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The vibration of inclined backrests: perception and discomfort of vibration applied parallel to the back in the *z*-axis of the body

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ABSTRACT

This study determined how backrest inclination and the frequency of vibration influence the perception and discomfort of vibration applied parallel to the back (vertical vibration when sitting upright, horizontal vibration when recumbent). Subjects experienced backrest vibration at frequencies in the range 2.5 to 25 Hz at vibration magnitudes up to 24 dB above threshold. Absolute thresholds, equivalent comfort contours, and the principal locations for feeling vibration were determined with four backrest inclinations: 0° (upright), 30°, 60° and 90° (recumbent). With all backrest inclinations, acceleration thresholds and equivalent comfort contours were similar and increased with increasing frequency at 6 dB per octave (i.e., velocity constant). It is concluded that backrest inclination has little effect on the frequency dependence of thresholds and equivalent comfort contours for vibration applied along the back, and that the W_d frequency weighting in current standards is appropriate for evaluating *z*-axis vibration of the back at all backrest inclinations.

Relevance of the findings for ergonomics practice

To minimise the vibration discomfort of seated people it is necessary to understand how discomfort varies with backrest inclination. It is concluded that the vibration on backrests can be measured using a pad between the backrest and the back, so that it reclines with the backrest, and the measured vibration evaluated without correcting for the backrest inclination.

Keywords: Backrest angle; seat comfort; frequency weighting

1. INTRODUCTION

Many seats have backrests that can be adjusted to a preferred inclination. In a static environment this involves finding the inclination giving greatest 'static comfort', but in transport a change in the backrest inclination may be expected to alter the vibration transmitted to the body and the vibration discomfort, or 'dynamic discomfort'. Optimising the dynamic comfort of a seat for a range of backrest inclinations requires understanding of the dynamic characteristics of the seat pan and the seat backrest and the sensitivity of people to vibration at the seat pan and at the seat backrest.

The discomfort caused by vibration depends on the frequency and the direction of the vibration and the location of contact with the vibration (e.g. the seat pan or the backrest). Frequency weightings have been standardised to assist the reporting of the likely discomfort caused by vibration occurring in each direction and at each location (BS 6841:1987; ISO 2631-1:1997). These include frequency weightings for vibration of the back, but the weightings were based on limited experimental data obtained from subjects sitting with upright backrests. The frequency-dependence of the discomfort caused by the vibration of a backrest may be expected to change as the backrest is inclined. In part, this is because the static force applied to the back will increase as the backrest inclines and the biodynamic response of the body may change. Additionally, vertical vibration of a backrest is in the *z*-axis of the body when the backrest is vertical, partly in the *z*-axis and partly in the *x*-axis of the body when the seat is inclined, and entirely in the *x*-axis of the body when the backrest is fully reclined. The convention in current standards assumes that the same frequency weighting is applicable to vibration applied to the body irrespective of the orientation of the body. So *z*-axis vibration of the back (i.e. vibration in the longitudinal direction of the body) might be evaluated with the same frequency weighting irrespective of whether the backrest is vertical (caused by vertical vibration), or fully reclined (caused by horizontal vibration).

British Standard 6841 (1987) and International Standard 2631-1 (1997) advocate the use of the W_c frequency weighting for evaluating *x*-axis backrest vibration and the W_d frequency weighting for evaluating *z*-axis backrest vibration. The W_c and the W_d weightings were developed from equivalent comfort contours for fore-and-aft and vertical vibration of an upright backrest over the frequency range 2.5 to 63 Hz (Parsons *et al*., 1982). When a backrest is inclined at 20° or 40° from vertical, it has been reported that the W_c weighting underestimates the discomfort caused by *x*-axis vibration of the back at frequencies greater than 8 Hz and overestimates discomfort at lower frequencies (Kato and Hanai, 1998). The frequencies at which *x*-axis acceleration of the back cause greatest discomfort appears to shift from less than 8 Hz with an upright backrest to around 10 or 12.5 Hz with a backrest inclined between 30°

and fully reclined (Basri and Griffin, 2011). The shift in frequencies was attributed to differences in body resonances previously observed between the extreme postures: resonance between 4 and 8 Hz in the fore-and-aft apparent mass of the back when seated upright (Abdul Jalil and Griffin, 2008) and resonance between 8 and 12 Hz in the vertical apparent mass when semi-supine (Huang and Griffin, 2009).

