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COMFORT CONTOURS: INTER-AXIS EQUIVALENCE

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Inter-axis equivalence for sinusoidal vibrations as stipulated by ISO/DIS 2631 for seated persons was studied by adjusting the acceleration of a horizontal sinusoidal test vibration ($x \vee y$) until it caused equal sensation as a vertical sinusoidal reference motion of the same frequency. The reference vibrations consisted of sine waves ranging from 1·6 to 12·5 Hz and were presented with three weighted accelerations of $a_{zw} = 0{\cdot}3$, 0·6 and 1·2 ms^{-2} r.m.s. (reference contours). 26 subjects (15 men, 11 women, 20–56 yrs, 153–187 cm) participated in the respective experiments. Based on the three reference contours, predicted values for horizontal motions were calculated by using the weighting factors provided in ISO/DIS 2631. The International standard was confirmed insofar as the shape of the contours determined for horizontal motions was independent from vibration magnitudes and as sensitivity to fore-and-aft and to lateral motions was similar. However, the accelerations adjusted for horizontal vibrations were considerably lower than predicted, suggesting that the weighing factors provided in ISO/DIS 2631 need to be corrected.

1. INTRODUCTION

Comfort contours, which relate vibration magnitudes to frequencies for equal sensation, were determined for seated, standing and recumbent persons. The majority of studies executed so far have dealt with vertical vibrations; a few have been executed with horizontal and even fewer with rotational vibrations [1].

Most contours were built up by matching "test" vibrations with an external criterion which might be a comfort label (e.g., intolerable), a reference vibration or another stimulus such as noise [2–4]. In most of the later studies, either the experimenter or the subject varied the magnitude of the test signal until it caused the same sensation as a preceding reference vibration (see e.g., references [5–7]). Apart from a very few exceptions [6], the reference and test motions concerned the same axis. Despite different methods and considerable quantitative differences between various studies the shapes of the contours elaborated by different authors are remarkably similar.

ISO/DIS 2631 [8] provides weighting factors to estimate equal discomfort for sitting, standing and recumbent persons mainly exposed to translational but also—when seated—to rotational vibrations in the three orthogonal axes within the range of 0·5–80 Hz. Appropriate contours for seated persons were calculated according to this standard and are presented in Figure 1 for translational, vertical (z) and horizontal (x, y) vibrations at three vibration magnitudes ($a_W = 0{\cdot}3$, 0·6 and 1·2 ms^{-2} r.m.s.). Presupposing the same weighted accelerations, one expects equal discomfort at any point of the contours for vertical and horizontal motions. As their shapes are typical to though not necessarily

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congruent with the contours obtained by different authors, intra-axis validity can be accepted at least for the most often studied vertical motions (not for individuals but for groups).

2. OBJECTIVES

Using the method of adjustment, Fothergill and Griffin [9] determined equal discomfort for five octave centre frequencies from 2·5 to 40 Hz in the vertical direction. The authors presented these frequencies (and a random vibration) as reference motions with acceleration magnitudes of 1 ms^{-2} r.m.s. The same frequencies were used as test motions, so that eventually each of the six vibrations were tested against each other. Neither the shapes nor the magnitudes of the resulting six comfort contours which refer to either of the six references varied significantly, but in any case large inter-subject variability increased gradually with frequency separation between the reference and the test motion. Accordingly, other studies revealed increasing standard deviations with frequency separation (see, e.g., reference [10]).

Griffin *et al*. [6] related equal comfort for sinusoidal translational vibrations of 1 to 100 Hz and of the three orthogonal axes to a 10 Hz vertical motion of 0·8 ms^{-2} r.m.s. The fact that the variability of the adjusted accelerations (indicated by the distances between the 25th and 75th percentiles) was greater for horizontal than for vertical motions led to the conclusion that the comparison task becomes more difficult if vibrations from different axes are matched, and that inter-axis equivalence as stipulated by ISO/DIS 2631 is questionable. Therefore, the present study was executed to investigate equivalence for sinusoidal motions between axes by adjusting the acceleration of a sinusoidal horizontal test vibration ($x \vee y$) until it produces equal sensation as a vertical sinusoidal reference motion. To avoid the bias caused by frequency separations, the test and reference stimuli had the same frequency.

