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Examination of perceptions (intensity, seat comfort, effort) and reaction times (brake and accelerator) during low-frequency vibration in x- or y-direction and biaxial (xy-) vibration of driver seats with activated and deactivated suspension

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Abstract

The optimal design of driver seats with horizontal suspension requires knowledge of human response with respect to the perception of the vibration intensity and seat comfort or of the performance in motor tasks. In an experimental study, 12 male volunteers (body mass 59–97.3 kg) were exposed to whole body vibrations in isolated x- or y-direction (three levels of magnitude) and biaxial xy-direction (combination of the x- and y-exposures on level two) sitting on a driver seat. The suspensions in x- and y-directions were randomly locked or unlocked. A brake and an accelerator foot pedal had to be pressed on demand as fast as possible. The perceptions of the vibration intensity, the seat comfort and the effort to carry out the motor task were judged by cross modality matching (modality: length of a line). The intensity judgements significantly increased with raising vibration magnitude. They were significantly higher for locked suspension. With only some exceptions, the judgements of the seat comfort decreased significantly with increasing magnitude, locked suspension and time. The effort judgements significantly increased with raising magnitude and time and revealed a tendency towards a lower effort with activated suspension. The reaction times showed no significant influences of vibration magnitude, suspension or time, but higher demands seemed to be compensated by enhanced effort. The w_d-weighting did not adequately reflect the perceptions for the frequency spectra applied in this study in the x-axis. A modified 'overall vibration total value' determined from the non-weighted accelerations instead of the weighted ones (ISO 2631-1, Article 8.2.3) corresponded with the subjective judgements in case of exposure in x- and xy-directions. A clear definition of 'comfort' or 'discomfort' or the use of 'intensity' instead of these terms is recommendable.

1. Introduction

The potentially adverse health effects of horizontal vibration in some vehicles have led to the development of suspension seats with horizontal isolation systems. The optimal design of such suspensions requires

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knowledge of human response with respect to the perception of vibration and seat comfort or of the performance in motor tasks when driving the vehicle.

The term 'vibration discomfort' is commonly used for measurements of the subjective feelings about the vibration [1–5]. Some papers use the term 'effect of vibration on the comfort' [6] or they combine discomfort and comfort on scales varying from uncomfortable to comfortable [7]. Apart from the variety in several studies, the use of these phrases is linked with semantic and linguistic problems. For example, there is no term 'discomfort' in German, but 'comfort' exists. One could suppose the inversion of the scale using the term 'comfort' to be a solution. But probably, 'comfort' is not merely the opposite of 'discomfort'. Discomfort seems to be associated with biomechanical factors (joint angles, muscle contractions, pressure distribution) and tiredness, whereas 'comfort' is rather associated with feelings of relaxation and well-being [8]. In a preceding 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. However, the translation from German into English and vice versa probably changes the meanings of the words. Presumably, an experiment with English speaking subjects could lead to completely different results. Possibly, for similar reasons, Griefahn and Bröde [9] determined the equal 'comfort' contours asking the German speaking volunteers to alter the test signal until they judged it to be equal in 'magnitude'—not in 'comfort'—of a reference signal. Because of the vagueness of 'vibration discomfort' in German, it was decided to measure the perception of vibration with 'vibration intensity' in the present study. It was expected, that the judgements of vibration intensity (i) increase with raising magnitude of exposure and (ii) are higher in case of locked suspension compared with activated suspension—a sufficient effect of suspension assumed -, and (iii) are repeatable and independent of the duration of the entire examination.

From the drivers, point of view, the comfort of the driver seat seemed to be of more interest than the feelings about vibration alone. Ebe and Griffin [2] developed models of seat 'discomfort'. They included static and dynamic seat characteristics. The dynamic characteristic reflected the increase of 'vibration discomfort' with increasing vibration magnitude and the static factor (cushion stiffness only) reflected seat comfort without vibration. When the vibration was low, the seat discomfort was dominated by static factors. Conversely, the seat discomfort became dominated by dynamic factors, when the vibration magnitude increased. Assuming this model as suited, the 'seat discomfort' only reflects the 'vibration discomfort' as long as the static seat factors remain constant, i.e. when the same seat is used in all experiments. Kolich and Taboun [10] developed a more complicated model for static conditions without vibration. They described and validated an 'overall comfort index' with a linear regression model integrating seat interface pressure characteristics, individual anthropometric and demographic data and perceptions of seat appearance. De Looze et al. [11] reviewed the literature concerning 'sitting comfort and discomfort' without vibration. They conclude, that pressure distribution appears to be the measure with the most clear association with the subjective judgements.

In summary, what concerns the 'seat comfort', the static factor seems to depend on various characteristics of the seat and the subject. Additionally, a time dependency has to be assumed. The dynamic factor, i.e. the 'vibration discomfort', is ambiguously defined (see above), but is associated with the vibration magnitude.

What concerns the present study, the seat comfort can be expected to be independent from the vibration magnitude, if the subjects are able to separate this judgement clearly from other perceptions (see briefing). However, concomitant factors may modify the perception. It could be perceived as better with activated suspension due to a lower perceived vibration intensity or less unpleasant frequency content. On the other hand, the related enlargement of relative displacement between the subject and the cabin could lead to a reduction of the seat comfort. Taking into account these arguments, the independence of the seat comfort from vibration characteristics was to be tested. If the subjects were not able to separate between static and dynamic perceptions one could suppose (i) a decrease of 'seat comfort' with increasing vibration magnitude, (ii) an increase of 'seat comfort' due to suspension because of a lower perceived vibration intensity or less unpleasant frequency content—assuming a sufficient effect of suspension—and (iii) a decrease of 'seat comfort' with increasing duration of examination.

McLeod and Griffin [12] summarised the effects of translational whole-body vibration on continuous manual control performance. Manual control performance is not directly comparable with foot pedal operations. Even so, pressing foot pedals on demand as conducted in this study also includes visual, cognitive and neuro-muscular performance. From that point of view, their paper gives some clues to possible hypotheses. The most disruptive effects on performance are observed at vibration frequencies below about 1 and 3 Hz. Random motions seem to have more detrimental effects than the predictable sinusoidal motions. Probably, the subjects are able to induce voluntary eye movements to compensate for the displacement between the head and the display. Obviously, the disturbance of manual performance increases with vibration intensity across a wide range of magnitudes, frequencies and task conditions. Hornick [13] examined foot operations under vibration. He found significant disruptions of 'maintaining a constant foot pressure', increasing with raising sinusoidal vibration intensity at frequencies between 1.5 and 3.5 Hz in the x- and y-axis. In the current experimental study, the volunteers were exposed to random vibration of different magnitudes, characterized by a dominant frequency content from about 1–4 Hz (see Section 2). Detrimental effects on the performance were expected to increase with vibration magnitude. McLeod and Griffin [12] described, that the effects could be removed by an active vibration isolation system which compensated for platform movements. However, the performance disruption was not eliminated if the display was not isolated from the platform motion. In the present study, the seat suspension system only isolated the subjects from the vibration. So, in comparison with the locked suspension, the relative displacement between the subjects' heads and the display decreased, but the displacement between the seat position and the foot pedals increased. A worsening of the performance was expected, assuming more important effects of the mechanical interference on the neuro-muscular part than on the visual and cognitive parts of the complex performance 'pressing a pedal on demand'. Time-dependencies of the performance are probably affected by the task presented, its difficulty and the subjects' motivation and experience. A definition of a simple quantitative relationship between duration and performance effects seems not to be possible. The requirements concerning attention and cognitive processes appear to be the only factors affected by vibration duration [12]. Metz [14] reported on constant performance over time in a simple short-term signal discrimination test, comparable with the test used in this study. Probably, the volunteers compensated adverse effects by enhanced effort. In the current study, obvious time-dependency of the performance was not supposed because of the low requirements of cognitive processes. Moreover, fatigue was not expected due to short exposure times and breaks between the exposures. To sum up one may suppose (i) a decrease of performance with increasing vibration magnitude, (ii) a decrease of performance due to suspension and (iii) no time-dependency of performance in the current investigation.

The effort to carry out the reaction task is supposed to be highly associated with the performance. With regard to the known hypotheses from the literature, an increase of effort may be expected with (i) increasing vibration magnitude, (ii) activated suspension and (iii) time of examination.

The examination aimed at investigating the influence of the vibration magnitude, the vibration direction and the relative motion between the operator seat and the control elements on the driver's performance and on the judgements of the vibration intensity, the seat comfort and the effort to carry out the operating task during horizontal whole-body vibration of practical relevance and using a suspension seat.

2. Method

2.1. Operator seat and pedals

The seat used was fitted with suspension systems in the x-, y- and z-axis. The suspension in z-direction was permanently locked by a mechanical device. The angle between the seat and the backrest and the slope of the seat were kept constant in order to realise a subjects' posture given in Ref. [15] (see Section 2.3). The backrest extension was completely pulled out. The seat was positioned in the centre. The fore/aft adjustment (locking lever) of the whole seat was set to a medium position and remained. Only the seat depth was adjusted according to the length of the subjects' thighs. A hip roll belt was used for safety reasons.