There is no known study of the effect of backrest inclination on equivalent comfort contours for *z*-axis vibration of the back. For an upright backrest, the *z*-axis vibration acceleration required to cause similar discomfort at all frequencies seems to increase at approximately 6 dB per octave from 2.5 to 63 Hz (i.e. the same vibration velocity at all frequencies) (Parsons *et al*., 1982). A similar constant velocity trend has been reported in thresholds for the perception of longitudinal horizontal vibration of the back in recumbent persons (Miwa and Yonekawa, 1969). In equivalent comfort contours for recumbent people, there is a trend for a similar (i.e. velocity constant) contour except at frequencies less than about 3 Hz, where the response might be approximated as constant acceleration (Miwa and Yonekawa, 1969; Szameitat and Dupuis, 1976; Gibson, 1978), consistent with increased sensitivity due to a resonance in the longitudinal horizontal apparent mass of the supine body (Huang and Griffin, 2008).

The biodynamic responses of the body that influence the frequency-dependence of subjective responses to vibration may be expected to depend on the inclination of a backrest. It was therefore hypothesised that both thresholds for the perception of *z*-axis vibration of the back and equivalent comfort contours for *z*-axis vibration of the back would depend on the frequency of vibration and the backrest inclination.

The main objectives of the study reported here were to test the hypotheses, to understand the findings, and to determine useful perception thresholds and equivalent discomfort contours. The study was comprised of four parts designed to determine: (i) absolute thresholds for the perception of *z*-axis vibration of the back at frequencies between 2.5 and 25 Hz with each of four backrest inclinations (0°, 30°, 60°, and 90°); (ii) the rate of growth of vibration discomfort at each frequency so as to determine equivalent comfort contours within each backrest inclination; (iii) the relative discomfort between the four backrest inclinations; (iv) the location of principal discomfort in the body caused by each frequency of vibration.

2. METHOD

2.1 Apparatus

The apparatus comprised a vibrating backrest with a stationary seat-pan, a stationary footrest (or support for the calves when recumbent), and a stationary headrest. The rigid flat wooden backrest (350 mm high by 310 mm wide) was attached to the table of a Derritron VP 85 vibrator so as to provide backrest vibration in the *z*-axis of the back (z_{back}) for all backrest inclinations (i.e. in the vertical direction with an upright backrest (0°), in the longitudinal horizontal direction when recumbent (90°) – Figure 1). The inclination of the backrest was adjustable to 0° (upright), 30°, 60°, and 90° (recumbent) by rotating the vibrator within a trunnion. With each backrest inclination, the height of the seat-pan, the angle and height of the footrest and the position of the headrest were adjusted to a comfortable sitting posture for a 50th percentile British male aged 19-45 years (Pheasant, 1990). The positions were achieved using an H-point manikin with knee and ankle angles set to 120° and 100°, respectively. The sitting height was adjusted so that contact between the back and the backrest was mostly at the upper back, with no contact around the lumbar and pelvic regions. The backrest and headrest were covered with 1-mm thick neoprene rubber to provide friction between the supports and the body.

Figure 1 ABOUT HERE

Vertical vibration of the hand (used to provide a common reference for subjective assessments – see below), was produced by a cylindrical wooden handle (3.18-cm diameter and 12-cm long) attached to a vertically-oriented Derritron VP4 vibrator. To maintain a similar posture of the hand with all postures and subjects, the location and height of the handle were adjusted accordingly (Figure 1). It was considered important to maintain the upper-arm and forearm with a slight bend (about 90 to 120 degrees) so as to minimise the transmission of hand vibration to the shoulders and localise the principal discomfort caused by hand vibration to the area around the hand with all backrest inclinations.