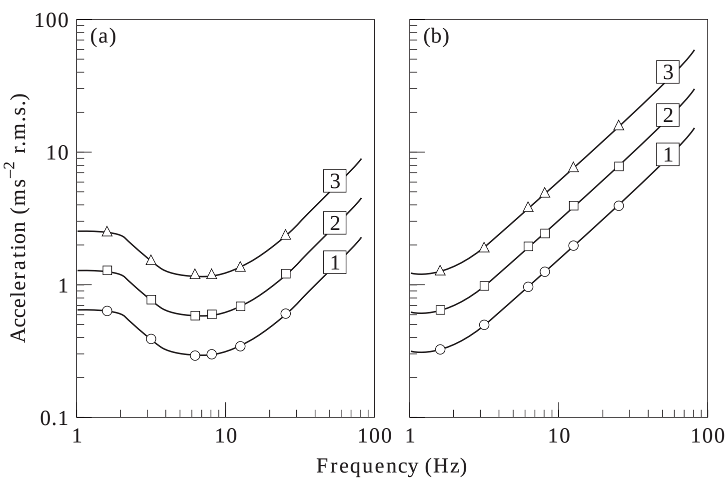

Figure 1. Comfort contours for seated persons for (a) vertical (z) and (b) for horizontal vibrations ($x \vee y$) and three vibration magnitudes computed according to ISO/DIS 2631 [8]. (3), Uncomfortable; (2), fairly uncomfortable; (1), not uncomfortable.

TABLE 1

Cross-axis coupling during test vibrations; means and standard deviations of accelerations in the indicated axis during the presentation of vibrations given in brackets

	1·6 Hz	3·15 Hz	6·3 Hz	8 Hz	12·5 Hz	25 Hz
Reference motion: $a_{zw} = 0{\cdot}3\ \mathrm{ms}^{-2}$ r.m.s.						
x-axis (z)	0·11 ± 0·04	0·11 ± 0·03	0·10 ± 0·02	0·11 ± 0·02	0·14 ± 0·03	0·49 ± 0·16
z-axis (x)	0·14 ± 0·03	0·14 ± 0·03	0·13 ± 0·02	0·13 ± 0·02	0·17 ± 0·03	0·26 ± 0·07
y-axis (z)	0·08 ± 0·02	0·08 ± 0·03	0·08 ± 0·03	0·09 ± 0·03	0·10 ± 0·02	0·34 ± 0·07
z-axis (y)	0·14 ± 0·03	0·14 ± 0·03	0·15 ± 0·03	0·15 ± 0·03	0·18 ± 0·02	0·30 ± 0·09
Reference motion: $a_{zw} = 0{\cdot}6\ \mathrm{ms}^{-2}$ r.m.s.						
x-axis (z)	0·13 ± 0·03	0·12 ± 0·03	0·12 ± 0·03	0·13 ± 0·03	0·17 ± 0·04	0·84 ± 0·25
z-axis (x)	0·14 ± 0·03	0·14 ± 0·03	0·14 ± 0·02	0·14 ± 0·03	0·18 ± 0·04	0·34 ± 0·12
y-axis (z)	0·08 ± 0·02	0·08 ± 0·03	0·08 ± 0·03	0·09 ± 0·03	0·11 ± 0·02	0·49 ± 0·14
z-axis (y)	0·14 ± 0·03	0·14 ± 0·03	0·16 ± 0·03	0·17 ± 0·03	0·21 ± 0·04	0·37 ± 0·11
Reference motion: $a_{zw} = 1{\cdot}2\ \mathrm{ms}^{-2}$ r.m.s.						
x-axis (z)	0·18 ± 0·03	0·14 ± 0·04	0·16 ± 0·04	0·16 ± 0·04	0·24 ± 0·06	1·49 ± 0·48
z-axis (x)	0·15 ± 0·03	0·15 ± 0·03	0·15 ± 0·02	0·17 ± 0·04	0·23 ± 0·06	0·51 ± 0·20
y-axis (z)	0·10 ± 0·03	0·08 ± 0·02	0·08 ± 0·03	0·09 ± 0·03	0·15 ± 0·03	0·83 ± 0·29
z-axis (y)	0·15 ± 0·03	0·10 ± 0·03	0·17 ± 0·03	0·19 ± 0·03	0·25 ± 0·04	0·53 ± 0·13

3. MATERIAL, METHODS AND EXPERIMENTAL DESIGN

3.1. TECHNICAL EQUIPMENT

The motions of two hydropulse vibrators operating in the vertical and in the horizontal direction respectively with frequency ranges 1–100 Hz and maximum displacements of ±12·5 cm were transmitted to an aluminium platform with an area of $50 \times 70\ \mathrm{cm}^2$ operating reliably within the above-mentioned frequency range.

A rigid, slightly contoured wooden seat without a backrest was mounted on the platform. Translational vibrations were measured according to ISO 2631 between the seat and the ischial tuberosities in the three orthogonal axes (unweighted measurements performed with a Brüel and Kjaer (B&K) 4322, Sound Level Meter 22341, BZ 7105 Module, 2522 Human Vibration Unit) during the presentation of the reference motions and immediately after the subjects had signalled equality.