The pedals used met the requirements for comfortable operating (small pedal travel, low pedal resistance) [16].

2.2. Exposure

Corresponding to the typical field of application of the seat, the exposure conditions (frequency content, magnitudes, directions of whole body vibration at the seat base) were selected and prepared with consideration of field measurements on the floor of a Tractor 'Deutz 150' under typical conditions [17]. 'The field data were characterized by a dominant frequency content from 1 to 3 and 7 to 12 Hz in the x-axis and from 1 to 4 Hz in the y-axis. Random control signals with similar frequency content and a duration of 166 s were generated (FasTest Manager Software by FCS Control Systems B.V. The Netherlands). These exposures were produced by a man-rated electro-hydraulic Hexapod with a control system by FCS Control Systems B.V. (The Netherlands), considering the guidelines for human experiments with WBV (ISO 13090-1 [18]).

Since the conditions measured in the field caused very different magnitudes, a similar range of magnitudes (6 dB) was chosen for the x- and y-directions. Due to the different frequency content of whole-body vibration in the x- and y-directions, non-weighted root-mean square (rms)-values alone seemed to be not very informative. It was decided to adjust the magnitudes of vibration in the x- and y-directions to nearly identical values of w_d-weighted accelerations at the floor (platform), with a basic magnitude of the weighted rms-value of $0.55\,\mathrm{m\,s^{-2}}$. The authors were well aware of the fact that the weighted acceleration at the platform is different from that at the seat. By multiplying the desired accelerations in the time domain, the basic amplitude (magnitude 1 = M1) was increased by about 3 dB (magnitude 2 = M2) and 6 dB (magnitude 3 = M3) in order to realise three levels of magnitudes for the experimental conditions within the balanced design.

To obtain preliminary results on the significance of a simultaneous exposure in two axis, M2 of the x- and y-axis were combined. This exposure was presented as a 'reference' stimulus and was designated as MC.

Table 1 shows the mean non-weighted and weighted rms values of the accelerations according to ISO 2631-1 [6] during the first 25 s for all subjects measured in x-direction during excitation in the x-axis (M1, M2, M3) and biaxial xy-excitation (MC), and measured in y-direction during excitation in the y-axis (M1, M2, M3) and biaxial xy-excitation (MC). This first part of the exposure was relevant for cross-modality matching (see time schedule for every exposure in Section 2.3). The measuring points/conditions were: platform/activated and locked suspension, seat cushion/locked suspension and seat cushion/activated suspension.

Figs. 1 and 2 present the mean values, minimum and maximum of the weighted and non-weighted accelerations at different measuring points (Figs. 1(a) and (c), 2(a) and (c)) and the overall vibration total values, strictly calculated according to ISO 2631-1 (Figs. 1(d) and 2(d)) and additionally calculated from the non-weighted accelerations (Figs. 1(b) and 2(b)). Corresponding to ISO 2631-1, the overall vibration total value was calculated as follows (Figs. 1, 2(d))

$$
\begin{aligned}
a_{v\,\text{total}} = {} & [(0.25^2 a_{pkx}^2 + 0.25^2 a_{pky}^2 + 0.25^2 a_{pkz}^2) + (a_{cdx}^2 + a_{cdy}^2 + a_{cdz}^2) \\
& + (0.8^2 a_{bcx}^2 + 0.5^2 a_{bdy}^2 + 0.4^2 a_{bdz}^2)]^{1/2},
\end{aligned} \tag{1}
$$

Table 1
Mean values and standard deviations (in brackets) of the non-weighted (n.w.) and the weighted (w.) rms—values of the accelerations, all exposures, all subjects, measured in x-direction for isolated excitation in the x-axis or biaxial (xy-) excitation, measured in y-direction for isolated excitation in the y-axis or biaxial (xy-) excitation, measured at the seat base (platform) and the cushion from the 2nd s to the 25th s of exposure, bold letters: acceleration is higher with activated than with locked suspension. M1, M2, M3 = exposure magnitudes 1, 2, 3. MC = biaxial exposure magnitude 2, frequency weightings: platform w_k, cushion w_d

	Measuring point/suspension	rms n.w. x (m/s^2)	rms w. x (m/s^2)	rms n.w. y (m/s^2)	rms w. y (m/s^2)
M1	Platform	1.06 (0.01)	0.60 (0.00)	0.77 (0.00)	0.52 (0.00)
	Cushion/locked	1.21 (0.05)	0.67 (0.02)	0.83 (0.02)	0.57 (0.01)
	Cushion/activated	0.99 (0.02)	**0.78 (0.02)**	0.66 (0.02)	0.48 (0.02)
M2	Platform	1.47 (0.01)	0.84 (0.00)	1.12 (0.00)	0.76 (0.00)
	Cushion/locked	1.74 (0.07)	0.98 (0.2)	1.20 (0.02)	0.83 (0.01)
	Cushion/activated	1.40 (0.03)	**1.11 (0.03)**	0.94 (0.03)	0.69 (0.02)
M3	Platform	2.03 (0.01)	1.19 (0.00)	1.57 (0.00)	1.07 (0.00)
	Cushion/locked	2.47 (0.07)	1.38 (0.03)	1.70 (0.03)	1.17 (0.02)
	Cushion/activated	2.03 (0.05)	**1.56 (0.06)**	1.31 (0.04)	0.96 (0.03)
MC	Platform	1.45 (0.01)	0.83 (0.00)	1.12 (0.00)	0.77 (0.00)
	Cushion/locked	1.74 (0.06)	0.97 (0.02)	1.24 (0.02)	0.84 (0.02)
	Cushion/activated	1.39 (0.04)	**1.09 (0.04)**	0.99 (0.03)	0.71 (0.02)

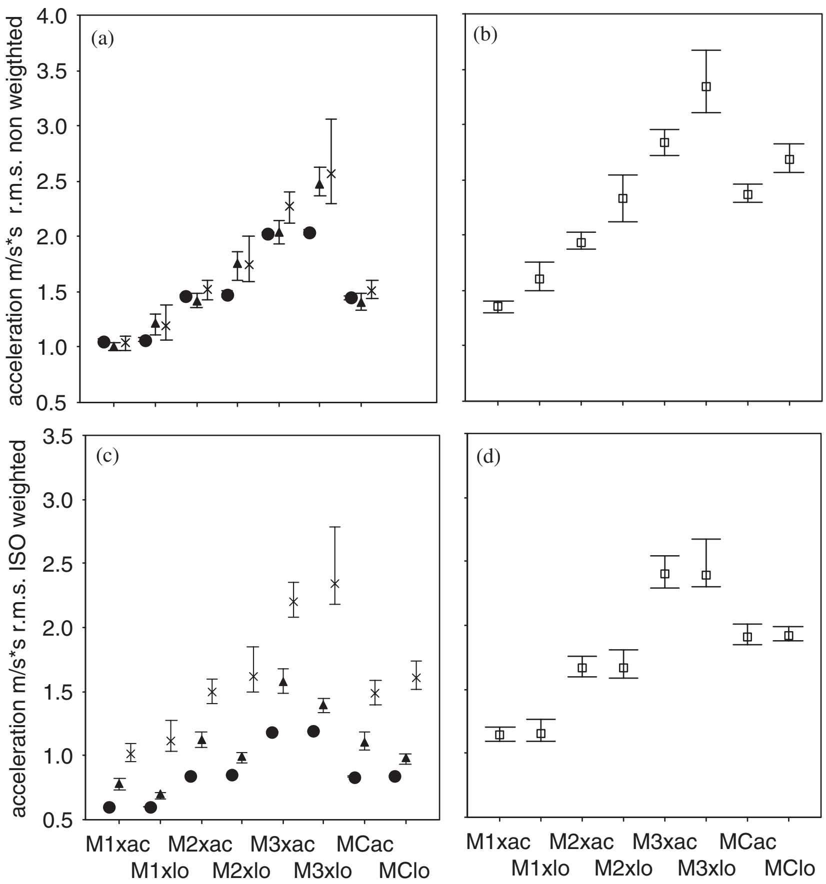

Fig. 1. Mean value, maximum and minimum of the acceleration (rms, 2nd to the 25th second of exposure). Excitation in the *x*- and combined *xy*-axis. Vibration magnitudes M1, M2, M3 and MC. Suspension ac = activated, lo = locked. (a) and (b) non-weighted values (c) and (d) w_k-, w_d- and w_c-weighted values according to ISO 2631-1. (a) and (c) measuring points (measured in *x*-direction) ● platform, ▲ cushion, × backrest. (b) and (d) overall vibration total value according to ISO 2631-1, but (b) calculated with non-weighted values.

respectively, without frequency weightings (Figs. 1 and 2(b)).

$$a_{v\,\mathrm{total}}(\mathrm{n.w.}) = [(0.25^2 a_{px}^2 + 0.25^2 a_{py}^2 + 0.25^2 a_{pz}^2) + (a_{cx}^2 + a_{cy}^2 + a_{cz}^2) + (0.8^2 a_{bx}^2 + 0.5^2 a_{by}^2 + 0.4^2 a_{bz}^2)]^{1/2}. \tag{2}$$

The first indices *p*, *c* and *b* reflect the measuring points platform, cushion and backrest, the second indices *k*, *d* and *c* indicate the kind of frequency weighting (ISO 2631-1) in Eq. (1).