2.2 Vibration and signal generation

The vibration signals were generated and sampled using *HVLab* software (version 3.81) and low-pass filtered at 40 Hz before output via a digital-to-analogue converter (PCL-818) at 1000 samples per second.

Single-axis piezo-resistive accelerometers (Entran Model EGCSY-240D-10) were used: two accelerometers were attached perpendicular and parallel to the surface of the back of the rigid backrest and one accelerometer was attached on to the base of the rigid wooden handle. Signals from the accelerometers were filtered at 40 Hz (via a Techfilter anti-aliasing filter) and then sampled at 1000 samples per second.

The background vibration was predominantly caused by electrical noise at 50 Hz and was imperceptible at a magnitude less than 0.011 ms^{-2} r.m.s. in the *z*-axis direction of the back on the backrest.

2.3 Vibration stimuli

The vibration stimuli were all 2-second duration sinusoidal vibrations (with 0.25-second cosine-tapering at the start and end) at the 11 preferred one-third octave centre frequencies from 2.5 to 25 Hz.

Backrest vibration (8 Hz at 0.65 ms^{-2} r.m.s.) was used as a reference stimulus when studying discomfort within backrest inclinations (Part 2) and applied in the *z*-axis of the back (i.e. in the longitudinal axis of the body, parallel to the surface of the back). For each of the four backrest inclinations there were 99 test stimuli: an array of 11 frequencies (2.5 to 25 Hz) and nine magnitudes (0.2 to 3.23 $mm.s^{-1}$ r.m.s. in 3 dB steps).

Vertical vibration of the hand (8 Hz at 2.0 ms^{-2} r.m.s.) was used as a reference stimulus when studying the relative discomfort between backrest inclinations (Part 3). The test stimuli were the same nine magnitudes of 8-Hz vibration applied to the back in Part 2.

The stimuli for investigating the location of discomfort (in Part 4) were the middle and greatest magnitudes of each frequency applied to the back in Part 2.

2.4 Procedure

The experiment was conducted in four sessions corresponding to sitting with four different backrest inclinations (i.e. 0°, 30°, 60°, and 90°). Using a within-subject experimental design, each subject attended all four sessions on four different days in a balanced order between subjects. Each session composed of four psychophysical tests and lasted no more than an hour:

Part 1: Perception thresholds within each backrest angle,

Part 2: Equivalent comfort contours within backrest angle,

Part 3: Relative discomfort between backrest angles, and

Part 4: Location of discomfort

There was a short break between Part 1 and Part 2.

Subjects sat comfortably on the seat pan with their backs and heads supported by the backrest and the headrest in all conditions except with an upright backrest. No headrest was provided with an upright backrest to allow natural contact of the upper back with the backrest. Subjects were requested to maintain contact of their upper back with the backrest throughout the test, with their hands resting on their laps, or folded together on top of their stomach when the backrest was inclined to 60° and 90° (recumbent). For backrest inclinations of 0°, 30°, and 60°, the feet were supported, whereas when recumbent (at 90°), the calves were supported.

Subjects wore earphones presenting white noise at 75 dB(A) and were provided with an emergency stop button. Written instructions were placed on a board in front of them. Subjects were trained and practiced with several trials during their first visit to confirm their understanding on the procedures.

