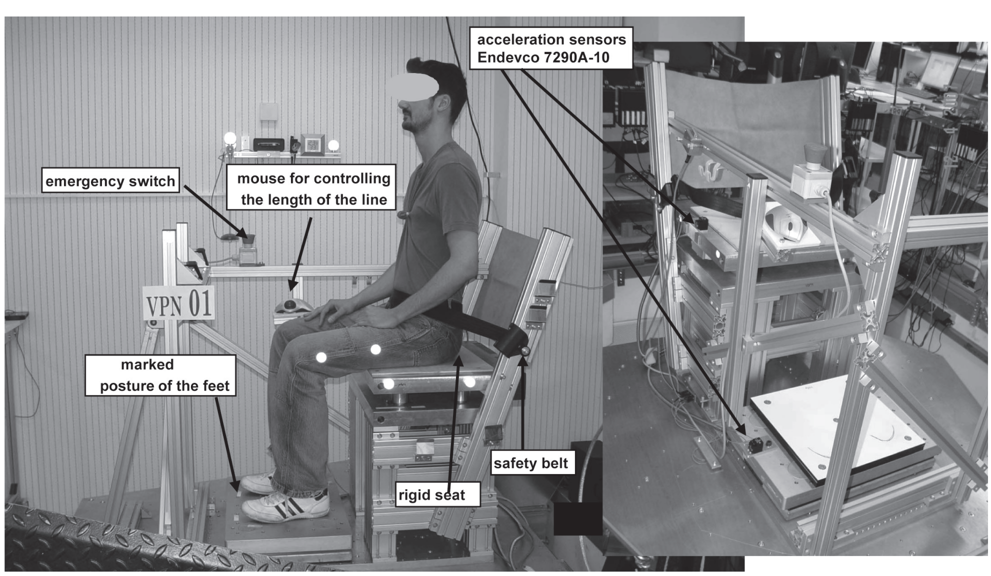

Fig. 3. Subject sitting on the rigid seat and location of the acceleration sensors.

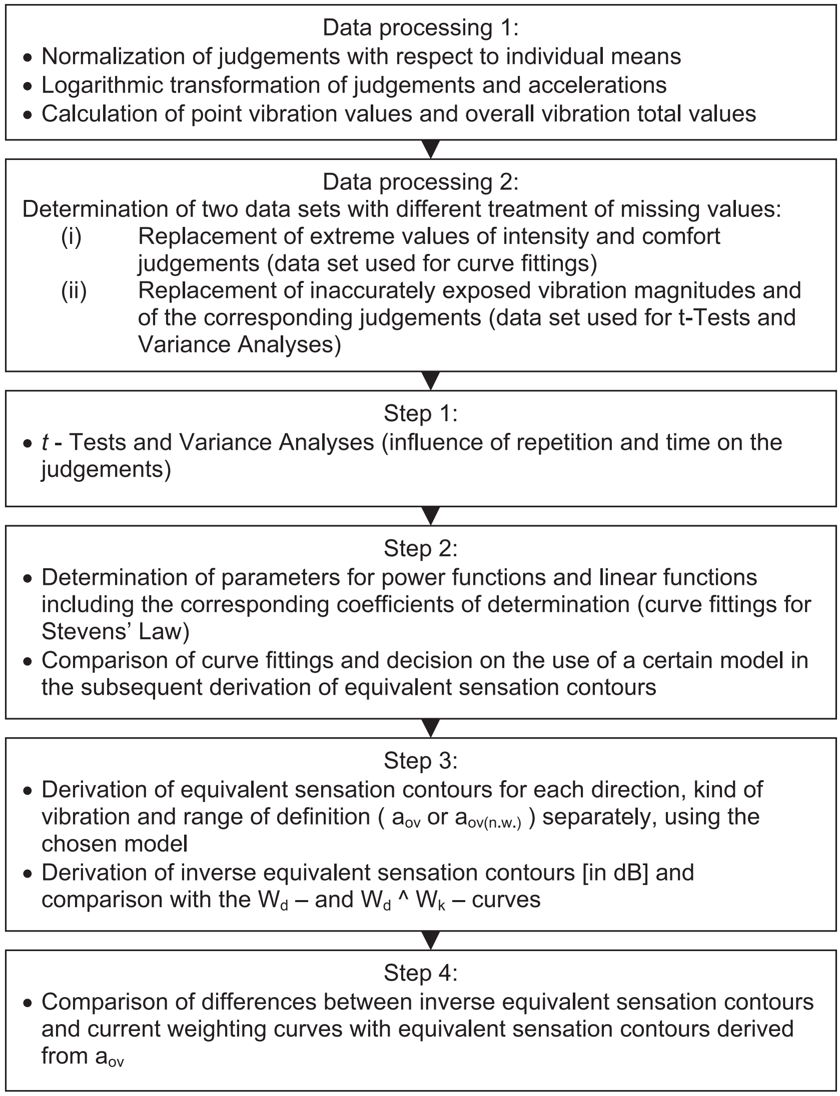

Fig. 4. Order of successive steps in data processing and analyses.

(13)

$$a_{ov} = (a^2_{Wd,x,seat} + a^2_{Wd,y,seat} + a^2_{Wk,z,seat} + 0.25^2 \times a^2_{Wk,x,feet} + 0.25^2 \times a^2_{Wk,y,feet} + 0.4^2 \times a^2_{Wk,z,feet})^{1/2}$$

according to ISO 2631-1

with

$a_{Wd,x,seat}$, $a_{Wd,y,seat}$, $a_{Wk,z,seat}$ = measured weighted acceleration (r.m.s.) on the seat in the x-, y- and z-axis and

$a_{Wk,x,feet}$, $a_{Wk,y,feet}$, $a_{Wk,z,feet}$ = measured weighted acceleration (r.m.s.) at the feet (platform) seat in the x-, y- and z-axis

For curve fittings, only the extreme values of the length of the lines were considered as missing values (intensity: 1 value, comfort: 16 values out of 1,440 single exposures in the main directions x and y without reference stimuli). In contrast to the variance analyses and t-tests, the differing excitations and the corresponding responses were not excluded from the linear regressions analyses.

Values normalized with respect to individual means per experimental day or individual means over all days were derived from the length of the lines measured as pixels. In addition, a logarithmic transformation of data was performed. Because of the simultaneous exposure to vibration on the seat and at the feet in the experiment and the instruction to judge integratively the entire vibration exposure, the judgements were assumed to be reflected more accurately by the overall vibration total value a_{ov} than by the point vibration total value a_v or the vibration in the axis of excitation only. Consequently, the relations between the a_{ov} and the subjective judgements were determined by curve fitting to power functions and linear associations for each frequency, direction and type of vibration signal separately in order to test the agreement with the Stevens' law.