Fig. 3 illustrates the power spectrum density of the accelerations, isolated excitations in the *x*- and *y*-axis, magnitude 2. The spectra of the magnitudes 1 and 3 had the same shape.

2.3. Experimental design

The subjects took part in the experimental studies on two different days. On the first day they were exposed in *x*-direction, on the second day in *y*-direction. Bearing in mind the results of pilot studies [19], a training trial was inserted before the two main trials (randomised locked and activated suspension) to avoid training effects during the main trials. The different magnitudes (see Table 1) were exposed in a randomised order (fully balanced design) with two repetitions. Table 2 gives an example for the experimental plan of the first main trial on the first day. The suspension was activated (subject numbers 1–11) or locked (subject numbers 12–18) by the levers for the isolator during the 5 min break between the two main trials. The suspension was switched

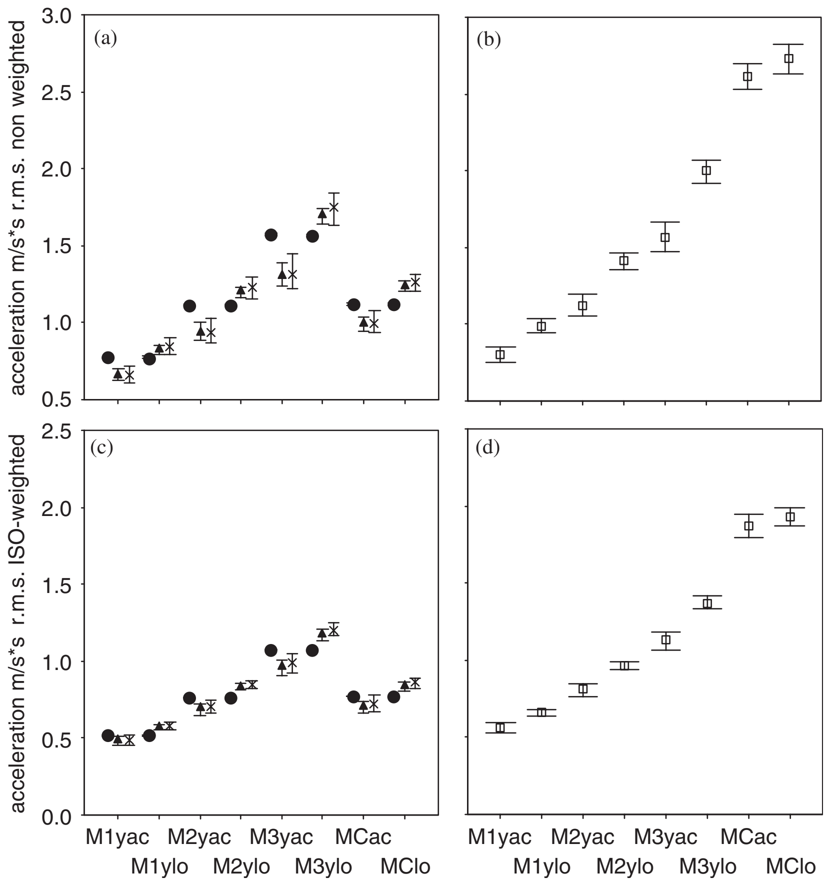

Fig. 2. Mean value, maximum and minimum of the acceleration (rms, 2nd to the 25th second of exposure). Excitation in the *y*- and combined *xy*-axis. Vibration magnitudes M1, M2, M3 and MC. Suspension ac = activated, lo = locked. (a) and (b) non-weighted values (c) and (d) w_k- and w_d-weighted values according to ISO 2631-1. (a) and (c) measuring points (measured in *y*-direction) ● platform, ▲ cushion, × backrest. (b) and (d) overall vibration total value according to ISO 2631-1, but (b) calculated with non-weighted values.

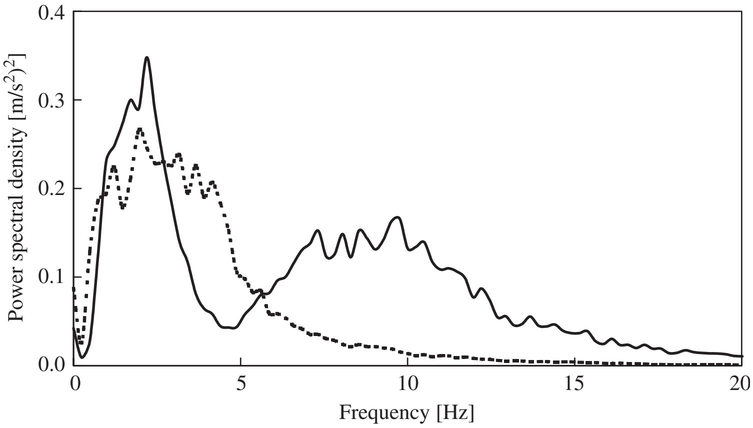

Fig. 3. Power spectrum density of the acceleration, isolated excitation in the *x*-axis (——) and the *y*-axis (- - - - - -). Magnitude M2.

on/off only in the direction of excitation on the levels M1, M2 and M3, that means either in the *x*-direction (day 1) or in the *y*-direction (day 2). The other horizontal suspension was locked, also in the case of biaxial excitation MC. The locking/activating of the suspensions was carried out secretly. The subjects were not

Table 2
Example of the experimental plan, day 1 (exposure in x-direction), main trial 1, F = locked suspension, A = activated suspension, R = repetition, M = magnitude, Reference: biaxial (xy-) vibration with magnitude 2 (see Section 2.2)

Subject	Reference	Exposure 1	Exposure 2	Exposure 3	Exposure 4	Exposure 5	Exposure 6	Reference
1	FR1M2	FR1M1	FR1M2	FR1M3	FR2M2	FR2M1	FR2M3	FR2M2
4	FR1M2	FR1M1	FR1M3	FR1M2	FR2M3	FR2M1	FR2M2	FR2M2
6	FR1M2	FR1M2	FR1M1	FR1M3	FR2M1	FR2M2	FR2M3	FR2M2
9	FR1M2	FR1M2	FR1M3	FR1M1	FR2M3	FR2M2	FR2M1	FR2M2
10	FR1M2	FR1M3	FR1M1	FR1M2	FR2M1	FR2M3	FR2M2	FR2M2
11	FR1M2	FR1M3	FR1M2	FR1M1	FR2M2	FR2M3	FR2M1	FR2M2
12	AR1M2	AR1M1	AR1M2	AR1M3	AR2M2	AR2M1	AR2M3	AR2M2
13	AR1M2	AR1M1	AR1M3	AR1M2	AR2M3	AR2M1	AR2M2	AR2M2
14	AR1M2	AR1M2	AR1M1	AR1M3	AR2M1	AR2M2	AR2M3	AR2M2
15	AR1M2	AR1M2	AR1M3	AR1M1	AR2M3	AR2M2	AR2M1	AR2M2
17	AR1M2	AR1M3	AR1M1	AR1M2	AR2M1	AR2M3	AR2M2	AR2M2
18	AR1M2	AR1M3	AR1M2	AR1M1	AR2M2	AR2M3	AR2M1	AR2M2

informed about the existence of a suspension in order to avoid an influence of the volunteers' knowledge on the subjective judgements.

The following sequence of events was the same for all trials every day, beginning with the training trial: reading the written information—sitting down—adjustment of the sitting posture by varying the position of the pedals and the hand support—application of the reflex markers for the motion analysis—driving the simulator in the neutral position—checking the visibility of the reflex markers—photography—verbal briefing concerning the judgements—start of the exposure—when the trial was completed: driving the simulator in the ground position—switching off the simulator—standing up. The subject should walk or stand during the 5 min pause between the trials.

The first trial and the second trial started with sitting down and continuing with driving the simulator in the neutral position.

The following time schedule was used for every exposure (exposure duration 166 s): request 'Please take up the right posture' on the subject's monitor 3 s before the start of the exposure—start of the exposure—start of the judgements (in the order intensity, comfort) at the 27th second of the exposure—request 'brake' or 'accelerator' at the time points (in s) 62.7/67.8/76.2/81.45/86.85/92.8/96.9/103.7/110.7/116.45/120.35/124.1/134.75/138.15/143.3/148.95 on the subject's monitor (eight times 'brake' and eight times 'accelerator' in a randomised order)—judgement of the effort—request 'brake' at the end of the exposure (166th second)—judgement of the comfort immediately after the exposure.