2.4.1 Perception thresholds (Part 1)

Subjects were presented with stimuli in a period indicated by the illumination of a cue light on the instruction board placed in front of them. They were required to respond by saying either 'yes' or 'no' when the cue light went off so as to indicate whether they had felt the vibration. The perception thresholds were determined using 1-up and 2-down procedure of the up-down transformed response (UDTR) method (Levitt, 1971). The level of the vibration was increased by 2 dB after each 'no' response, and decreased by 2 dB after two consecutive 'yes' responses. The procedure was repeated for six reversals (i.e. until 3 peaks, *p,* and 3 troughs, *t*, had been obtained). Perception thresholds were calculated for each frequency from the average of the last two peaks and the last two troughs (Figure 2). The procedure determines thresholds at 70.7% probability of perception (Levitt, 1971).

$$\text{Perception threshold} = 0.25\sum_{n=2}^{3}\left(p_n + t_n\right) \qquad \text{Equation 1}$$

Figure 2 ABOUT HERE

2.4.2 Equivalent comfort contours within backrest angle (Part 2)

Using the method of magnitude estimation, subjects estimated the magnitude of their discomfort, ψ, caused by each test stimulus of acceleration magnitude, φ. They judged their discomfort relative to the discomfort caused by the reference stimulus (8-Hz at 0.65 ms^{-2} r.m.s.), assumed to correspond to a magnitude estimate of 100. The reference stimulus and the test stimuli (both z_{back} vibration) were presented in pairs separated by 1-second pauses. The frequencies and magnitudes of the test stimuli were presented in randomized orders. This part was completed in approximately 20 minutes.

The method of magnitude estimation was employed in conjunction with Stevens' power law (Equation 2) to determine a series of equivalent comfort contours within each backrest angle (Stevens, 1975):

$$\psi(f) = k\ \varphi(f)^n \qquad \text{Equation 2}$$

The exponent, n, and constant, k, were determined at each frequency, f, by linear least squares and subsequently used to construct equivalent comfort contours for sensation magnitudes from ψ = 40 to ψ = 250.

2.4.3 Relative discomfort between backrest angles (Part 3)

Using a method similar to that employed in Part 2, subjects estimated the magnitude of discomfort caused by each test stimulus presented to their back relative to the discomfort caused by the common reference stimulus (8-Hz at 2.0 ms^{-2} r.m.s.) presented to the hand. The test stimuli were nine levels of 8-Hz z-axis vibration of the back presented in Part 2. This part was completed in approximately 3 minutes.

2.4.4 Location of discomfort (Part 4)

Subjects were requested to indicate the part of their body that felt the most discomfort on a body map displayed in front of them after being presented with each stimulus. There were 22 stimuli (the middle and greatest magnitudes of the 11 frequencies of z-axis vibration of the backrest presented in Part 2) presented in random order. This part was completed in approximately 5 minutes.

2.5 Subjects

Twelve male subjects participated in all four sessions of the experiment. Subjects had a mean age of 26.2 (SD: ±5.3) years, a mean stature of 1.73 (SD: ±5.2) m, and a mean weight of 66.3 (SD: ±8.4) kg. The subjects were students and staff of the University of Southampton and were healthy with no history of any serious illness, injury, or disability that might impair their judgement of vibration sensations.

The experiment was approved by the Human Experimentation Safety Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton at the University of Southampton. All subjects gave their voluntary consent prior to each session.

3. RESULTS

3.1 Perception thresholds (Part 1)

The absolute thresholds for the perception of *z*-axis vibration of the backrest varied with frequency within all backrest inclinations ($p<0.001$, Friedman; Figure 3 and Table 1).

Figure 3 AND Table 1 ABOUT HERE

The absolute thresholds for the perception of vibration were not significantly dependent on backrest inclination at any frequency ($p>0.05$, Friedman; Figure 3).