The unweighted triaxial background acceleration was $<0{\cdot}1\ \mathrm{ms}^{-2}$ r.m.s., and its frequency weighted magnitude was $<0{\cdot}02\ \mathrm{ms}^{-2}$ r.m.s. Background motions contained a great amount of high frequencies (>100 Hz) which were perceptible through the feet. As this might influence the entire sensation, the platform was covered with damping material (Armaflex™, 28 mm) whereafter the subjective input of high frequency background vibrations were eliminated.

As listed in Table 1, vertical test vibrations were accompanied by horizontal motions (cross-axis coupling) and the reverse. Cross-axis coupling was almost the same in both situations. It was small below 25 Hz but considerably higher at 25 Hz. As this failure probably contributed to overall discomfort and consequently to the settings of the horizontal test motions (this suspicion is supported by the data), the presentation of the results was restricted to frequencies up to 12·5 Hz. Acceleration distortion as calculated according to Griffin *et al*. [6] for the highest vibration magnitude ($a_w = 1{\cdot}2\ \mathrm{ms}^{-2}$ r.m.s.) varied within the considered frequency range between 7% and 10% for vertical vibrations and between 17% and 23% for horizontal vibrations.

A 17 inch monitor used for information and instructions was located 1·5 m in front of the subject and adjusted to the head level.

3.2. ENVIRONMENTAL CONDITIONS

The technical equipment was installed into a climatic chamber (area 21 m^2) and air temperature was adjusted to 25°C (±0·1°C), and air velocity to 0·3 m/s (±0·05 m/s); radiation temperature was equal to air temperature. Humidity varied between 40% and 50%. Specific noises produced by the equipment during operation were masked by a pink noise of 63 dB(A).

3.3. REFERENCE SIGNALS

With validity assumed for intra-axis equivalence of vertical motions, the 18 sinusoidal reference vibrations were selected from comfort contours stipulated by ISO/DIS 2631. These were five sinusoidal frequencies from 1·6 to 25 Hz spaced at octave intervals (open symbols in Figure 1(a)) which were applied vertically at three vibration magnitudes ($a_{zw} = 0{\cdot}3$, 0·6, and 1·2 ms^{-2} r.m.s., also labelled as reference contours). Another 8 Hz motion was added to achieve an equal number of trials in each session (see below). Due to the considerable cross-axis coupling the results for 25 Hz were discarded from presentation (see above).

3.4. DESIGN AND PROCEDURE

The design and procedure is illustrated in Figure 2. As the equipment operates in only one horizontal axis, fore-and-aft (x) and lateral motions (y) were studied in separate sessions and achieved by rotating the seat through 90° (z/x- and z/y-experiments). To assess possible methodological errors test motions were presented not only in the fore-and-aft and in the lateral direction but equally often vertically. As each matching was executed three times, the determination of inter-axis equivalence required 108 comparisons for either of the horizontal axes (six frequencies, three magnitudes, two axes [z and $x \vee y$], three repetitions). To avoid fatigue, low (1·6 and 3·15), medium (6·3 and 8), and high frequencies (12·5 and 25) were applied in separate sessions. Therefore, each subject took part in six sessions (two horizontal axes, three frequency ranges).

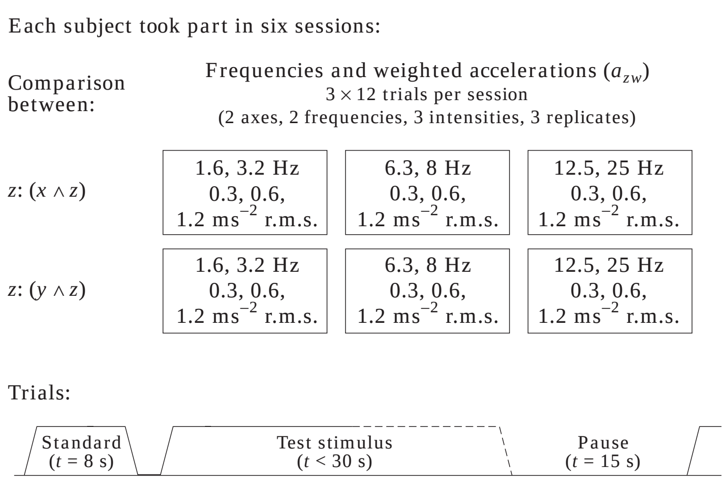

Figure 2. The experimental design and structure of the trials.