The 16 time points for the requests 'brake' or 'accelerator' were chosen to guarantee that the subjects had to press the pedals just at the moment when the displacement between seat and pedals reached its maximum. The time points were determined in a pilot experiment by means of the motion analysis system. The measurements of the accelerations started 5 s before the exposure and ended 5 s after the exposure. The registration of the subject's motion started 5 s before the exposure and lasted 30.2 s. So, the subject's seating posture was observed during the first part of exposure which was relevant for cross-modality matching.

2.4. Subjects and posture

A total of 12 healthy male volunteers took part in the experimental studies. Six subjects were necessary to meet the requirements of a completely balanced study design (three magnitudes, two kinds of suspension). The number was doubled to improve the power of the study. Although a lot of statistical parameters were known from a pilot study [19], the optimal sample size was not calculated. There were doubts, if the statistical parameters taken from the pilot study without vibration could be used for an investigation with whole body vibration.

It could be supposed that the measured values are influenced by the gender. We selected male subjects only, because the majority of the truck and tractor drivers are male. The subjects were selected in order to

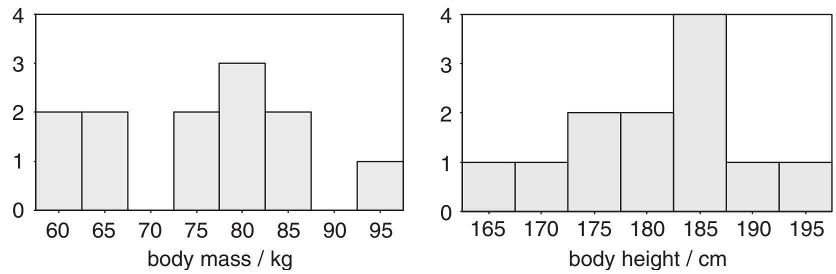

Fig. 4. Histograms of the body mass and the body height.

investigate a representative group concerning the distribution of the body mass in a normal population [20] or in drivers of coaches and trucks [21]. The body mass varied from 59.0 to 97.3 kg, the body height from 163.7 to 197 cm. Fig. 4 presents the corresponding histograms.

From previous studies it is known that the subjects should have a similar level of education, because the subjective judgements depend on the understanding of semantic nuances. Our subjects were university or advanced technical college students. Considering the age dependence of the reaction time, we recruited young subjects (age 20–31 years).

The subjects sat in an upright relaxed posture using the backrest and the hand support during the exposure. The right foot stood between the brake and the accelerator for the first 60 s of the exposure before the requests for pressing the pedals (see Fig. 5).

The posture was adjusted according to the angles given in Ref. [15] using an anatomical goniometer and varying the position of the pedals and the hand support. Fig. 6 illustrates the real sitting postures of the lightest (Subject 12) and the heaviest (Subject 13) subject (mean value of the markers, 2nd to the 25th s of exposure) in relation to the posture given in Ref. [15]. The measured angles were corrected in some cases for further analyses, because the lines from marker to marker did not correspond to the orientation of the bones. That is in particular obvious for the angle between the foot and the lower leg (see Fig. 5 for example).

2.5. Measurements

The following values were measured (for the measuring points see Ref. [22]):

- Translational accelerations (x, y, z) at the seat base, localisation at point P [22], with accelerometers (metal bloc Endevco 7290 with three accelerometers Endevco 7290A-10), sample frequency 1 kHz.
- Translational accelerations (x, y, z) at the seat frame below the seat cushion and above the suspension, with accelerometers (same above), sample frequency 1 kHz.
- Translational accelerations (x, y, z) at the seat cushion (Endevco 65–100 in seat pads Endevco 2560)—sample frequency 1 kHz—to estimate the magnitude below the buttocks and the transmissibility. For some subjects, the centre of the disc was located slightly in front (up to 5 cm) of the ischial tuberosities for comfort reasons (see Ref. [22]).
- Translational accelerations (x, y, z) at the seat backrest (Endevco 65–100 in seat pads Endevco 2560), localisation at point L [22], lumbar support of the seat was adjusted as flat as possible, sample frequency 1 kHz.
- Relative motions between the body parts (head, hand, right foot, right knee, left hip, including different angles) and platform, seat, pedals (motion analyses, frame frequency 100 Hz, 30.200 ms from the exposure start, 5 s pre-registration), for measuring points see Figs. 5 and 6.
- Subjective judgements (length of the line, questions: vibration intensity, seat comfort, effort to carry out the reaction test).
- Reaction times (eight times break, eight times accelerator in a randomised order, for time points see Section 2.3).

Fig. 5. Subject with applied markers for the motion analysis.

The modality length of a line (LL) was preferred among the methods of cross modality matching [23]. The magnitude estimation (ME) [23] was additionally used in a pilot study (unpublished). The findings of the pilot study suggested that LL results in more precise measurements. Seidel et al. [24] reported on similar conclusions when they tried to predict the subjective responses by multiple regression. The multiple regression analysis revealed much smaller coefficients of determination for ME than for LL. Analyses of variance showed, that the share of explained variance caused by between subject effects was about 3.5 times higher with ME. The between-subject-effects were more significant with ME and accounted for the smaller shares of variance explained by multiple regression.

The written and verbal briefings were carefully specified. The following instructions and specifications were given to the subjects:

Vibration intensity:

- Concentrate on the vibration.
- Ignore different influences like noise, climate, light, *seat comfort*.
- The seat comfort has to be judged separately.

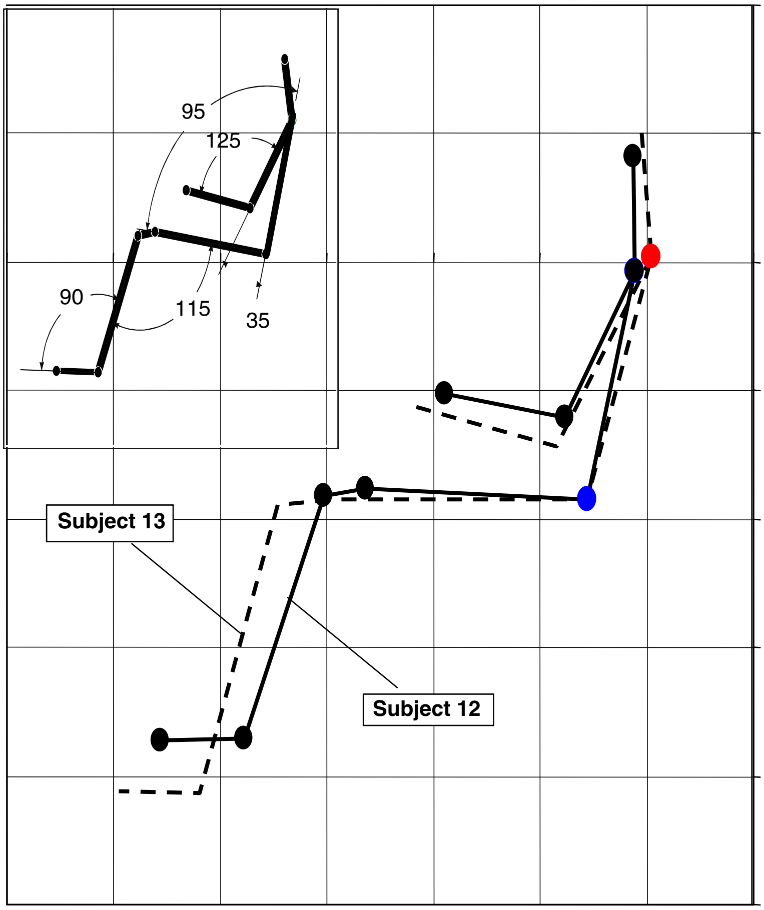

Fig. 6. Sitting postures of the lightest (Subject 12) and the heaviest (Subject 13) subject (mean value of the markers, 2nd to the 25th second of exposure). Small pictogram: Angles in degree between different body parts of the sitting operator, given in Ref. [15].

Seat comfort:

- sensation of pressure on the buttocks, the thighs and the back
- latent feeling of 'getting pins and needles' in body parts
- accessibility of the pedals
- sensation of lateral body fixation

Effort:

- integral judgement considering the entire situation without thinking about the particular reasons of the effort to carry out the reaction test

2.6. Statistics

The data were examined with the statistical programme SPSS 11.5.1. Considering the study design, analyses for repeated measures were used. Mainly, univariate variance analyses were carried out. Mauchly's test of sphericity was used to test the assumption of sphericity on the variance–covariance matrix of the orthonormalized transformed dependent variable. If the significance of the test was large, the hypothesis of sphericity could be assumed and the not adjusted p-values were presented in this paper. If the significance was small, that means the sphericity assumption appeared to be violated, the p-values adjusted with the lowest possible epsilon ('lower bound') were given as result. The Bonferroni adjustment was selected for the post hoc tests.