3.2 Equivalent comfort contours within backrest angle (Part 2)

3.2.1 Rate of growth of discomfort

Linear regressions were performed between the logarithm of the magnitude estimates of discomfort, ψ, and the logarithm of the acceleration magnitudes of the test stimulus, φ, to determine the rate of growth of discomfort, n, and constant k for each subject at each frequency, f, with each backrest inclination:

$$\log_{10} \psi(f) = n.\log_{10}\varphi(f) + \log_{10} k \qquad \text{Equation 3}$$

The rates of growth of discomfort were significantly dependent on the frequency of vibration with the upright backrest (0°) and the fully reclined backrest (90° - recumbent) ($p<0.001$, Friedman), but not with the backrest inclined at 30° ($p=0.11$) or 60° ($p=0.14$) (Figure 4).

Backrest inclination affected the rate of growth of discomfort at 3.15 Hz ($p=0.006$; Friedman), and at frequencies greater than 12.5 Hz ($p<0.05$; Friedman). The rates of growth of discomfort were higher with the fully reclined backrest (90° – recumbent) than with the upright backrest (0°) at 3.15 Hz and from 12.5 Hz to 25 H, and with the 30°-inclined backrest at 3.15 Hz and from 16 Hz to 25 Hz ($p<0.008$; Wilcoxon). There were no significant differences in the rate of growth of discomfort with the fully reclined backrest (90°) or the 60°-inclined backrest at any frequency except 25 Hz ($p<0.008$; Wilcoxon).

Figure 4 ABOUT HERE

3.2.2 Equivalent comfort contours within backrest angle

Equivalent comfort contours for each subject were constructed from the exponent, n, and the constant, k, obtained from linear regression by determining the vibration acceleration, φ, required to produce a selected sensation magnitude, ψ:

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

Equation 4

where the sensation magnitudes are relative to a sensation of 100 for the reference vibration (0.65 ms^{-2} r.m.s. of 8-Hz *z*-axis vibration of the backrest). Values were determined for nine sensation magnitudes (ψ = 40, 50, 63, 80, 100, 125, 160, 200, and 250).

Within each backrest inclination, median equivalent comfort contours were calculated from the 12 individual equivalent comfort contours (Figure 5). Similar contours can be constructed from the median values of *n* and *k* over all subjects (see Table 1).

Figure 5 ABOUT HERE

3.3 Relative discomfort between backrest angles (Part 3)

The subjective magnitude (i.e. discomfort) produced by the reference vibration (i.e. 8-Hz 0.65 ms^{-2} r.m.s.) may differ between backrest inclinations. It was therefore necessary to adjust the equivalent comfort contours within each backrest inclination so as to yield equivalent comfort contours that applied over all backrest inclinations. This was achieved by adjusting the comfort contour of each subject to the sensation magnitude of the 8-Hz *z*-axis vibration of the backrest that produced discomfort equivalent to a sensation magnitude of 100 with the common reference (8-Hz vertical hand vibration at 2.0 ms^{-2} r.m.s.). The median of these twelve individual 'adjusted' equivalent comfort contours was then calculated for each backrest inclination (Figure 6). The adjustment procedure was similar to that reported elsewhere (Basri and Griffin, 2011).

Figure 6 ABOUT HERE

There was no significant difference between the four 'adjusted' equivalent comfort contours (corresponding to four backrest inclinations) at any frequency (p>0.05; Friedman) – indicating the magnitude of z-axis vibration of the backrest required at any frequency to produce a sensation magnitude of 100 with the common reference vibration was similar with all backrest inclinations.

3.4 Location of discomfort (Part 4)

At all frequencies and with all backrest inclinations, discomfort was generally felt most in the upper-back (Figure 7). However, with an upright backrest and a fully inclined backrest, some subjects (20 to 40%) felt discomfort in the lower back, particularly at mid magnitudes (Figure

7a and Figure 7d). With the backrest inclined to 30° and 60°, some subjects (10 to 40%) felt discomfort in the head and neck at high frequencies (Figure 7b and Figure 7c).