TABLE 2

Gender, height, and weight of the subjects

	Mean	Standard deviation	Minimum	Maximum
Eleven Women				
Age (yrs)	38·3	9·1	25	50
Height (cm)	166·9	5·8	153	172
Weight (Kg)	63·6	9·5	47	80
Fifteen men				
Age (yrs)	32·3	11·8	20	56
Height (cm)	177·7	5·4	169	187
Weight (Kg)	76·5	11·1	61	95
Twenty-six subjects				
Age (yrs)	34·8	11·0	20	56
Height (cm)	173·2	7·7	153	187
Weight (Kg)	71·1	12·2	47	95

During each session ($\approx$30 min), a set of 12 randomly presented trials (two frequencies, three magnitudes, two axes [z and $x \vee y$]) was applied three times.

Each trial started with a reference motion (8 s plus rise–decay time of 2 s). After a pause of 2 s the test signal occurred (2 s rise–decay time) with the same frequency as the reference signal and a vibration magnitude of about 0·1 ms^{-2} r.m.s. and the subjects altered its magnitude until it caused equal sensation as the reference.

The time for adjustment was limited to 30 s (it actually did not exceed 17 s in 95% of the cases; the very maximum was 29 s). After equality was signalled, the actual vibration continued for a further 2 s to measure its magnitude. The trial was terminated with a pause of 15 s. The respective phases of the trials were announced on the monitor. During the presentation of the test stimuli the subjects were asked to adjust its intensity until it was sensed as equal to the reference signal.

The subjects adopted a slightly kyphotic posture. They held a small board equipped with three keys which were inactive during reference vibrations. Test motions were amplified/attenuated by pressing the upper right or the upper left key respectively. Equality was signalled by the key located in the middle below the others.

3.5. SUBJECTS

Twenty-six subjects (15 men and 11 women) participated in the experiments. Their data are presented in Table 2. The volunteers were screened using an extended list of medical contra-indications based on BSI 7085 [11]. They were informed about the experiment and took part in a training session to familiarize them with the procedure and their task.

3.6. ETHICAL RECOMMENDATIONS

The experiments were approved by the local ethics committee. The safety aspects listed in BSI 7085 [11] were taken into account. The experimenter and the subjects were in easy reach of an emergency button/handle capable of stopping the vibrations. As injuries were unlikely, no criteria were defined for break-off, apart from subjects' decisions.

4. RESULTS

The deviations between intended and acutally applied accelerations as measured between seat and ischial tuberosities were almost negligible and did not exceed 1·5%. Nevertheless, some calculations and presentations refer to the realized values of the 18 vertical references.

4.1. EVALUATION

Each trial was presented three times and the median of the three accelerations adjusted for the test motions was taken for further analyses. The medians were normally distributed, allowing the calculation of arithmetic means, standard deviations, *t*-tests and an analysis of variance (see Table 3).

4.2. VERTICAL VIBRATIONS, METHODOLOGICAL ERROR

The reference motions were presented vertically. In order to assess possible methodological errors, test stimuli were presented not only in both the horizontal directions but also vertically and no deviations were expected between the accelerations of vertical reference motions and those "readjusted" for the respective vertical test vibrations. This also implies the expectation to obtain the same settings for vertical test motions in those sessions executed to determine equivalence between vertical and fore-and-aft or between vertical and lateral vibrations.

The appropriate results are shown in Figure 3, separately for z/x- and z/y-experiments and separately for the three magnitudes (a_{zw}: 0·3, 0·6, 1·2 ms^{-2} r.m.s.). Thin lines represent the reference signals, bold lines and circles the appropriate values adjusted for the test signals.

Reference and "readjusted" values did not differ at the lowest vibration magnitude. Slightly, still insignificant lower settings were observed at the medium magnitude, but the vertical accelerations adjusted to the upper magnitude were significantly below those of the appropriate references (with p-values $< 0·01$ for each frequency). This was also true for z/x- and z/y-experiments.

TABLE 3

Mean differences between expected (according to ISO/DIS 2631; see text) and adjusted accelerations for vertical and horizontal vibrations