3. Results

3.1. Displacement

The relative displacement between the seat base (platform) and the seat frame was assessed with the motion analysis. The coordinates of the markers were recorded as time series. We calculated the difference between the x-coordinates (excitation in x-direction) or the y-coordinates (excitation in y-direction) of a marker at the seat base and a marker at the seat frame and determined the mean values, standard deviations, minimum and maximum for the period from the 2nd to the 25th second of the exposure and for 6 subjects, first repetition only (the two heaviest, the two lightest and two subjects with average weight).

As expected, the mean values varied around zero. The standard deviation reached a maximum of 12.8 mm for the excitation in x-direction and 8.2 mm for the excitation in y-direction. The maximum of the displacement varied from -39.9 to $+36.4$ mm (x-direction) and from -21.2 to 23.5 mm (y-direction). The displacement showed a clear dependence on the vibration magnitude measured on the platform, the kind of suspension (locked/activated) and the body mass. Table 3 illustrates the results of the correlation analyses for the association between the standard deviation of the displacement and the body mass. Even the small displacements under locked suspension conditions reached in some cases a significant dependence on the body mass. The mean values of the standard deviation of the displacements differed significantly between the magnitude levels and the kind of suspension (variance analyses for repeated measures, all p-values $= 0.000$, except for magnitude in x-direction (p-value $= 0.002$)). Fig. 7 illustrates the mean values of the standard deviation subdivided into magnitude and suspension.

3.2. Reaction time

Firstly, the distribution of the 16 reaction times (eight times brake, eight times accelerator) was checked for every single exposure. The samples had great skewness values in a lot of cases. Therefore, it was decided to eliminate the extreme values. Extreme values are defined as cases with values more than three interquartile ranges above the 75% percentile or below the 25% percentile. 2.84% of the brake reaction times (all extreme values above the 75% percentile) and 0.89% of the accelerator reaction times (0.87% above the 75% percentile and 0.02% below the 25% percentile) were removed.

Table 3
Pearson correlation coefficients and corresponding p-values for the association between the body mass and the standard deviation of the displacement between the platform and the seat frame, 2nd–25th second of exposure, subjects: 1, 9, 12, 13, 14, 17 (two heaviest, two lightest, two with average body mass)

	Suspension locked		Suspension activated	
	Corr. coeff.	p-value	Corr. coeff.	p-value
Magnitude 1 X	0.903 (*)	0.014	0.942 (**)	0.005
Magnitude 2 X	0.905 (*)	0.013	0.973 (**)	0.001
Magnitude 3 X	0.776	0.070	0.454	0.365
Magnitude 2 XY (reference, day 1)	0.556	0.252	0.982 (**)	0.000
Magnitude 1 Y	−0.418	0.409	0.862 (*)	0.027
Magnitude 2 Y	0.872	0.024	0.947 (**)	0.004
Magnitude 3 Y	0.909 (*)	0.012	0.958 (**)	0.003
Magnitude 2 XY (reference, day 2)	0.904 (*)	0.013	0.938 (**)	0.006

* = Correlation is significant at the 0.05 level (2-tailed), ** = Correlation is significant at the 0.01 level (2-tailed).

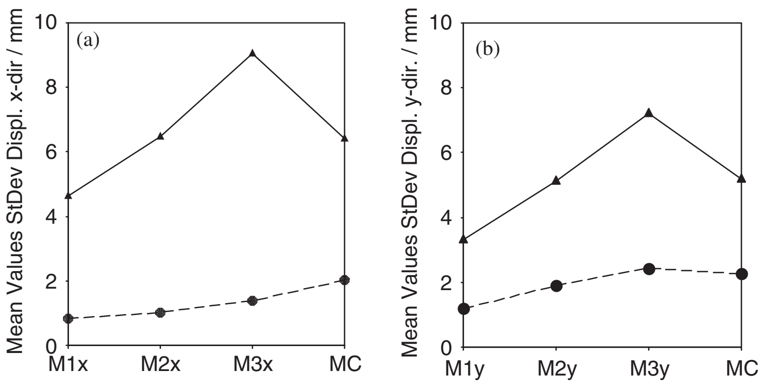

Fig. 7. Mean values of the standard deviations of the displacement between platform and seat frame, six subjects. Vibration magnitudes M1, M2, M3 and MC. (a): Excitation in the x- and xy-axis. (b): Excitation in the y- and xy-axis. ● suspension locked, ▲ suspension activated.

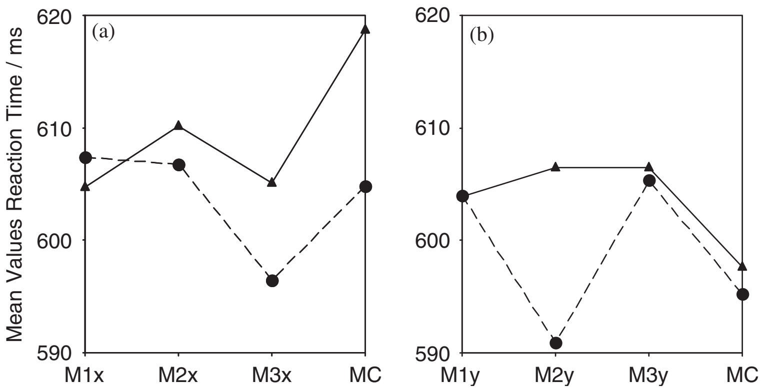

Fig. 8. Mean values of the reaction time. Vibration magnitudes M1, M2, M3 and MC. (a): Excitation in the x- and xy-axis. (b): Excitation in the y- and xy-axis. ● suspension locked, ▲ suspension activated.

Nevertheless, there was no significant difference between the brake and the accelerator reaction times (t-test for dependent samples). Additionally, the extreme values were steadily distributed over the different magnitude levels and the activated/locked suspension. So, both variables were summarised and the mean value of this new variable was considered in the variance analyses for repeated measures (factors: magnitude, suspension, repetition).

In summary, all p-values for main effects and interaction effects were far away from any significance. Fig. 8 presents the mean values of the reaction time for excitation in the x-, y- and xy-axis.

3.3. Judgement of the vibration intensity

Table 4 summarises the results of the variance analyses with regard to the judgements of the vibration intensity (design repeated measures, factors: line up/down, magnitude, suspension, repetition). The analyses were calculated twice, with and without the biaxial (xy) reference signal. That means, the magnitude had either three levels (magnitudes 1, 2 and 3) or four levels (magnitudes 1, 2, 3 and $2xy$, the last one designated as MC).

The factor line up/down was included for methodical reasons. The subjects had to give their judgements by adjusting the length of a line. This line was presented firstly with automatically rising length (up) and secondly with automatically falling length (down) on the subject's monitor. The dependency of the adjustment on the direction of presenting the line is known. It was checked, if there were significant differences between the

Table 4
Results of the variance analysis (p-values) of the judgements of the vibration **intensity**, only p-values $\leqslant 0.05$ presented; design: repeated measures, factors: line up/down, magnitude, suspension, repetition (all subjects)

		Magnitude	Suspension	Repetition	Comments
x-direction	Without reference	**0.000** (0.000, 0.000, 0.000)	**0.024**	—	Higher magnitude—higher intensity locked suspension—higher intensity interaction magnitude $*$ repetition (p-value 0.02)
	With reference	**0.000** (0.001, 0.000, 0.000, 0.000, *0.000,* 0.004)	**0.037**	—	Higher magnitude—higher intensity locked suspension—higher intensity interaction magnitude $*$ repetition (p-value 0.019)
y-direction	Without reference	**0.000** (0.000, 0.000, 0.001)	**0.001**	—	Higher magnitude—higher intensity locked suspension—higher intensity
	With reference	**0.000** (0.000, 0.000, 0.000, 0.002, *0.000,* 0.027)	**0.001**	**0.028**	Higher magnitude—higher intensity locked suspension—higher intensity increase of intensity with time interaction magnitude $*$ repetition (p-value 0.000) interaction suspension $*$ repetition (p-value 0.030)

In brackets: p-values for t-tests (Bonferroni) of the factor levels pairwise in the following order: 1–2, 1–3, 2–3 in the case of 3 factor levels (without reference) and 1–2, 1–3, 1–4, 2–3, 2–4, 3–4 in the case of 4 factor levels (with reference); significant main effects in bold letters, t-test for the pair 2–4 in italic letters.

conditions 'line up' and 'line down' in this investigation. Sometimes the difference reached significance. These results were neglected in the tables of the outcomes because they had only methodical importance.

Fig. 9 illustrates the mean values of the judgements of the vibration intensity, subdivided into those for different magnitude levels, suspension conditions (locked/activated) or repetitions (1/2). The 95% confidence intervals (SPSS error bars) were not revealed, since they do not reflect the results of the analyses for repeated measures.