It is a point of discussion, whether the modified overall vibration total value used in this study is valid (Eq. (9) and Eq. (12)). The multiplying factors k for multiple input locations were applied without frequency weighting of the input signals. As mentioned in the discussion later, there seems to be a lack of literature concerning an exact explanation of methods which were used to derive the frequency-weighting curves and the multiplying factors k recommended in ISO 2631-1. An appropriate experiment should strictly differentiate between input location effects and frequency effects and a combination of both influences. Moreover, for estimation of the effect of vibration on the comfort according to the standard, the point vibration total value 'shall be calculated' and the overall vibration total value 'can be determined' (ISO 2631-1, paragraph 8.2.3). Griffin[15)] mentioned that there is 'a conceptual problem in the choice of the frequency, axis and input position weightings when evaluating the vibration which occurs at several input positions' (Griffin[15)], page 82). The effects of relative motions between body parts due to excitations in different directions and at different input points are complex and hardly predictable. At present, there is no standardised evaluation method which considers this fact. Further considerations seem to be necessary. In fundamental investigations, the body parts are often separately exposed in one direction. The curves of equivalent sensation are subsequently derived on the basis of the point vibration total value on the seat $a_{v,seat,(n.w.)}$ or even the non-weighted acceleration in the main axis only, neglecting the cross-axis vibration. Considering the multiplying factors is not necessary in these studies. In the current investigation, seat and feet were exposed simultaneously and identically. It would have been inaccurate if the effect of the exposure at the feet was not taken into account. The authors decided to suppose an influence of the vibration at the feet to be smaller than that on the seat regardless of whether the input signals were frequency-weighted or not. In the absence of further scientific findings the recommended multiplying factors k=0.25 (x- and y-axis) and k=0.4 (z-axis) were applied (Eq. (12) and (13)). However, for mathematical reasons, applying the non-weighted forms of (i) the overall vibration total value $a_{ov,(n.w.)}$ (Eq. (12)), or (ii) the point vibration total value on the seat $a_{v,seat,(n.w.)}$ or (iii) the root-sum-square of $a_{v,seat,(n.w.)}$ and $a_{v,feet,(n.w.)}$ without using the multiplying factors to the linear regressions (see Eq. (14) and Eq. (16)) do lead to identical results. The difference between the levels of magnitudes always amounts to 6 dB and the logarithmically transformed magnitude levels have equal differences. Hence, linear regression delivers the same slope for all three values mentioned above. The shapes of the derived equivalent sensation contours and the frequency-weighting curves depend only on the slope m of the calculated regression lines, not on the constant n (Table 5). One could hypothesize that the evaluation methods recommended in ISO 2631-1 do not correctly reflect the sensations. Therefore, it was supposed that the shape of the frequency-weighting curves derived from M1 to M3 differed from the W_d- curve. The equivalent intensity contours associated with the weighted accelerations M4 to M6 should deviate from a horizontal and straight line. If the assumption were true, the shape of the derived curves would reflect the deviation from the current evaluation methods.

Results

Step 1: Influence of repetition and time on the judgements

Differences between the judgements from the first and the second repetition were examined with the t-Test for paired samples (normal distribution, Kolmogorov-Smirnov-Test p=0.000 for all variables). No significant difference was found for the judgements of vibration intensity (p=0.122), but the judgements of comfort were significantly lower at the second repetition (p=0.001). Time effects on the reference signals were checked with Variance Analyses for repeated measures. There was no significant influence of time on the judgements ($p \geq 0.165$).

Table 4. Code of prediction method, basic functions, dependent and independent variables

Code of prediction	Function	Independent Variable	Dependent variable
A	power	a_{ov}	$LL_{original}$
B	power	a_{ov}	$LL_{norm,\ day}$
C	power	a_{ov}	$LL_{norm,\ all}$
D	linear	$lg(a_{ov})+c_1$	$lg(LL_{original})$
E	linear	$lg(a_{ov})+c_1$	$lg(LL_{norm,\ day}+c_2)+c_3$
F	linear	$lg(a_{ov})+c_1$	$lg(LL_{norm,\ all}+c_2)+c_3$

$LL_{original}$ – originally measured length of line in pixel, $LL_{norm,\ day}$ – length of line normalized with respect to individual means per experimental day, $LL_{norm,\ all}$ – length of line normalized with respect to individual means over all experimental days (normalized values in arbitrary units), a_{ov} – overall vibration total value, c_1, c_2, c_3 – constants for shifting values into positive ranges.

Step 2: Growth of sensation

According to Stevens' Law, the relation between physical stimulus and response can be described by a power function. Consequently, the relation between the logarithmically transformed stimuli and responses should be a linear function. Six prediction methods (see Table 4) were evaluated by comparing the coefficients of determination using (i) the original length of line and (ii) the normalized data with respect to individual means. The variables and functions are listed in Table 4. The parameters of the functions and the coefficients of determination were determined for each frequency, direction and type of vibration signal separately. In order to decide which model should be used for subsequent determination of equivalent sensation contours, the coefficients of determination of all frequencies, directions and types of vibration were organised according to the kind of function and range of definition. Figure 5 provides the mean values and confidence intervals of the coefficients of determination for the judgements of vibration intensity summarizing all frequencies, directions and types of vibration and divided as explained above.

The prediction models type E with the definition ranges M1–M6 n.w. and M1–M6 w. were used in the subsequent determinations of equivalent sensation contours as these models displayed the highest coefficients of determination (circled values in Fig. 5).

The values were shifted into positive ranges for the logarithmic transformation and the subsequent linear regression. Therefore, the minimum of $LL_{norm,day}$ of the entire data set was identified and used as c_2 (Table 4). Afterwards, the logarithmic transformation was performed. In the next step, the minima of $lg(a_{ov(n.w.)})$ and $lg(LL_{norm,day} + c_2)$ were detected and used as c_1 and c_3 (Table 4).

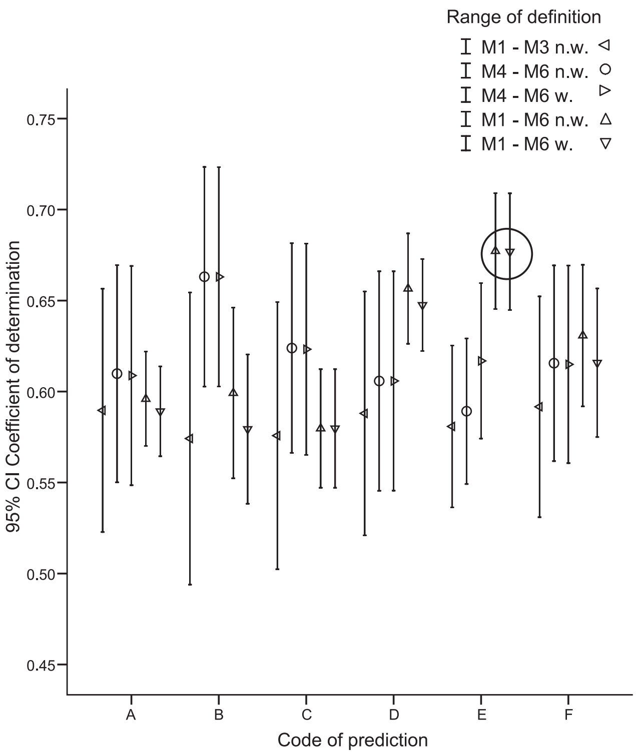

Fig. 5. Mean values and 95% confidence intervals (CI) of the coefficients of determination for the prediction of the judgements of vibration intensity summarizing all frequencies, directions and kinds of vibration, depending on the prediction method and on the range of definition.

The circle indicates the highest mean values of these coefficients of determination.

For the judgements of vibration intensity:

(14) Type E (M1–M6 n.w.):

$$(\lg(LL_{norm,day} + 374.1) + 1.466) = m \times (\lg(a_{ov(n.w.)}) + 0.51) + n$$

(15) Type E (M1–M6 w.):

$$(\lg(LL_{norm,day} + 374.1) + 1.466) = m \times (\lg(a_{ov}) + 1.01) + n$$

For the judgements of vibration comfort:

(16) Type E (M1–M6 n.w.):

$$(\lg(LL_{norm,day} + 428.1) + 2.1) = m \times (\lg(a_{ov(n.w.)}) + 0.51) + n$$

(17) Type E (M1–M6 w.):

$$(\lg(LL_{norm,day} + 428.1) + 2.1) = m \times (\lg(a_{ov}) + 1.01) + n$$

with

$LL_{norm,\ day}$ = length of line normalized with respect to individual means per experimental day

$a_{ov(n.w.)}$ = overall vibration total value, modified, non-weighted

a_{ov} = overall vibration total value, according ISO 2631-1, weighted

m = slope of the regression line

n = constant of the regression line

Figure 6 illustrates as an example the linear regression lines, equations with slopes, constants and coefficients of determination for the prediction of judgements of vibration intensity for sinusoidal vibration excitation in the x-axis (range of definition M1–M6 n.w.), depending on the vibration frequency. The parameters of the regression equations (14) and (16) for both types of signals and directions of excitation are listed in Table 5 (intensity, equation (14)) and Table 6 (comfort, equation (16)).