	1·6 Hz	3·15 Hz	6·3 Hz	8 Hz	12·5 Hz
Reference motion: $a_{zw} = 0·3$ ms^{-2} r.m.s.					
x-axis	$-0·02 \pm 0·10$	$0·20 \pm 0·09$	$0·49 \pm 0·21$	$0·67 \pm 0·29$	$1·18 \pm 0·43$
y-axis	$0·03 \pm 0·13$	$0·21 \pm 0·11$	$0·29 \pm 0·24$	$0·59 \pm 0·25$	$1·17 \pm 0·32$
z-axis	$-0·11 \pm 0·13$	$-0·08 \pm 0·09$	$-0·00 \pm 0·05$	$-0·01 \pm 0·06$	$-0·03 \pm 0·09$
Reference motion: $a_{zw} = 0·6$ ms^{-2} r.m.s.					
x-axis	$0·17 \pm 0·15$	$0·59 \pm 0·12$	$1·19 \pm 0·27$	$1·43 \pm 0·39$	$2·67 \pm 0·48$
y-axis	$0·24 \pm 0·17$	$0·53 \pm 0·16$	$0·87 \pm 0·33$	$1·30 \pm 0·36$	$2·68 \pm 0·47$
z-axis	$-0·01 \pm 0·23$	$-0·04 \pm 0·15$	$0·07 \pm 0·09$	$0·05 \pm 0·12$	$0·06 \pm 0·13$
Reference motion: $a_{zw} = 1·2$ ms^{-2} r.m.s.					
x-axis	$0·43 \pm 0·27$	$1·41 \pm 0·19$	$2·58 \pm 0·53$	$3·15 \pm 0·65$	$5·62 \pm 0·84$
y-axis	$0·56 \pm 0·30$	$1·24 \pm 0·32$	$2·09 \pm 0·79$	$2·92 \pm 0·70$	$5·67 \pm 0·87$
z-axis	$0·23 \pm 0·37$	$0·27 \pm 0·25$	$0·30 \pm 0·25$	$0·29 \pm 0·18$	$0·29 \pm 0·26$

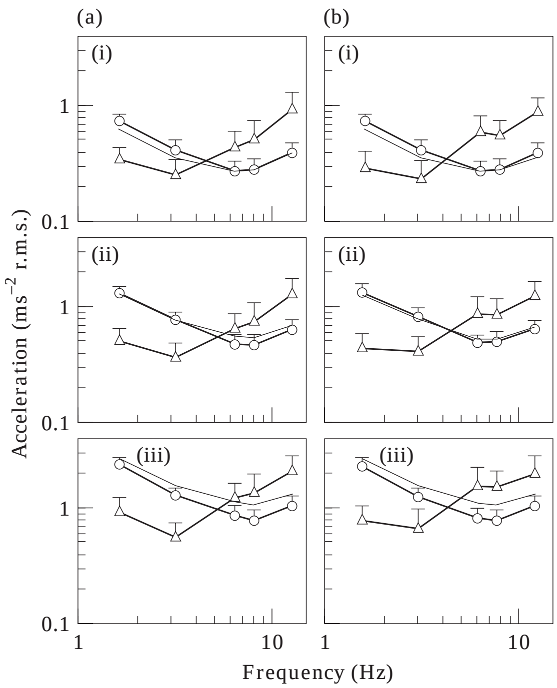

Figure 3. Means and standard deviations of accelerations at three vibration magnitudes in (a) z/x- and (b) z/y-experiments (see text). —, vertical reference vibrations; —○—, readjusted vertical motions; —△—, horizontal motions. To avoid overlaps, standard deviations are presented in only one direction. (i) Reference: $a_{zw} = 0{\cdot}3$ ms^{-2} r.m.s. (ii) Reference: $a_{zw} = 0{\cdot}6$ ms^{-2} r.m.s. (iii) Reference: $a_{zw} = 1{\cdot}2$ ms^{-2} r.m.s.

4.3. INTER-AXIS VALIDITY

Due to the lower settings, the "readjusted" accelerations of the vertical test vibrations were multiplied by the ratio w_k/w_d (Table 4), where w_k and w_d denote the respective frequency weighting factors in ISO/DIS 2631 for the vertical and for the horizontal vibrations. If the weighting factors in the International Standard are valid, the resulting values (in the following labelled as response-related expected accelerations) are supposed to cause the same sensation as the respective "readjusted" vertical vibrations.

TABLE 4

Weighting factors w_d and w_k used for the calculation of the expected horizontal accelerations on the basis of readjusted vertical vibrations (according to ISO/DIS 2631, *Table* 2)

Frequency (Hz)	Weighting factors w_k	w_d	Ratio w_k/w_d
1·6	0·494	0·968	0·510
3·15	0·804	0·642	1·252
6·3	1·054	0·323	3·263
8	1·036	0·253	4·095
12·5	0·902	0·161	5·602