Figure 7 ABOUT HERE

4. DISCUSSION

4.1 Perception thresholds

4.1.1 Effect of frequency

There was a similar frequency-dependence in the perception thresholds for *z*-axis vibration of the back with all backrest inclinations. Sensitivity to *z*-axis vibration of the back decreased with increasing frequency at approximately 6 dB per octave, corresponding to a constant velocity trend (Figure 3). This may suggest the same mechanism is involved in perceiving this type of vibration and that the mechanism is not greatly affected by the backrest inclination.

4.1.2 Effect of backrest inclination

The non-significant trend for lower thresholds (greater sensitivity) at frequencies less than 4 or 5 Hz with an upright backrest (0°) than with inclined backrests (30°, 60°, and 90°) is similar to that found with *x*-axis vibration of the back and is thought to be associated with relative motion between the moving backrest and the stationary seat pan (Basri and Griffin, 2011). The relative motion may have also increased sensitivity to low frequencies of *z*-axis vibration of the back, but with a more similar effect over the four backrest inclinations.

4.1.3 Comparison with previous studies

The thresholds obtained with the fully reclined backrest (90°) have a similar frequency-dependence to the averaged sensitivity to longitudinal horizontal vibration of recumbent subjects (Figure 8; Miwa and Yonekawa, 1969, Szameitat and Dupuis, 1976; Miwa *et al*., 1984; Yonekawa *et al*., 1999). Miwa and Yonekawa determined the relative sensitivity of different parts of the recumbent body exposed to longitudinal vibration (i.e., head, back, buttocks plus femora, calves plus heels, and the whole body). Sensitivity of the back was less than sensitivity of the whole body (by about 6 dB) at frequencies greater than 4 Hz. At low frequencies, thresholds for the perception of the vibration of individual parts of the body can be reduced by the perception of relative motion between parts that are vibrated and parts that are stationary. With no relative motion (i.e. whole-body vibration), the perception thresholds are higher at low frequencies (Figure 8; Miwa and Yonekawa, 1969). For the same acceleration magnitude, displacement amplitudes become larger at lower frequencies, increasing the relative displacement between the moving backrest and non-moving supports for the buttocks or head. The thresholds for the back obtained in the present study are consistently greater than thresholds for whole-body vibration reported for recumbent subjects in previous studies. This might be due to less force at the back in the present study because body weight was partially supported at other locations, due to inter-subject variability, or due to the use of different psychophysical methods. Morioka and Griffin (2002) showed that different psychophysical methods used in determining the absolute thresholds for vibration perception yielded different thresholds.

Figure 8 ABOUT HERE

4.2 Vibration discomfort

4.2.1 Effect of frequency

As expected, the equivalent comfort contours are frequency-dependent (Figure 5). With an upright backrest (0°), the overall shape of the equivalent comfort contours is consistent with the contour for a full upright backrest equivalent to 10-Hz vertical seat vibration at 0.8 ms^{-2} r.m.s. as reported by Parsons *et al*. (1982) (Figure 9). The median equivalent comfort contours for the upright backrest (0°) and all inclined backrests (30°, 60°, and 90°) are similar and show that to produce similar discomfort the acceleration needs to increase approximately in proportion to frequency (i.e. a slope of 6 dB per octave corresponding to constant velocity; Figure 5). However, with the backrest inclined to 60° and 90° (recumbent), the responses at frequencies less than 4 Hz were flatter, particularly at lower magnitudes. The contours obtained with the fully reclined backrest (90° - recumbent) are consistent with equivalent comfort contours for longitudinal horizontal whole-body vibration of recumbent subjects (Miwa and Yonekawa, 1969; Szameitat and Dupuis, 1976; Gibson, 1978: Figure 10).