The coefficients of determination were much lower for the prediction of vibration comfort ($0.08 \le r^2 \le 0.58$) in particular for frequencies higher than 1.6 Hz ($0.08 \le r^2 \le 0.44$) (see Table 6).

Step 3: Equivalent vibration intensity and vibration comfort judgement contours

A model can be assumed to be sufficient when the coefficient of determination reaches a value of r^2 = 0.5 or more. Unfortunately, the prediction models for the comfort judgements had much lower coefficients (see Table 6). Therefore, equivalent sensation contours were derived only from the judgements of vibration intensity, not from the judgements of vibration comfort.

Equivalent intensity contours were determined by calculating the vibration acceleration corresponding to the intensity judgement at each frequency according to Equation (14) and Table 5, changing the range of value and the range of definition. Limits of the range of definition were taken into account when calculating the accelerations from the lengths of the lines. Therefore, the range of judgements (range of values) slightly varies between the figures for the different vibration directions and types (Figs. 7 and 8). The lowest and highest values were chosen so that the range of definition was completely filled but not exceeded at each frequency. The equivalent contours were then calculated in 12 steps of equidistant arbitrary units from the lowest to the highest equivalent contour. The equivalent intensity contours illustrate the vibration magnitudes required to produce the same strenght of sensation across the frequency range. They provide information on what frequencies produced greater sensation of intensity. A lower acceleration at a particular frequency indicates greater sensation of vibration intensity at that frequency. The overall shapes and the frequencies of highest sensitivity obviously depended on the magnitude, the direction and the type of vibration.

Figures 9 and 10 show ratios of predicted accelerations for frequencies above 0.8 Hz in relation to those at 0.8 Hz set to 1, and the inverted ratios in order to illustrate the effect of vibration magnitude on frequency weightings (Figs. 9 and 10). All values were multiplied with 1,000 in order to derive values comparable to those in ISO 2631-1 Table 3. The reference frequency f_{ref} = 0.8 Hz was selected as it was the frequency closest to that of highest sensitivity of the weighting curves W_d and $W_d \wedge W_k$ (f_{sens} = 1.0 Hz, see ISO 2631-1 Table 3 and Eq. (11)) and exposed in this study. Table 7 contains the values for sinusoidal excitation simultaneously exposed on the seat and the platform in the x-direction in 12 steps of equidistant arbitrary units (see Fig. 7(a) and Fig. 9 (a)). Additionally, the table encloses the magnitude independent factors for the W_d- and W_k-frequency weightings of ISO 2631-1 Table 3 and $W_d \wedge W_k$ (see Eq. (11)).

The following paragraph explains an example for the

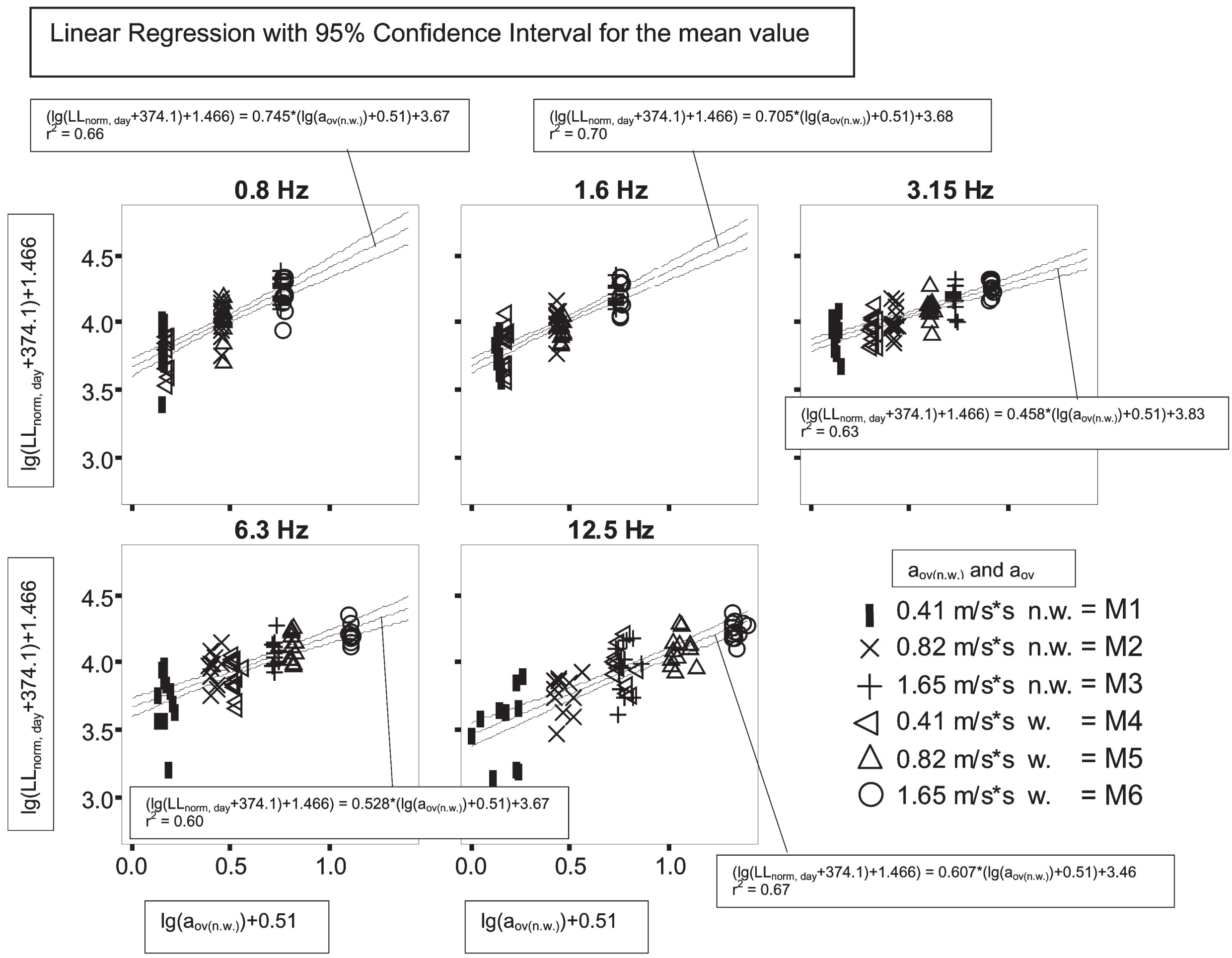

Fig. 6. Linear regression lines, slopes, constants and coefficients of determination for the prediction of judgements of vibration intensity for sinusoidal vibration, excitation in the x-axis, depending on the vibration frequency, range of definition M1–M6 n.w.

Table 5. Slope m, constant n and coefficient of determination r^2 of the linear regression

Type/Direction	Frequency [Hz]	Slope m	Constant n	Coefficient of determination r^2
Sinus X	0.8	0.745	3.67	0.66
	1.6	0.705	3.68	0.70
	3.15	0.458	3.83	0.63
	6.3	0.528	3.67	0.60
	12.5	0.607	3.46	0.67
Sinus Y	0.8	1.036	3.52	0.71
	1.6	0.901	3.61	0.75
	3.15	0.816	3.54	0.67
	6.3	0.565	3.62	0.67
	12.5	0.608	3.46	0.69
Band X	0.8	0.834	3.64	0.72
	1.6	0.784	3.71	0.76
	3.15	0.646	3.74	0.76
	6.3	0.504	3.65	0.56
	12.5	0.685	3.37	0.59
BandY	0.8	1.025	3.56	0.66
	1.6	0.819	3.71	0.79
	3.15	0.749	3.62	0.77
	6.3	0.648	3.55	0.60
	12.5	0.611	3.42	0.60

Equation (14) for the prediction of the judgement of vibration intensity.