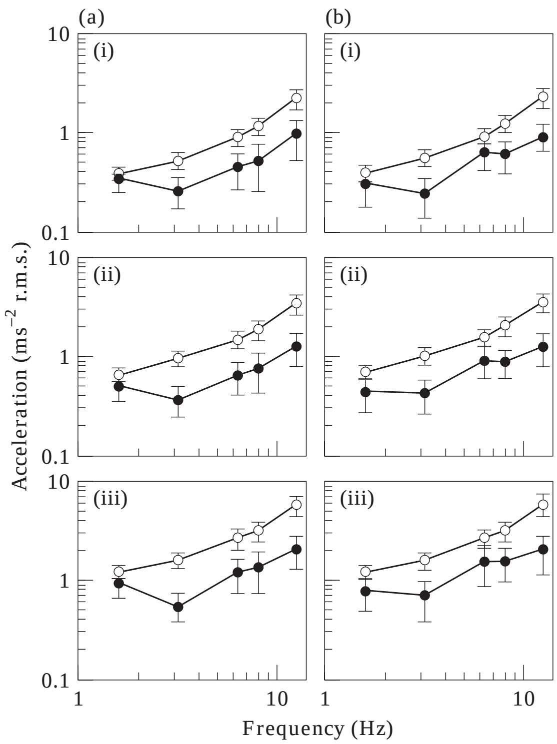

Figure 4. Means and standard deviations of response-related expected accelerations for horizontal test vibrations according to ISO/DIS 2631 (—○—) and acutally adjusted accelerations (—●—) at three vibration magnitudes. (a) Fore-and-aft (x); (b) lateral (y). (i) Reference: $a_{zw} = 0{\cdot}3$ ms^{-2} r.m.s. (ii) Reference: $a_{zw} = 0{\cdot}6$ ms^{-2} r.m.s. (iii) Reference: $a_{zw} = 1{\cdot}2$ ms^{-2} r.m.s.

In Figure 4 are presented means and standard deviations of response-related expected accelerations (open circles) and of accelerations adjusted for horizontal motions (full circles), separately for the three magnitudes, and the five frequencies. This presentation reveals that the general shapes of the adjusted contours are similar for both horizontal motions and for the three vibration magnitudes as well. However, according to Figure 3 the variabilities (standard deviations) of the adjusted horizontal contours are considerably greater than for the "readjusted" vertical contours.

Despite the correction of the expected values, the actual settings were significantly lower for both the horizontal test motions (Figure 4, $p < 0{\cdot}001$, except for 1·6 Hz at the lowest magnitude); the appropriate differences and the respective ratios are listed in Table 5. The latter varied between 1·1 and 1·7 at 1·6 Hz and between 2 and 3 at higher frequencies.

The differences were submitted to a multivariate analysis of covariance (MANCOVA [12]) where the within-subject effects of frequencies (1·6, 3·15, 6·3 and 12·5 Hz), vibration magnitudes of reference signals ($a_{zw} = 0{\cdot}3$, 0·6 and 1·2 ms^{-2} r.m.s.) and horizontal axes (x, y) were considered as well as the between subjects effect of gender. The corresponding interaction terms and age and height as subject-specific covariates were also included in the analysis. Thereafter, none of the personal data (gender, age and height) had an influence on the result, whereas the differences increased gradually and significantly with vibration frequencies and with vibration magnitude ($p < 0{\cdot}001$; in Figure 4 these effects are masked by the logarithmic presentation). Another significant influence arises from the interaction of frequencies and axes ($p < 0.005$), probably related to lower settings at 6·3 and 8 Hz for fore-and-aft test motions.

DISCUSSION

5.1. METHODOLOGICAL ASPECTS

5.1.1. *Subjects*

Twenty-six subjects (15 men and 11 women) participated in the experiments. Apart from medical contra-indications, no other selection criteria were applied. Age, height and weight were normally distributed and well within the range expected in representative samples.

None of these personal variables had a significant influence on the result. Negligible effects of age and gender were also reported by other authors [5, 6, 13, 14]; only Jones and Saunders [15] reported a slightly higher sensitivity in female subjects at 4–6 Hz.

Griffin *et al*. [6] and Donati *et al*. [5] reported that taller subjects were less sensitive to low frequencey vertical vibrations but more sensitive to fore-and-aft vibrations. This was not true in the present study, and might be explained by the fact that the heights varied in a rather narrow range (161–180 cm) if the smallest and the tallest subject are disregarded.

5.1.2. *Posture*

Griffin [16] and Dupuis [17] pointed out that posture has a significant effect on the transmissibility of vertical motions. In the present study the subjects adopted a slightly kyphotic posture, which particularly reduces the transmission of higher frequencies. Although this might be less relevant here, it is questionable in any case whether this affects subjective comfort. Whereas Griffin *et al*. [6] found a correlation between transmissibility and comfort, Oborne and Boarer [7] obtained the same comfort contours for subjects sitting erect or slouched, and Donati *et al*. [5] reported merely weak associations between subjective assessments and biodynamic parameters (which the authors studied in separate experiments).