3.4. Judgement of the seat comfort

Table 5 reviews the results of the variance analyses concerning the judgements of the seat comfort during the vibration exposure (point 3 of the time schedule for every exposure, Section 3.3). For the design of the analyses see Section 3.3. The analyses were calculated twice, with and without the biaxial (xy) reference signal. That means, the magnitude had either three levels or four levels. The results regarding the second judgement of the seat comfort (point 7 of the time schedule for every exposure, Section 3.3) did not differ from the first judgement and were not presented.

Fig. 10 demonstrates the mean values of the judgements of the seat comfort, subdivided into different magnitude levels and suspension locked/activated or repetition 1/2. The 95% confidence intervals (SPSS error bars) were not revealed, since they do not reflect the results of the analyses for repeated measures.

3.5. Judgement of the effort

Table 6 summarises the results of the variance analyses concerning the judgements of the effort to carry out the reaction tests (design repeated measures, factors: line up/down, magnitude, suspension, repetition—for the factor line up/down see Section 3.3). The analyses were calculated twice, with and without the biaxial (xy) reference signal. That means, the magnitude had either three levels or four levels.

Fig. 11 illustrates the mean values of the judgements of the effort, subdivided into different magnitude levels and suspension locked/activated or repetition 1/2. The 95% confidence intervals (SPSS error bars) were not revealed, since they do not reflect the results of the analyses for repeated measures.

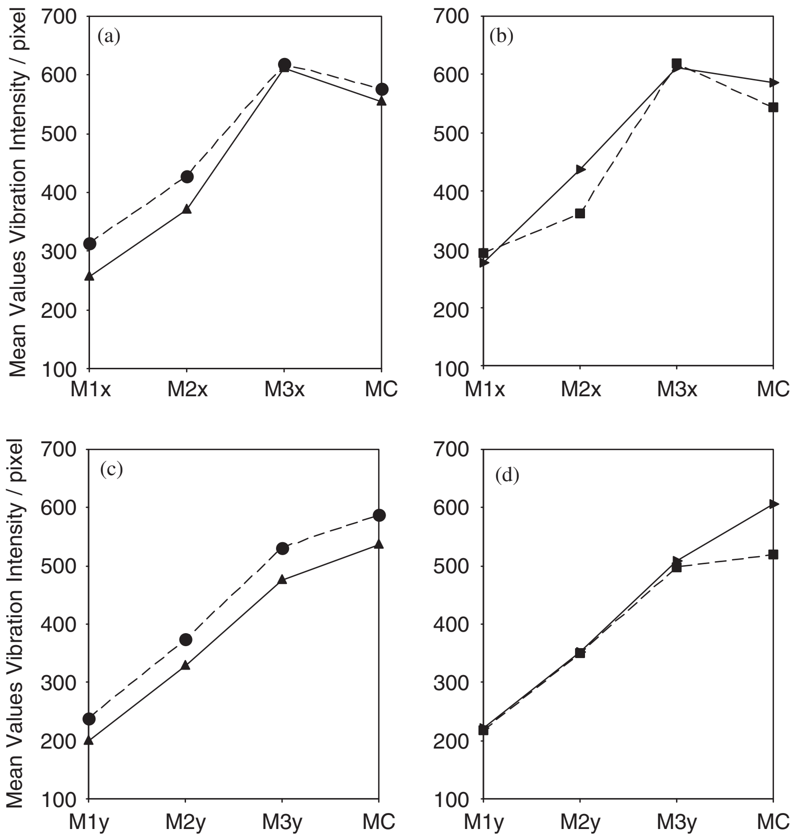

Fig. 9. Mean values of judgements of the vibration **intensity** (length of a line in pixel). Vibration magnitudes M1, M2, M3 and MC. (a) and (b) Excitation in the x- and xy-axis. (c) and (d) Excitation in the y- and xy-axis. (a) and (c) ● suspension locked, ▲ suspension activated. (b) and (d) ■ repetition 1, ▶ repetition 2.

Table 5
Results of the variance analysis (p-values) of the judgements of the seat **comfort**, only p-values$\leqslant$0.05 presented; design: repeated measures, factors: line up/down, magnitude, suspension, repetition (all subjects)

		Magnitude	Suspension	Repetition	Comments
x-direction	Without reference	**0.000** (0.4, 0.005, 0.009)	**0.016**	**0.019**	Higher magnitude—lower comfort locked suspension—lower comfort decrease of comfort with time
	With reference	**0.008** (0.8, 0.010, 0.039, 0.018, *0.117*, 1.0)	**0.022**	**0.002**	Higher magnitude—lower comfort locked suspension—lower comfort decrease of comfort with time interaction magnitude * repetition (p-value 0.000)
y-direction	without reference	**0.010** (0.023, 0.023, 0.196)	—	—	Higher magnitude—lower comfort
	With reference	**0.011** (0.046, 0.047, 0.033, 0.391, *0.450*, 1.000)	—	**0.023**	Decrease of comfort with time tendency: higher magnitude—lower comfort interaction magnitude * repetition (p-value 0.005)

In brackets: p-values for t-tests (Bonferroni) of the factor levels pairwise in the following order: 1–2, 1–3, 2–3 in the case of 3 factor levels (without reference) and 1–2, 1–3, 1–4, 2–3, 2–4, 3–4 in the case of 4 factor levels (with reference); significant main effects in bold letters, t-test for the pair 2–4 in italic letters.

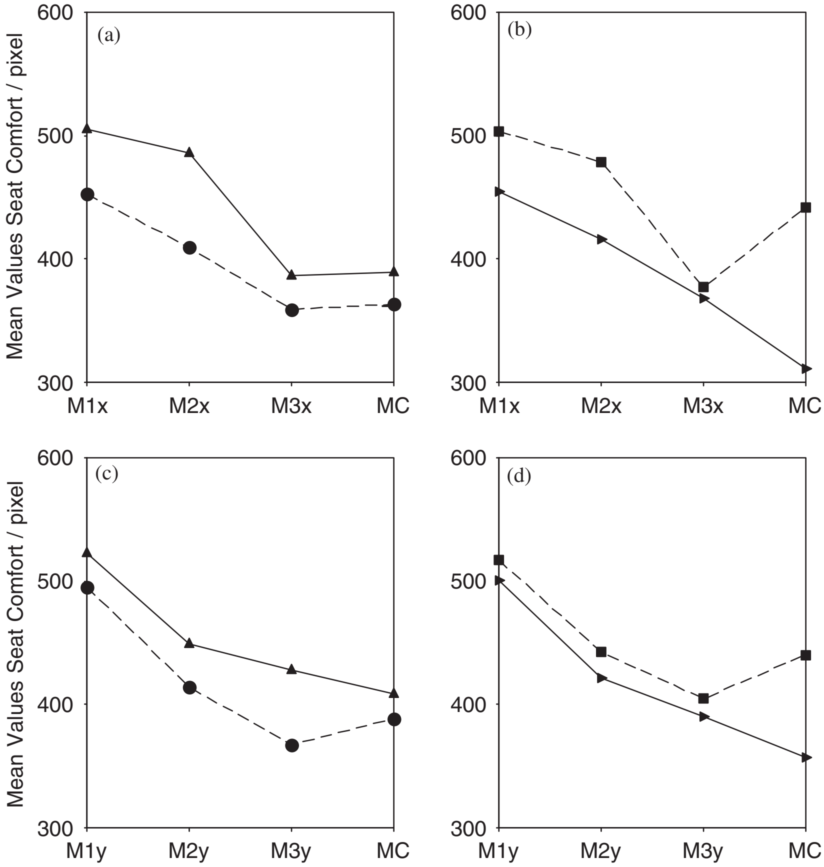

Fig. 10. Mean values of judgements of the seat **comfort** (length of a line in pixel). Vibration magnitudes M1, M2, M3 and MC. (a) and (b): Excitation in the *x*- and *xy*-axis. (c) and (d) Excitation in the *y*- and *xy*-axis. (a) and (c) ● suspension locked, ▲ suspension activated. (b) and (d) ■ repetition 1, ▶ repetition 2.

Table 6
Results of the variance analysis (*p*-values) of the judgements of the **effort** concerning the reaction test, only *p*-values$\leqslant$0.05 presented; design: repeated measures, factors: line up/down, magnitude, suspension, repetition (all subjects)

		Magnitude	Suspension	Repetition	Comments
x-direction	Without reference	**0.000** (0.458, 0.007, 0.016)	—	**0.048**	Higher magnitude—higher effort increase of effort with time
	With reference	**0.011** (0.915, 0.015, 0.075, 0.032, *0.198*, 0.751)	—	**0.031**	Higher magnitude—higher effort increase of effort with time
y-direction	Without reference	**0.013** (0.237, 0.065, 0.307)	—	**0.045**	Higher magnitude—higher effort increase of effort with time
	With reference	**0.029** (0.474, 0.130, 0.116, 0.613, *0.130*, 0.434)	—	**0.012**	Higher magnitude—higher effort increase of effort with time

In brackets: *p*-values for *t*-tests (Bonferroni) of the factor levels pairwise in the following order: 1–2, 1–3, 2–3 in the case of 3 factor levels (without reference) and 1–2, 1–3, 1–4, 2–3, 2–4, 3–4 in the case of 4 factor levels (with reference); significant main effects in bold letters, *t*-test for the pair 2–4 in italic letters.