Table 6. Slope m, constant n and coefficient of determination r^2 of the linear regression

Type/Direction	Frequency [Hz]	Slope	Constant	Coefficient of determination
Sinus X	0.8	–0.371	4.95	0.48
	1.6	–0.474	4.94	0.58
	3.15	–0.361	4.88	0.42
	6.3	–0.269	4.88	0.27
	12.5	–0.195	4.91	0.25
Sinus Y	0.8	–0.731	5.06	0.44
	1.6	–0.551	4.94	0.49
	3.15	–0.408	4.95	0.44
	6.3	–0.210	4.89	0.22
	12.5	–0.093	4.80	0.08
Band X	0.8	–0.497	4.91	0.53
	1.6	–0.493	4.84	0.52
	3.15	–0.424	4.82	0.38
	6.3	–0.253	4.82	0.35
	12.5	–0.182	4.85	0.27
Band Y	0.8	–0.763	4.96	0.50
	1.6	–0.633	4.82	0.33
	3.15	–0.490	4.85	0.36
	6.3	–0.319	4.88	0.27
	12.5	–0.142	4.83	0.23

Equation (16) for the prediction of the judgement of vibration comfort.

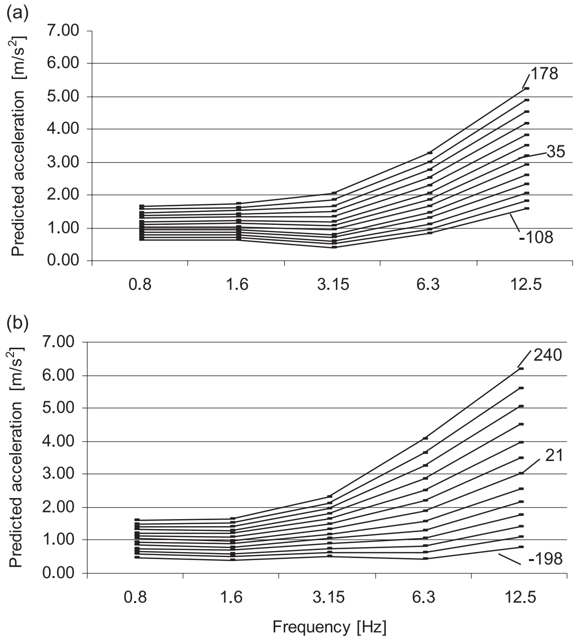

Fig. 7. Equivalent intensity contours for arbitrary sensation units from minimum to maximum of the range of value in order to meet the range of definition (range of actually exposed vibration magnitudes) in steps of 12 equidistant units determined from Eq. (14) and Table 5: (a) sinusoidal excitation in x-axis, (b) sinusoidal excitation in y-axis.

Predicted acceleration in [m/s^2] = overall vibration total value modified without frequency weighting $a_{ov(n.w.)}$ r.m.s.. Numbers attached to the lines: normalized intensity judgements $LL_{norm,\ day}$ (see Eq. (14)).

magnitude-dependence of the filter factors (2nd and 6th rows, marked in grey in Table 7). A sinusoidal vibration stimulus at 3.15 Hz with a magnitude of $a_{ov(n.w.)}$ = 0.49 m/s^2 (0.69 m/s^2 × 0.716) produces a sensation equal to that of a sinusoidal vibration stimulus at 0.8 Hz with a magnitude of 0.69 m/s^2. In order to convert a measured sinusoidal vibration at 3.15 Hz with a magnitude of $a_{ov(n.w.)}$ = 0.49 m/s^2 into a sinusoidal vibration stimulus at 0.8 Hz with equal intensity sensation, the acceleration has to be multiplied with 1.396 (filter factor), i.e. it has to be increased by 2.90 dB (20 × lg(1.396)). When the vibration signal has a magnitude of 0.93 m/s^2 (1.02 m/s^2 × 0.910) it has to be multiplied with 1.099 (filter factor), that means it has to be increased by 0.82 dB (20 × lg(1.099)) only.

Step 4: Equivalent intensity contours derived from weighted overall vibration total values

The equivalent intensity contours associated with the weighted accelerations a_{ov} were determined by the same method as described in step 3 but using Eq. (15). The slopes and constants are not given in detail. Assuming that the evaluation methods recommended in ISO 2631-1 correctly reflect the sensation, the equivalent intensity contours associated with the weighted accelerations a_{ov} should be horizontal and straight lines. But, they differed from straight lines. As expected from the results derived from the non-weighted accelerations,

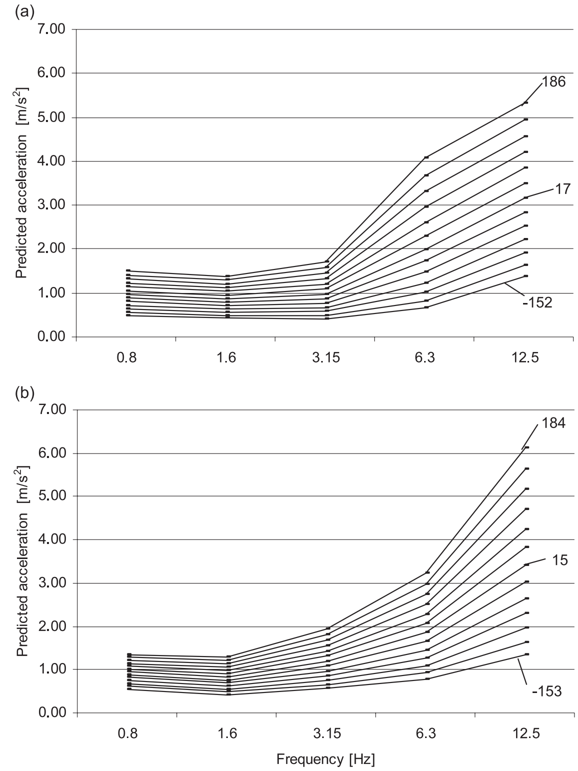

Fig. 8. Equivalent intensity contours for arbitrary sensation units from minimum to maximum of the range of value in order to meet the range of definition (range of actually exposed vibration magnitudes) in steps of 12 equidistant units determined from Eq. (14) and Table 5: (a) random octave band-width white noise excitation in x-axis, (b) random octave band-width white noise excitation in y-axis.

Predicted acceleration in [m/s^2] = overall vibration total value modified without frequency weighting $a_{ov(n.w.)}$ r.m.s..

Numbers attached to the lines: normalized intensity judgements $LL_{norm,\ day}$ (see Eq. (14)).

these contours reflected the differences between the contours obtained from the non-weighted accelerations $a_{ov(n.w.)}$ and the combination of the current weighting curves and multiplying factors $W_d \wedge W_k$ (Eq. (11)).

Discussion

Influence of repetition and time on the judgements

One experimental set lasted roughly two hours to two and a half hours. There were some doubts, whether the subjects were able to differentiate between the vibration comfort and the comfort of the entire situation including permanent demands on concentration and sitting a long period of time on the rigid seat without exercise. Schust[21] revealed that the subjects were not able to differentiate between the vibration comfort and the comfort of the entire situation when they had to judge the seat comfort. In Schust[21], the seat comfort decreased significantly with time. So, it could be the case that the vibration comfort judgements were influenced by time. Nevertheless, no significant decrease in comfort judgements of the identical reference stimuli per daily exposure set

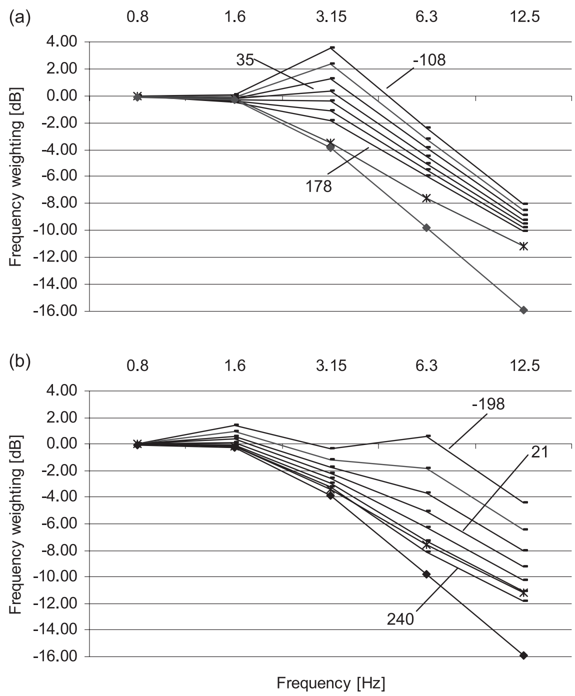

Fig. 9. Effect of vibration magnitude on frequency weightings (inverted equivalent intensity contours in steps of 6 equidistant arbitrary sensation units).