TABLE 5

Differences (means ± standard deviations) of response-related expected (according to ISO/DIS 2631 [8]) and adjusted accelerations for horizontal vibrations and the geometric mean of their ratios in brackets

	1·6 Hz	3·15 Hz	6·3 Hz	8 Hz	12·5 Hz
Reference motion: $a_{zw} = 0{\cdot}3$ ms^{-2} r.m.s.					
x-axis	0·04 ± 0·10 (1·1)	0·28 ± 0·10 (2·1)	0·48 ± 0·20 (2·2)	0·68 ± 0·23 (2·5)	1·29 ± 0·58 (2·5)
y-axis	0·09 ± 0·11 (1·4)	0·33 ± 0·09 (2·1)	0·31 ± 0·24 (1·6)	0·67 ± 0·25 (2·3)	1·44 ± 0·62 (2·6)
Reference motion: $a_{zw} = 0{\cdot}6$ ms^{-2} r.m.s.					
x-axis	0·16 ± 0·12 (1·4)	0·62 ± 0·16 (2·8)	0·89 ± 0·32 (2·5)	1·17 ± 0·40 (2·7)	2·31 ± 0·72 (2·9)
y-axis	0·25 ± 0·15 (1·7)	0·60 ± 0·18 (2·6)	0·67 ± 0·36 (1·8)	1·16 ± 0·52 (2·4)	2·38 ± 0·91 (3·0)
Reference motion: $a_{zw} = 1{\cdot}2$ ms^{-2} r.m.s.					
x-axis	0·29 ± 0·23 (1·4)	1·06 ± 0·25 (3·0)	1·54 ± 0·63 (2·4)	1·89 ± 0·73 (2·5)	3·83 ± 1·51 (2·9)
y-axis	0·44 ± 0·26 (1·7)	0·91 ± 0·25 (2·5)	1·15 ± 0·63 (1·8)	1·83 ± 0·97 (2·5)	4·08 ± 1·46 (3·1)

5.1.3. *Seat*

The rigid seat was probably ideal for the purpose of this study and suitable for the obtaining of repeatable results [1]. It might be debatable that no backrest was used during the experiments, particularly with respect to the findings of other authors [5, 10, 18, 25], who reported not only greater discomfort in this more realistic situation but also a shift of maximum sensitivity towards higher frequencies [5]. The main goal of the present experiment, however, was to study the validity of the weighting factors provided by ISO/DIS 2631 *per se*.

5.1.4. *Method of adjustment*

According to Griffin and Whitham [19] and Griffin *et al*. [6], the method of adjustment applied here, and also in several other studies [5, 7, 9], might be susceptible to lower settings. This proved to be true in the present study. To estimate possible methodological errors, the subjects were asked to readjust the intensities of vertical test vibrations as often as to adjust the magnitudes of horizontal vibrations to the same vertical reference motion until they caused equal sensation. "Readjustments" of vertical motions were sufficiently accurate at $a_{zw} = 0{\cdot}3\ \mathrm{ms}^{-2}$ r.m.s., but the settings were somewhat or significantly lower at $0{\cdot}6$ and $1{\cdot}2\ \mathrm{ms}^{-2}$ r.m.s. respectively. Therefore, the expected horizontal settings were adequately corrected to lower settings.

The matching procedure chosen here might account for the lower settings. As already stated by other authors [5, 6, 20, 21], discomfort of the second stimulus ("test" stimulus) is probably overestimated due to frequently used reference-test orders, to uncontrolled and mostly longer durations of test motions, to the fact that the test signal always started from low values and, finally, as the subjects prefer a more comfortable situation than experienced during reference motions.

As already stated by Fothergill and Griffin [9], the reliability of this method, however, proved to be high. Irrespective of lower settings, the "readjustments" of the vertical test vibrations were exactly the same during the sessions in which either equivalence between vertical and fore-and-aft or between vertical and lateral test stimuli were determined.

5.2. INTER-AXIS EQUIVALENCE

The majority of studies on comfort contours were designed to determine intra-axis equivalence, meaning that reference and test motions were applied in the same direction. Comparisons between different axes were scarcely executed.

In their fundamental study, Griffin *et al*. [6] determined the vibration magnitudes required for translational vibrations applied in the three orthogonal axes to produce discomfort equal to that caused by a 10 Hz motion of $0{\cdot}8\ \mathrm{ms}^{-2}$ r.m.s. The variability of adjusted accelerations which corresponds to the difficulty of the comparison task was greater for horizontal vibrations and increased with frequency separations.