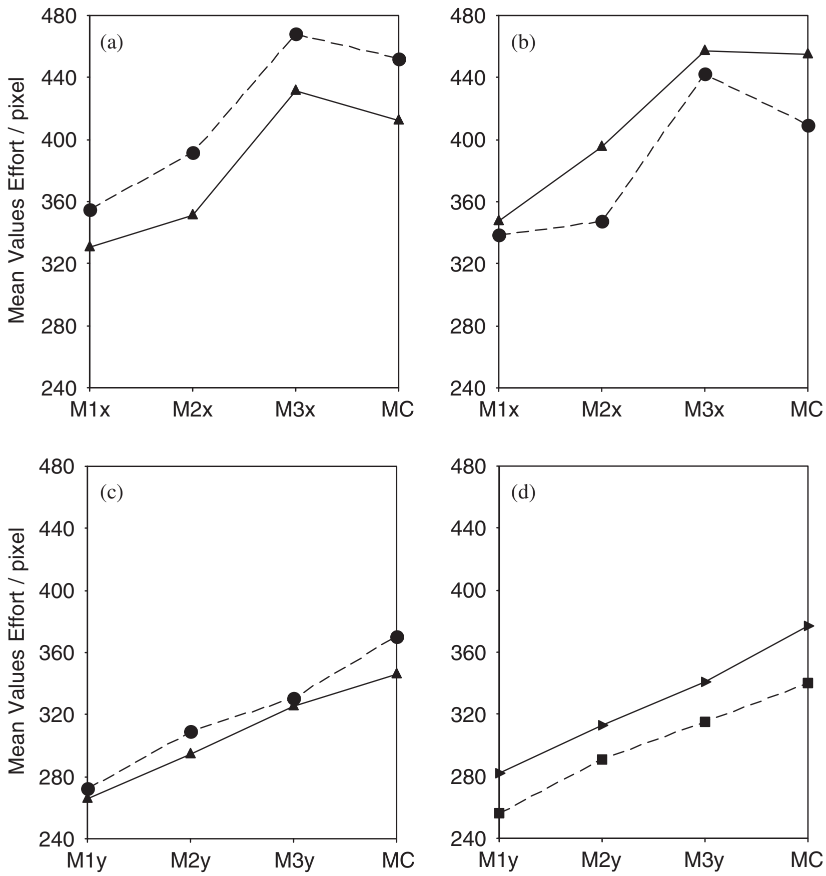

Fig. 11. Mean values of judgements of the **effort** concerning the reaction test (length of a line in pixel). Vibration magnitudes M1, M2, M3 and MC. (a) and (b) Excitation in the *x*- and *xy*-axis. (c) and (d) Excitation in the *y*- and *xy*-axis. (a) and (c) ● suspension locked, ▲ suspension activated. (b) and (d) ■ repetition 1, ▶ repetition 2.

4. Discussion

4.1. Displacement

The results concerning the relative displacement were not very surprising. As expected, the extent of the movement of the seat frame in relation to the base increased with growing magnitude of excitation and with the volunteers' body mass. This effect appeared even under locked suspension conditions, however on a lower level (see Fig. 7). It indicates that a very stiff constructional connexion between the seat base and the seat suspension was hardly realisable. The entire mechanical construction was not supposed to be a rigid mass. Therefore, little movements of the seat were possible also with locked horizontal suspensions. These negligible movements reached sometimes significance because of the great sample size. Nevertheless, the examination of the relative displacement delivered three important results for the subsequent analyses: (i) The differences of displacements between the magnitudes and the locked and activated suspension conditions were large enough to consider both parameters within the subsequent variance analyses as an indicator of the relative motion between the operator seat and the control elements due to the horizontal suspension. (ii) In the case of unlocked suspension, the mean displacement difference between the exposure magnitude 2, isolated excitation in the *x*- or *y*-axis, and biaxial (*xy*-) excitation was very small (0.5 mm for the *x*-axis, 0.2 mm for the *y*-axis). That means, the relative displacement seemed to have not been significantly influenced by simultaneous excitation in the other horizontal axis. Consequently, possible different effects of isolated and biaxial vibration should not have been caused by different relative displacements, but by other reasons. (iii) The end stops of the suspension were not reached under the excitations used in this experimental study. So, the shape of the acceleration signal over time was not altered by hitting against the end stops.

4.2. Reaction time

In contrary to the hypotheses that an increasing displacement between the seat and the pedals and an increasing vibration magnitude could cause a decreasing performance in motor tasks, we found no significant effects. There was only a tendency to longer reaction times with unlocked suspension, except for the low magnitudes M1X and M1Y. The mean reaction times varied around 605 ± 15 ms (see Fig. 8). The variation of the mean values was higher than the precision of the measuring system (± 5 ms). So, effects should be detected, if they were due to the factors magnitude, suspension or repetition. Maybe, the relative motion between the seat and the brake/accelerator pedals arising from low-frequency horizontal suspension did really not impair the precision of foot movements. Probably, the relative motion in the z-axis is more important than that in the horizontal axis. At least for visual tasks, Griefahn et al. [25] observed a more pronounced disruption of performance for vertical motion compared with horizontal vibration. The hypothesis of time-independency of performance due to a relatively short duration of examination was confirmed.

In contrast to the results of the pilot study [19], the extreme values spread over the entire time period. In the pilot study, the first two pedal actions had to be eliminated. Probably, this effect was not observed in the present study because of a prolonged time period between the last judgement and the first request for pressing the pedal. The pilot investigations gave already evidence of more difficulties in pressing the brake (middle pedal) compared with the accelerator (right pedal). The subjects perceived the adduction of the leg to be more difficult than the lateral movement to the right. This fact is also reflected by the percentage of eliminated values in the present study.

The practical relevance of the alteration of the reaction time is a subject for discussion. Possibly, a prolongation by around 100 ms could be assumed as a critical value. It would cause an extension of the braking distance of a car driving with a speed of 100 km/h by approximately 3 m and, in the case of a speed of 50 km/h, by nearly 1.5 m. On this assumption, the observed variations of the mean reaction times were not of practical relevance.

However, considering the results of the effort judgements, the volunteers seemed to have compensated the effects of magnitude, suspension and repetition with enhanced effort (see discussion concerning the effort judgements). A more demanding task could cause a situation, where the subjects are not longer able to keep their performance stable. For example, it could be worth amplifying the frequency of the requests for pressing the pedals or prolonging the exposure time. Hornick [13], for instance, found an increase of foot tracking errors with time comparing the first 15 min with the last 15 min of exposure. Unfortunately, he did not present the total exposure duration.

4.3. Judgement of the vibration intensity

As assumed, the mean values of the judgements of intensity differed highly significantly between the levels (M1, M2, M3 and MC) of the vibration. The judgements of the intensity increased with growing vibration magnitude. This was true for the isolated x- and y-vibrations. When the biaxial (xy) vibration was additionally included in the analyses, a significant difference between the isolated and the combined vibrations was revealed. The subjects judged the intensity of the biaxial vibration MC significantly higher than the isolated x- or y- vibration M2X, M2Y and M3Y. Bearing in mind, that the level of both, the weighted and the non-weighted overall vibration total value of MC, laid between those of M2X and M3X for excitation in x- and xy-directions and above those of M3Y for excitation in y- and xy-directions, the results were plausible (see Figs. 1, 2 and 9).

Moreover, the results suggested a perception of decreased vibration intensity due to horizontal suspension. This effect seemed to be stronger for the vibration in y-direction. At least the p-values were much lower for the intensity judgement during the excitation in the y-axis (see Table 4).