Numbers attached to the lines: normalized intensity judgements $LL_{norm,day}$ – length of line normalized with respect to individual means per experimental day. Curves normalized at 0.8 Hz and converted into dB: (a) sinusoidal excitation simultaneously exposed on the seat and the platform in x-direction, (b) sinusoidal excitation simultaneously exposed on the seat and the platform in y-direction. The results are compared with the frequency weightings.

W_d (—◆—) and W_d ^ W_k (—✳—) according to Eq. (11).

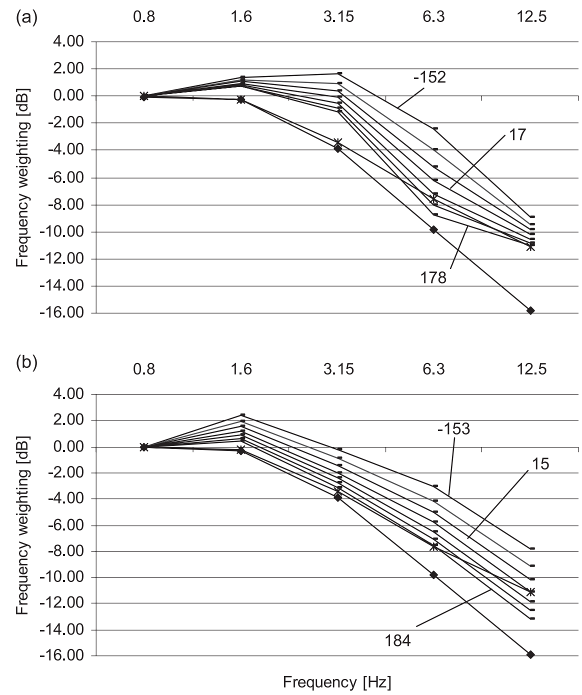

Fig. 10. Effect of vibration magnitude on frequency weightings (inverted equivalent intensity contours in steps of 6 equidistant arbitrary sensation units).

Numbers attached to the lines: normalized intensity judgements $LL_{norm,day}$ – length of line normalized with respect to individual means per experimental day. Curves normalized at 0.8 Hz and converted into dB: (a) octave band-width white noise excitation simultaneously exposed on the seat and the platform in x-direction, (b) octave band-width white noise excitation simultaneously exposed on the seat and the platform in y-direction.

The results are compared with the frequency weightings W_d (—◆—) and W_d ^ W_k (—✳—) according to Eq. (11).

was found. Moreover, the judgements of vibration intensity remained stable over time. A tendency to judge the very last exposure of the last experimental day less comfortable and more intensive was observed. Because of their four-day experience, the subjects knew that it was the very last exposure, even when it was not explicitly told them. That might be the reason for the slightly different judgement in comparison to the other reference stimuli. However, this tendency did not influence the general time independency of the judgements on one experimental day. The results suggest that the subjects were able to separate the intensity and comfort judgements from other perceptions associated with time effects.

On the other hand, the judgements of vibration comfort were significantly lower at the second repetition which was performed on a separate day. The reasons of this effect are not clear and so the interpretation is difficult. Possibly, the internal reference system concerning 'comfort' might vary from day to day. The topic is discussed more comprehensively in Section 1 and in the following paragraph. However, the results indicate an insufficient repeatability of the vibration comfort judgements.

Growth of sensation and equivalent sensation contours

The theory of cross-modality matching and the importance of Stevens' power law are described in Section 1. The Stevens' exponent was determined by regression analyses. The coefficients of determination for the prediction of comfort judgements were very low (see Table 6), so that these judgements supposed to be not suited for an adequate reflection of growth of sensation with vibration magnitude.

The interpretation of the outcomes relates to the term 'comfort'. As mentioned in Section 1, the term 'discomfort' does not exist in German. A simple inversion of the scale using the term 'comfort' does not seem to be a solution. Probably, 'comfort' is not just the opposite of 'discomfort'. 'Comfort' is rather associated with feelings of relaxation and well-being, whereas discomfort seems to be associated with biomechanical factors (joint angles, muscle contractions, pressure distribution) and tiredness (Zhang[22]). In a pilot study with 12 German speaking subjects (unpublished), the authors of the present investigation found that 'convenient' was the most appropriate word for 'comfortable', followed by cosy, pleasant, homelike, proper and easy. Therefore, the subjects were briefed to judge the vibration comfort bearing in mind all sensations related

Table 7. Ratios derived from equivalent vibration intensity contours dependending on the presented modified non-weighted overall vibration total value $a_{ov(n.w.)}$ at the reference frequency f_{ref} = 0.8 Hz ($a_{ov(n.w.), 0.8 Hz}$) in case of sinusoidal excitation simultaneously presented on the seat and the platform in x-axis

		Ratios of predicted accelerations					Filter factors				
$a_{ov(n.w.)}$	f_{ref}	Ratio $a_{ov(n.w.)}$ / $a_{ov(n.w.), 0.8 Hz}$ × 1,000					Ratio $a_{ov(n.w.), 0.8 Hz}$ / $a_{ov(n.w.)}$ × 1,000				
		Frequency [Hz]					Frequency [Hz]				
		0.8	1.6	3.15	6.3	12.5	0.8	1.6	3.15	6.3	12.5
0.62	0.8	1,000	995	666	1,323	2,538	1,000	1,005	1,501	756	394
0.69	0.8	1,000	1,002	**716**	1,387	2,606	1,000	998	**1,396**	721	384
0.77	0.8	1,000	1,008	765	1,449	2,669	1,000	992	1,306	690	375
0.85	0.8	1,000	1,013	814	1,508	2,730	1,000	987	1,229	663	366
0.93	0.8	1,000	1,018	862	1,566	2,787	1,000	982	1,160	639	359
1.02	0.8	1,000	1,023	**910**	1,622	2,842	1,000	977	**1,099**	617	352
1.10	0.8	1,000	1,028	957	1,676	2,895	1,000	973	1,045	597	345
1.19	0.8	1,000	1,032	1,003	1,729	2,945	1,000	969	997	578	340
1.28	0.8	1,000	1,036	1,049	1,781	2,994	1,000	965	953	561	334
1.37	0.8	1,000	1,040	1,095	1,832	3,041	1,000	961	913	546	329
1.46	0.8	1,000	1,044	1,141	1,881	3,086	1,000	958	877	532	324
1.56	0.8	1,000	1,048	1,186	1,930	3,130	1,000	954	843	518	319
1.65	0.8	1,000	1,051	1,231	1,977	3,173	1,000	951	813	506	315
	f_{sens}						Factor × 1,000 (ISO 2631-1, Table 3)				
W_d	1.0	-	-	-	-	-	992	968	642	323	161
W_k	10.0	-	-	-	-	-	477	494	804	1,054	902
W_d ^ W_k	1.0	-	-	-	-	-	999	976	673	417	277

Factors for W_d - and W_k - frequency weightings according to ISO 2631-1 Table 3 and for the combination of W_d - and W_k - factors and multiplying factors (W_d ^ W_k) according to Eq. (11). Highest sensitivity of the weighting curve W_d and the combination W_d ^ W_k: f_{sens} = 1.0 Hz. Highest sensitivity of the weighting curve W_k: f_{sens} = 10 Hz (see ISO 2631-1 Table 3 and Eq. (11)).