Therefore, the validity of inter-axis equivalence as stipulated by ISO/DIS 2631 is questionable, and the main goal of the present study was to prove this. To reduce the difficulty of the comparison task, reference stimuli were applied with the same frequencies as the test signals.

Due to the fact that the differences between expected and "reset" vertical vibrations, as well as between expected and adjusted horizontal vibrations, increased with vibration magnitudes, the predicted horizontal motions were appropriately corrected for lower settings. The resulting response-related predicted values shown in Figure 4 (open circles) were calculated by multiplying the vertical responses ("reset" vertical accelerations) by the appropriate weighting factors proposed in ISO/DIS 2631 [8] (see Table 4).

The actual settings for horizontal motions (full circles) revealed the following: the variability of adjustments is greater for horizontal than for vertical motions; the shapes of the contours are independent of the vibration magnitudes; the shapes of the contours are similar for fore-and-aft and for lateral motions; actually adjusted accelerations were significantly lower than predicted.

5.2.1. *Variability of adjustments*

A greater variability of the accelerations adjusted for horizontal test stimuli as compared to vertical test motions (see Figure 3) was expected due to the study executed by Griffin *et al*. [6], and probably reflects a greater difficulty of comparing vibrations of different axes.

5.2.2. *Shapes of the contours for horizontal motions*

The fact that the shapes of the contours were independent of the vibration magnitudes is supported by several other authors [6, 13, 15, 22, 23] as well as by ISO/DIS 2631 [8].

Similar contours for fore-and-aft and lateral motions are suggested by ISO/DIS 2631 and were also reported by several authors [5, 6, 24]. However, the contours determined here were not perfectly parallel. A significant influence on the result ($p < 0.005$) was related to the interaction of frequencies and axis due to lower settings at 6·3 and 8 Hz for fore-and-aft motions, indicating a somewhat greater sensitivity than that for lateral motions of the same frequencies. As this small but significant deviation occurred at any of the three vibration magnitudes, there might be a systematic difference.

5.2.3. *Expected versus adjusted horizontal motions*

Most remarkable are the great differences between predicted and actually adjusted accelerations. These differences were independent of gender, age and height, but increased gradually with frequencies and with vibration magnitudes (see Table 5), and they cannot be related to the method of adjustment, which accounts for the (appropriately corrected) lower settings. This conclusion is based on a recently executed methodological study by the authors using 16 subjects (unpublished). Reference vibrations (3·15 and 6·3 Hz) were equally often presented in the vertical and in the fore-and-aft and the consecutive test vibrations in the "opposite" direction. In any case, the difference between the horizontal and vertical accelerations sensed as equal were much greater than suggested by ISO/DIS 2631.

One major reason for the fact that the contours for horizontal motions are much flatter than those elaborated by several other authors is that most other authors varied the frequencies. In the presented study the direction of the vibrations was varied instead, and the difference is probably related to the transmissibility, which is considerably different for horizontal and for vertical motions (see, e.g., reference [1]).

The results are supported by Mistrot *et al*. [25], who presented first horizontal "reference" and then vertical "test" motions of the same frequencies (2–16 Hz). The authors also determined a higher sensitivity than predicted on the basis of ISO 2631 [8].

A study completed by Miwa [26] is scarcely comparable, although this author also matched vertical reference and horizontal test vibrations of the same frequencies. However, his subjects had to move between two vibration tables, one used for the vertical references and the other for the horizontal test motions. (The sensitivity was found to be about 10 dB less for horizontal vibrations with frequencies above 5 Hz.)

The present study was executed to evaluate the consistency of inter-axis equivalence with the frequency weighting provided in ISO/DIS 2631 [8]. When intra-axis validity is assumed for vertical vibrations, the great differences between expected and adjusted acceleration values lead to the conclusion, which is supported by other studies [25], that the frequency weighting of ISO/DIS 2631 underestimates the effects of horizontal vibrations. This is particularly true for frequencies above 1·6 Hz, where the ratios between expected and adjusted values varied between 2 and 3 against 1·1 and 1·7 for 1·6 Hz.

Due to the results of the present study and to the findings of Mistrot *et al*. [25], the comfort contours for horizontal motions are—at least within the frequency range of 1·6–12·5 Hz—considerably flatter than calculated according to ISO/DIS 2631 [8]. The data suggest the revision of the horizontal frequency weighting ($>1{\cdot}6$ Hz). However, the present study was focused on inter-axis equivalence for successively presented single-axis sinusoidal motions. It was not designed to determine correct frequency weightings for intra-axis equivalence. Further studies should also be extended to multi-axis and multi-frequency vibrations to prove the validity of the multiplying factor k which is introduced for the assessment of complex vibrations.

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