In this connection, we found an interesting result concerning the ISO w_d-weighting. The results regarding the association between the level of vibration magnitude and the judgement of intensity suggested, that vice versa the acceleration magnitude should have been higher with raising judgement. Indeed, this is the case, but with one exception—the w_d-weighted acceleration measured in x-direction on the cushion during exposure in the x-axis. The activation of the suspension did lead to an increase of the w_d-weighted acceleration measured on the cushion, instead of a decrease (Fig. 1(c)). The opposite effects of the suspension on the w_c-weighted accelerations of the backrest and the cushion result in equal overall vibration values for the activated and the locked suspension (Fig. 1(d)). On the other hand, the subjects' judgements did not reflect either this increase of the weighted acceleration measured on the cushion or the equalised weighted overall vibration total value considering the accelerations measured on the backrest (see Fig. 9(a)). Surely, the w_d-weighted acceleration on the cushion alone did not adequately reflect the subjective perception in case of excitation in the x-axis. A multiplying factor equal 1.4 is recommended in ISO 2631-1 (Paragraph 8.2.3, Note 4) instead of 1 for weighted accelerations on the cushion in the x- and y-axis in Eq. (1), if for technical reasons the vibration on the backrest cannot be measured. In the current study, this calculation would result in an increased weighted overall vibration total value instead of an equalised one in case of activated suspension and excitation in x-direction (see Fig. 1(c)). Consequently, the association with the judgements of vibration intensity would be much worse in comparison with the value calculated according to Eq. (1). A modified 'overall vibration total value' determined from the non-weighted accelerations, instead of the weighted ones (Eq. (2)), corresponded better with the subjective judgements in case of exposure in x- and xy-directions. This may be due to the shape of the frequency weighting in connection with the power density spectra (Fig. 3).

Probably, because of the different frequency content of the vibration input at the platform for the excitation in y-direction, the effect described above was not obtained. Griefahn and Bröde [9] found a disagreement between the frequency weighting according to ISO 2631-1 and subjective assessment in case of excitation in the y-axis. Their examinations with sinusoidal excitations revealed, that the weighting of lateral motions should be increased in order to meet the actual sensitivity, in particular in case of multi-axis vibrations.

Additionally, exposed in y-direction, the subjects judged the biaxial (xy) vibration at the end of a trial higher than at the beginning of a trial (see Fig. 9(d)). Therefore, the factor repetition and the interaction magnitude∗repetition became significant. The biaxial xy-exposure, repetition 2, was the last one on the last day of the study. Probably, the subjects perceived this last exposure to be especially intensive.

The significant interaction effects magnitude∗repetition indicate different tendencies in the alterations of the intensity judgements between the magnitude levels for the first and the second repetition. This was revealed by a cross of lines and different shapes of the curves in the diagrams (see Fig. 9(b) and (d)).

Exposed in y-direction, the volunteers judged the intensity with activated suspension at the second repetition much more higher then at the first repetition in comparison with the locked suspension (no figure). Hence, the interaction suspension∗repetition became significant. The reasons of this effect are not clear and so the interpretation is difficult.

4.4. Judgement of the seat comfort

The interpretation of the results relates to the phrase 'seat comfort' as subjects have been briefed in this study (Section 2.5), bearing in mind also the meaning of the word 'comfort' discussed in Section 1.

The judgements of the comfort significantly decreased with growing vibration magnitude, although the subjects were briefed to distinguish the vibration intensity from the seat comfort with their judgements (Table 5, Fig. 10(a) and (c)). It was not important, whether the subjects judged the comfort during or after the exposure (see time schedule for every exposure, Section 2.3). Obviously, the volunteers were not able to separate the vibration intensity and the seat comfort during vibration exposure, and they kept the perception of the intensity in mind, at least for some seconds after the exposure when judging the comfort again. Probably, one could not really expect, that (i) the sensation of pressure on the buttock, the thighs and the back, (ii) the latent feeling of 'getting pins and needles' in body parts, (iii) the accessibility of the pedals and (iv) the sensation of lateral body fixation were independent of the vibration magnitude (see instructions in Section 2.5).

The improvement of the seat comfort with activated suspension was significant for excitation in the x-direction. A similar tendency was observed for the y-direction (Table 5, Fig. 10(a) and (c)). The effect was consistent with the decrease of perception of vibration intensity discussed above. The non-weighted overall vibration total value corresponded better with the judgements than the weighted one in case of isolated excitation in the x- or y-axis. Moreover, the subjects judged the comfort at the second repetition significantly lower than at the first repetition (Fig. 10(b) and (d)). The reduction of the seat comfort with time can be explained with the postural fixity and the time dependent sensation of pressure on the buttocks and the back due to the seat pads (Endevco 2560).

Unlike the intensity judgements, the comfort judgements did not significantly differ between the isolated x- or y-exposure M2X or M2Y and the biaxial (xy) reference signal MC (italic letters in Table 5). The level of the judgements for MC were supposed to lay between M2X and M3X in case of excitation in x- and xy-axis respectively below M3Y in case of excitation in y- and xy-axis (Fig. 10(a) and (c)). Perhaps, the overall vibration total value—no matter if determined from weighted or non-weighted values -did not adequately reflect the perception of the 'seat comfort' in case of biaxial xy-exposure. In contrary, in a field study, Hassan and McManus [26] found stronger correlations between subjective perceptions and the weighted overall vibration total value compared with correlations for the modified non-weighted one. But, the investigation reveals some methodical shortcomings and is not comparable with the present study for the following reasons: (i) the volunteers judged the 'ride quality' instead of the 'seat comfort', (ii) the frequency content of the excitation in horizontal directions differed from that of the present study, (iii) there was an additional excitation in the z-axis, (iv) the acceleration has not been measured at the backrest (only assessed with multiplying factor 1.4 according to ISO 2631-1, Paragraph 8.2.3, Note 4), (v) the measurements of acceleration have been done only in one of several vehicles, supposing these values as representative.

Moreover, the subjects judged the seat comfort for the biaxial (xy) vibration at the end of a trial lower than at the beginning of a trial (see Fig. 10(b) and (d)). Therefore, the interaction magnitude$*$repetition became significant. This result was plausible. The biaxial excitations were the first and the last ones within a trial (see Table 2), and the judgement of the comfort decreased with the time.

The results regarding the w_d-weighting are the same as discussed in Section 4.3. For excitation in the x-axis, the volunteers' comfort judgements did not follow the increased transmission from the platform to the seat cushion, calculated with the w_d-weighted rms value (see Figs. 10(a), 1(a) and (c), for more details concerning the transmission see [27]). It seems, that the w_d-weighting and consequently the overall vibration total value calculated with the w_d-weighted values did not adequately reflect the perception of the seat comfort when exposed in the x-axis, too.

In summary, the associations of vibration magnitude or suspension with the 'seat comfort' were less pronounced than those with the 'vibration intensity', at least in case of excitation in the y-axis (compare p-values Tables 4 and 5). Considering the discussion of the term 'comfort' above, these results were plausible.

4.5. *Judgement of the effort*

Higher vibration magnitudes were significantly associated with higher effort to carry out the reaction task (see Table 6 and Fig. 11).

The suspension showed no significant effect on the effort judgements. However, the evident tendencies suggested lower effort with activated suspension (see Fig. 11(a) and (c)). Because of the greater displacement between seat base and seat frame with activated suspension, an opposite effect was assumed. One could suppose that the perceived lower magnitude and improved comfort led to a decreased subjective reflection of effort, in spite of larger relative displacements between the body and the pedal. Possibly, the extent of the relative displacement was of limited relevance for the kind of performance task required.

The difference between the effort judgements for the isolated x- or y-exposure and the biaxial (xy) exposure did not reach a significant level (italic letters in Table 6). Nevertheless, the tendency to higher judgements for the biaxial excitation was obvious (see Fig. 11(a) and (c)). The curves revealed shapes similar to those of the 'vibration intensity' (Fig. 9 (a) and (c)). They well reflected the levels of the non-weighted overall vibration total value (Figs. 1(b) and 2(b)).

The volunteers judged the effort at the second repetition significantly higher than at the first repetition (see Fig. 11(b) and (d)). These findings indicate an increase of effort with time. Possibly, the subjects were able to keep the performance stable over the time in this way.

The results corresponded to the absence of any influence of the magnitude or the repetition on the reaction times (see Section 4.2). Presumably, the volunteers compensated these effects with enhanced effort. Metz [14] reported on similar results concerning the missing effects of exposure duration on performance in the case of short exposures. But, the volunteers could maintain this enhanced effort for a limited time only. The prolongation of exposure times up to 3 hours caused a disruption of performance.

5. Conclusions

The possible inadequate reflection of the perception of the vibration intensity and the seat comfort by the w_d-weighting for low frequency vibration signals should be taken into account with a possible revision of the frequency weightings and further studies. For excitations in x- and xy-directions similar to those tested, an overall vibration total value calculated with the non-weighted accelerations instead of the weighted ones (ISO 2631-1, Article 8.2.3) seems to be the most appropriate one for the evaluation of the perceptions investigated in the present study. In general, a clear definition of vibration 'comfort' and/or 'discomfort' is recommendable with consideration of different psychological dimensions associated with these terms, and with respect to the large variety of semantic differences that can be expected in Europe. The subjective judgements concerning the 'vibration intensity' probably deliver more precise results. Maybe, the 'vibration intensity' should be preferred, because 'intensity' is a less ambiguous wording and exists presumably in any language. The performance of simple choice reaction tasks can remain stable, even with a somewhat increased mechanical interference caused by a horizontal seat suspension. The potential compensation of higher demands with enhanced effort to carry out motor tasks should be considered with prolonged exposure times.

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