Table 8. Stevens' exponents for the growth of discomfort derived from magnitude estimation (Howarth[10] and Morioka[14]) and for the vibration intensity derived from cross-modality matching (present study) depending on the frequency and the direction of the exposed sinusoidal vibration

	Howarth[10]	Morioka[14]		Present study	
	y-direction	x-direction	y-direction	x-direction	y-direction
0.8				0.745	1.036
1.6				0.705	0.901
2		0.948	0.635		
2.5		0.668	0.763		
3.15		***0.499***	***0.742***	***0.458***	***0.816***
4	0.68	0.461	0.932		
5		0.468	0.876		
5.6	0.85				
6.3		0.805	0.953	0.528	0.565
8	0.93	0.711	0.716		
10		0.735	0.935		
11.3	1.41				
12.5		0.854	0.907	0.607	0.608

to these terms. Moreover, they were requested to ignore the surrounding influences like climate, noise, demands on concentration and whether the mouse could easily be gripped or not. Notwithstanding this, the vibration comfort judgements seemed to be affected by many influences in addition to the vibration magnitude.

In contrast, coefficients of determination for the prediction of intensity judgements were high enough to presume the linear model to be appropriate for an adequate reflection of growth of sensation with increasing vibration magnitude (see Table 5). It was of interest to see whether the obtained exponents were similar to those derived from discomfort judgements reported by other authors. There are some comparable investigations with horizontal excitations of the seat or simultaneously of the seat and at the feet. Morioka[14] and Howarth[10] reported Stevens' exponents determined by magnitude estimation in their studies (Table 8).

For reasons discussed in the next paragraph, only the exponents derived at 3.15 Hz in the present study were reasonably comparable to those from Morioka[14] at the same frequency (in bold characters in Table 8). In spite of different methods, these exponents are very similar. In all three studies, Stevens' exponents varied within the frequency range, and frequency dependent Stevens' exponents cause magnitude dependent equivalent sensation contours.

In order to compare the results to those from other authors and to reveal a possibly systematic influence of relative body movements on the outcomes, some studies with horizontal vibrations were divided into investigations with and without relative body movements in the following paragraphs.

Griffin[7], Howarth[10] and Morioka[14] performed studies with vibration at the seat only, with stationary feet and hands.

Griffin[7] reported an experiment which determined the levels of fore-and-aft and lateral seat vibrations at seven frequencies (1, 2, 4, 8, 16, 31.5 and 63 Hz) causing discomfort equivalent to 0.5 and 1.25 m/s^2 r.m.s. 10 Hz vertical seat vibration. The vibration magnitudes of the test motions varied from 0.1 to 20 m/s^2. The subjects' feet were not vibrated and there was no backrest. Over the investigated range of levels the differences in equivalent sensation contours were small. The authors concluded that it seems reasonable to determine and apply a single equivalent comfort contour. They did not directly compare their results to the frequency weightings described in standards.

Howarth[10] exposed the subjects to six acceleration levels of sinusoidal vibrations in the y- and z-axes in a very low range from 0.04 m/s^2 to 0.4 m/s^2 at nine frequencies between 4 and 63 Hz. The footrest was stationary and there was no backrest. The authors found a magnitude dependence of the equivalent sensation contours. However, the frequency weightings were averaged over six magnitudes and compared with Wd frequency weighting defined in BSI 6841 (1987)[23] and ISO 2631 (1985)[24]. It was concluded that the averaged frequency weightings for sinusoidal vibration in the y-axis were in good agreement with W_d over the whole frequency range.

In experiments performed by Morioka[14], the subjects judged the discomfort caused by sinusoidal vibration in all three directions at frequencies between 2 and 315 Hz. The magnitudes varied from minimum 0.02 m/s^2 to maximum 1.25 m/s^2 r.m.s. in 3 dB steps. The range of exposed magnitude levels increased with increasing frequency in order to ensure that the stimuli were above the perception thresholds but not likely to be considered excessively unpleasant. There was no backrest and stationary handles and footrests were used. There were some magnitude dependent differences between the derived equivalent sensation contours and the W_d-curve, more pronounced for vibrations in the x-direction than in the y-direction (Fig. 8 in Morioka[14]).

Donati[25] and Corbridge[9] performed studies with identical exposure on the seat and at the feet.

Donati[25] compared the subjective response of seated subjects to sinusoidal vibrations in x-, y- and z-axes in the 1–10 Hz range with those produced by narrow-band random vibration centred at the same frequencies using the 'floating reference vibration' method. The accelerations varied from about 0.6 m/s^2 to about 4.0 m/s^2. The subjects sat on a semi-rigid seat or a rigid seat with and without support by a backrest. Identical vibrations were exposed simultaneously on the seat, the feet (footrest) and the hands (steering wheel). The differences between ISO-weighting and equivalent sensation contours were comparable with those obtained in the present study (Fig. 10 in[25]). The authors concluded that the equivalent sensation contours derived from these experiments related only roughly to the weighting curves in ISO 2631-1, particularly in the x-direction. The magnitude dependence of weighting curves was not systematically investigated in this study. Corbridge[9] conducted experiments with lateral sinusoidal vibration in the 0.5–5.0 Hz range. The magnitudes varied from 0.4 to 3.15 m/s^2. Subjects were seated on a rigid wooden seat and rested their feet on the moving vibrator table. The seat had a flat backrest, but the authors did not exactly describe whether it was used or not. The authors concluded that the experimentally determined contours for lateral vibration were in reasonable agreement with the curve defined in ISO 2631 (1978) (Fig. 9 in[9]). In both studies it remained vague whether the comparisons were related to the W_d- curves or to a combination of multiplying factors and W_d- and W_k-curves because of the simultaneous exposure of seat and feet.

Discussing the influence of relative body movements on the outcomes, one could suppose an increase of vibration sensitivity at least at low frequencies when only the seat was excited. When comparing the results of these studies with the outcomes of investigations with simultaneous vibration on the seat and the feet, a systematic difference at least at low frequencies may be expected. However, both types of experimental design delivered evidence varying from reasonable agreement with the ISO-curves to obvious differences without any systematic divergences. The relative body movements might influence the sensations less than assumed. In experiments with horizontal vibrations (modified signals of mobile machines) and professional driver seats with fixed or activated horizontal suspension, Schust[26] revealed high correlations between judgements of vibration intensity and vibration magnitude but only weak to middle correlations between intensity judgements and movements of the head in the room and the angle velocity of the bending of the trunk, the latter for exposures in y-direction and some exposure conditions only. The authors concluded that the subjective judgement of the intensity seems to depend rather on the vibration magnitude at the buttocks, the back and the feet than on the movements of the body parts in relation to the space coordinates or the relative movements between the body parts. Moreover, in this study twenty different values of acceleration were calculated for analyses of correlation between accelerations and subjective judgements, amongst others the point vibration total value av and the overall vibration total value a_{ov}. Comparing the results for av and aov the authors assumed the vibration measuring point (platform, seat or backrest) to be probably of minor importance for the association between acceleration and judgement of intensity, at least for the exposure conditions tested in this study with no extensively relative movements between these points.

Moreover, there is a lack of literature concerning an exact explanation of methods which were used to derive the frequency-weighting curves and the guide for their application with regard to health, comfort and perception (ISO 2631-1, Table 1) including the multiplying factors k (ISO 2631-1, clauses 7 and 8).

Bearing in mind the facts discussed above, it is difficult to decide whether equivalent sensation contours for the seat should be (i) derived from experiments with excitation on the seat only or with simultaneous exposure on the seat and the

Table 9. Predicted accelerations depending on arbitrary sensation units and on frequency derived by Morioka[14] (first two rows) and in the present study (last seven rows)

	Frequency [Hz]										
Arbitrary units	0.8	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5
50			0.073	0.062	0.055	0.057	0.071	0.195	0.226	0.308	0.421
25			0.041	0.030	0.023	0.023	0.026	0.091	0.101	0.145	0.219
–108	0.62	0.62			0.41			0.82			1.57
–84	0.69	0.70			0.50			0.96			1.81
–60	0.77	0.78			0.59			1.12			2.06
–36	0.85	0.86			0.69			1.29			2.33
–13	0.93	0.95			0.80			1.46			2.60
11	1.02	1.04			0.93			1.65			2.89
35	1.10	1.13			1.06			1.85			3.19

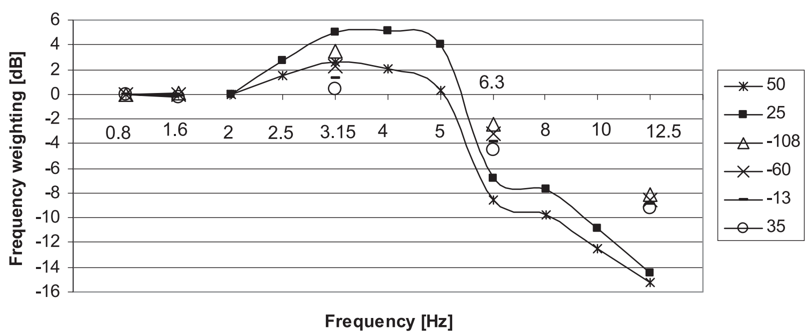

Fig. 11. Frequency weightings for vibration exposure in x-direction depending on arbitrary sensation units derived by Morioka (arbitrary units 25 and 50) and in the present study (arbitrary units –108, –60, –13 and 35).

feet, (ii) derived from the point overall vibration total value or the overall vibration total value (a_v or a_{ov}) and (iii) compared with W_d or W_d ^ W_k.

In the present study, due to technical reasons an excitation merely on the seat was not realizable. That means there was a simultaneous exposure to vibration on the seat and at the feet. Moreover, the subjects were briefed to judge integratively the entire vibration exposure. Therefore, it was supposed that the judgements were reflected more likely by the overall vibration total value a_{ov} than by the point vibration total value av or the vibration in the axis of excitation only. Consequently, the relations between the a_{ov} and the subjective judgements were determined by curve fitting and the obtained equivalent sensation contours were discussed mainly in comparison with W_d ^ W_k. In all Figures with frequency weightings, the W_d -curve is also given. At low frequencies both curves do not differ considerably but at frequencies from 6.3 Hz upwards they diverge by more than 2.2 dB and from 8 Hz upwards they diverge by more than 3 dB due to the effect of WBV acting on the feet. Assuming the current evaluation methods using the weighted overall vibration value a_{ov} adequately reflect the sensations, these differences were surely detectable by the subjects. It might be the case that, the effect of the WBV acting on the feet, when the seat and the feet are simultaneously excited, restricts the examination of the frequency-weighting curve W_d at frequencies above 5 Hz third-octave band mid frequency.

Comparing the results of the present study with these from Morioka[14], there seems to be some evidence for this assumption. Both studies are similar. Morioka[14] also investigated sinusoidal vibration, but no random excitation. The frequencies of standardisation for the frequency-weighting curves differed because of the different lowest frequencies (2 Hz in Morioka[14], 0.8 Hz in the present study). Moreover, there were only 3 common frequencies investigated (3.15, 6.3 and 12.5 Hz) and the magnitudes at the frequency of normalization were much more lower in Morioka[14] (0.041 m/s^2 to 0.417 m/s^2 r.m.s. in x- direction, 0.02 m/s^2 to 0.63 m/s^2 r.m.s. in y-direction) compared with the present study (0.41 m/s^2 to 1.70 m/s^2 r.m.s. in x- and y-directions, see Table 1). However, almost identical Stevens' exponents were obtained for frequencies at 3.15 Hz (see Table 8). Above 3.15 Hz, Morioka's exponents are higher, which indicates a deeper slope of the frequency-weighting curve.

For sinusoidal excitation in y-direction, similar filter factors for 3.15 Hz were derived when similar magnitudes were used at the frequency which was used for normalization (e.g. 0.6 m/s^2 at 2 Hz in Morioka[14] and at 0.8 Hz in the present study). However, above 3.15 Hz Morioka's curves are closer to W_d than the frequency weightings obtained in the present investigation. That might be due to separate vibration of the seat. Morioka[14] found similar shapes for the frequency-weighting curves for sinusoidal excitation in x-direction with the highest sensitivity around 2–3.15 Hz, but for lower vibration magnitudes (0.041 m/s^2 to 0.073 m/s^2 r.m.s. at 2 Hz) compared with the present investigation (0.62 m/s^2 to 1.19 m/s^2 r.m.s. at 0.8 Hz) (Table 9). Figure 11 shows the frequency weightings for vibration exposure in x-direction depending on arbitrary sensation units derived by Morioka (arbitrary units 25 and 50) and in the present study (arbitrary units –108, –60, –13 and 35).

One could be tempted to extrapolate the data to make some studies comparable by exceeding the range of definition but that would assume a questionable linearity in the human response. For instance, Miwa[26] reported a reduction in the exponent with increasing vibration magnitude.

Some differences in the results might be due to different judgement methods. The present investigation seems to be only one which used cross-modality matching. The method has the advantage not to be dependent on a 'vibration memory', which means that the subjects do not have to keep in mind the sensation regarding a previously exposed reference stimulus in order to judge the current stimulus. On the other hand, cross-modality matching takes more time because of the necessity of a pre-period for vibration sensation (about 20 s) before judging the stimulus. Therefore, the number of conditions (magnitudes, frequencies etc.) realizable in an experimental session is restricted in order not to exceed an acceptable duration.

The weighted magnitude levels M4, M5 and M6 had overall vibration total values numerically equal to the non-weighted magnitudes M1, M2, M3. Therefore, the experiment was performed de facto twice, once with non-weighted magnitudes and repeatedly with weighted values. The multiplying factors were used for calculating both, M1 to M3 and M4 to M6. Assuming that the evaluation methods recommended in ISO 2631-1 correctly reflect the sensations, one could hypothesize that the shape of the frequency-weighting curves derived from M1 to M3 reflected the W_d- curve or the $W_d \wedge W_k$ –curve and the equivalent intensity contours associated with the weighted accelerations M4 to M6 were horizontal and straight lines. If the assumption were not true, the shape of the derived curves would reflect the deviation from the current evaluation methods. The latter was the case (see Fig. 12).

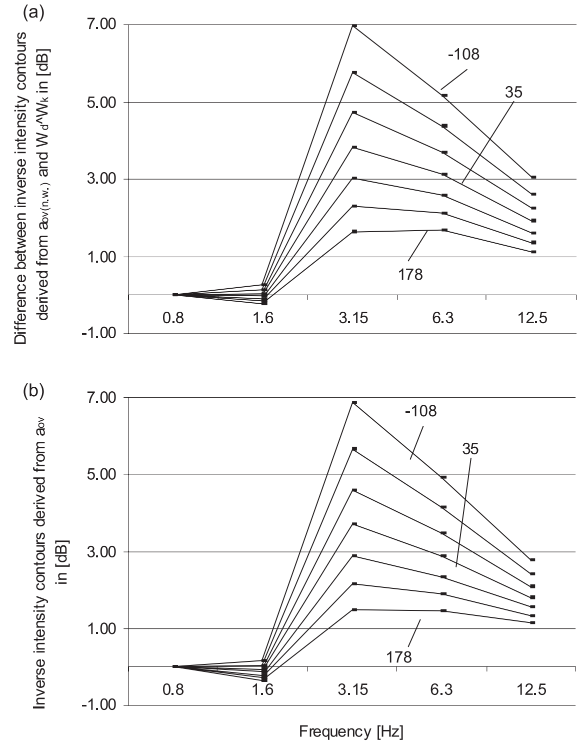

Fig. 12. (a) Difference between inverse intensity contours depending on arbitrary sensation units in 6 equidistant steps, derived from modified non-weighted overall vibration total values $a_{ov(n.w.)}$ (referred to 0.8 Hz) and $W_d \wedge W_k$ in dB for sinusoidal excitation x-direction (see Fig. 9 (a)) (b) Inverse intensity contours derived from weighted overall vibration total values a_{ov} (referred to 0.8 Hz) in dB.

All curves depending on arbitrary sensation units in 6 equidistant steps.

Conclusions

The differences between the obtained equivalent intensity contours and the current frequency weightings according to ISO 2631-1 were the following:

- strong dependency on vibration magnitude
- underestimation of the sensation varying in extent from 2 dB to 8 dB at 1.6, 3.15, 6.3 and 12.5 Hz in comparison with the reference frequency 0.8 Hz for all signals, with the most pronounced effects revealed at the frequencies 3.15 and 6.3 Hz and at lower intensities (a_{ov} around 0.48 m/s^2 to 0.8 m/s^2 r.m.s. at the reference frequency 0.8 Hz).
- some differences in the frequency weightings for sinusoidal and random octave band-width signals which should not be overinterpreted because of the restricted number of exposure conditions investigated in the study

The limitations of the study are the following:

- The study design did not allow differentiation between the frequency weightings W_d and W_k and the multiplying factor 0.25.
- Only five frequencies and six magnitude levels were investigated in order not to exceed an acceptable duration of a daily session.
- There was no multi-axis vibration.

The research on frequency weightings is currently not at a stage to be transferable for use in practice. More effort is needed to investigate the effects of vibrations typical for mobile workplaces, in particular for cases of multi-axis vibration. Moreover, further investigations should try to tackle the problem of evaluation of combined vibration at different input positions and relative movements between the body parts. Although it is commonly supposed that the sensation is a prerequisite for adverse health effects, there are doubts whether the findings from studies using subjective judgements are applicable, for instance, to the prediction of spinal injuries. The association between vibration signals weighted with altered filter factors and health effects should be confirmed.

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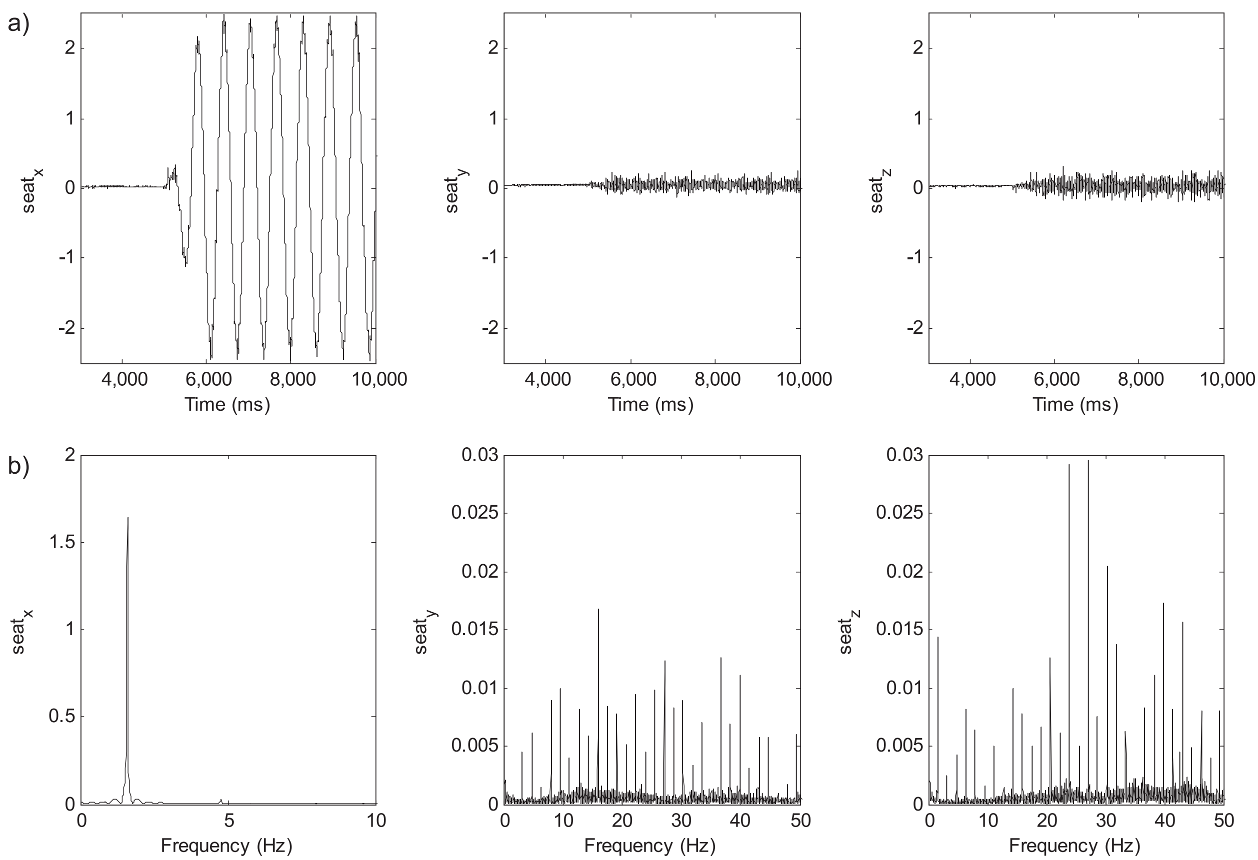
Appendix A

Example of measured non-weighted acceleration in m/s^2 at the seat in x-, y- and z-axes. Subject 36, sinusoidal excitation in x-direction, magnitude M3 (r.m.s. $a_{des,ex,seat}$ = 1.6 m/s^2), frequency F2 (1.6 Hz), repetition 1.
a) time signals (3rd to 10th second: 2 s pre-period + 1 s exposure with tapering + 4 s exposure).
b) FFT-analyses (6th to 69th second: 63 s exposure without tapering) (see also Fig. 2).



Appendix B: Instructions for the experiment

General information
You will sit down on a rigid seat and fasten the seat belt, which is not to be opened without a request by the operator. During the experiment, you will be exposed to vibration. The motions of the simulator will be monitored for the entire duration of the experiment. Minor deviations from the desired motions will lead to deactivation of the device. You will be able to shut the simulator down by using the emergency stop button. After switching off, the platform moves down slowly. During this process, the platform may temporarily remain in an inclined position. You will perceive different vibrations. The test conditions will vary and will be presented in random order. At certain times you will be asked to judge the intensity and the comfort of the vibration. Please follow the instructions given on the screen.

Judgements
A line will appear on the screen shortly after a question. The line will automatically become longer or shorter.

You should try to adjust the length of the line in accordance with your sensation, using the mouse buttons:
The *stronger* the sensation - the *longer* the line.

You can stop the extension and the shortening of the line with the right or the left mouse button. You can adjust the length of the line with the mouse buttons as well. Pressing the right button shortens the line, pressing the left button lengthens it. You can confirm the chosen length with a double click on the middle mouse button (the scroll wheel). Please tell the operator when you have been restricted due to the maximum length of the presented line.
You will be asked to judge the following sensations:

How intensive do you perceive the vibration to be?
This means the intensity of the vibration. Please concentrate on the vibration and disregard all additional influences such as noise, temperature, air quality, illumination or the comfort of the vibration. The latter will be judged separately.
The more intensive the vibration - the longer the line.

How comfortable do you perceive the vibration to be?
This means sensations which may relate to the comfort of vibration, for example sensations that you would associate with a convenient, cosy, pleasant, homely, proper etc. state.

Please, judge the experimental conditions only regarding the vibration comfort, and ignore, for example, the temperature, air quality, noise, accessibility of the mouse or the demands for your attention during the judgement.
The more comfortable the vibration - the longer the line.