Figure 9 ABOUT HERE

Discomfort was mostly felt in the upper and lower back at all frequencies and at all vibration magnitudes (Figure 7), consistent with the same mechanisms being involved in causing vibration discomfort in most conditions. Discomfort tended to localise around the source of the vibration at frequencies greater than 4 Hz, as reported by Griffin (1990). Stimulation of the somatosensory system, possibly arising from shear and compression of soft tissues of the upper back in contact with the backrest, may have caused discomfort. Systematic increases in strain, caused by increasing displacement between the back and the backrest with decreasing frequency, may explain the systematic increase in discomfort with decreasing frequency. With the greater inclinations of the backrest (i.e., 60° and 90°), the frequencies at which the least acceleration was required to produce similar discomfort (i.e. region of greatest discomfort) seems to be around 4 Hz at low magnitudes and decreases with increasing vibration magnitude. This is similar to the biodynamic nonlinearity measured at the back during longitudinal horizontal whole-body vibration of the semi-supine body (similar to the 90° backrest inclination used here): the resonance frequency in the apparent mass of the semi-supine body decreased from 3.7 to 2.4 Hz as the magnitude of random vibration increased from 0.125 to 1.0 ms^{-2} r.m.s. (Huang and Griffin, 2008; Figure 10). This suggests the resonance influences discomfort caused by vibration of the back over this frequency range.

Figure 10 ABOUT HERE

4.2.2 Effect of vibration magnitude

There is substantial evidence of a magnitude-dependence in equivalent comfort contours. With vertical seat vibration at magnitudes from 0.02 to 1.25 ms^{-1} r.m.s., the frequencies at which the least vibration acceleration was required to cause discomfort decreased as the vibration magnitude increased (Morioka and Griffin, 2006), similar to the nonlinearity of the body resonance (Fairley and Griffin, 1990). Similarly, the frequencies of greatest discomfort indicated by equivalent comfort contours for fore-and-aft vibration of a fully-upright backrest exhibit nonlinearity with vibration magnitude increasing from 0.6 to 1.25 ms^{-2} r.m.s. (Morioka and Griffin, 2009). In the present study there was a significant effect of frequency on the rate of growth of discomfort (the exponent, n, in Stevens' Power Law) with the upright backrest, consistent with a magnitude-dependence in the equivalent comfort contours. As mentioned above, with the fully reclined backrest (90°) an apparent trend towards a decrease in the frequency of greatest discomfort (from 4 Hz to 2.5 Hz) with increasing magnitude of vibration (as exhibited in the equivalent comfort contours across the nine sensation magnitudes, from ψ = 40 to 250; Figure 10) is consistent with reductions in the resonance frequency of the semi-supine body exposed to longitudinal horizontal whole-body vibration (Huang and Griffin, 2008).

4.2.3 Effect of backrest inclination

It was hypothesised that more support for the upper body when sitting with an inclined backrest would alter the dynamic force ($m \cdot g \cdot \sin\theta$) at the point of contact with vibration and change the frequency dependence of discomfort. Contrary to this hypothesis, the rescaled equivalent comfort contours showing the vibration magnitudes required to produce similar discomfort to the common reference (i.e. 2.0 ms^{-2} r.m.s. of 8-Hz vertical hand vibration) did not vary with backrest inclination (Figure 6). However, the rates of growth of discomfort were greater at 3.15

Hz with the fully reclined backrest (90°) than with the upright (0°) and the 30°-inclined backrests, indicating that these contours will differ at higher and lower magnitudes.

4.3 Frequency weightings

Current standards for the measurement and evaluation of human exposure to whole-body vibration (BS 6841:1987; ISO 2631-1:1997) do not define a frequency weighting for predicting the perception of *z*-axis vibration of the back. The present study suggests that acceleration thresholds for *z*-axis vibration of the back (with an upright backrest or any other inclination of the backrest) increase at approximately 6 dB per octave as the frequency increases from 2.5 to 25 Hz – well matched to the W_d frequency weighting defined in the standards (Figure 11).

There can be increased sensitivity to low frequencies of backrest vibration if there is relative motion between the moving backrest and stationary seat pan. The use of the W_d frequency weighting for evaluating *z*-axis backrest vibration may underestimate the probability of perceiving vibration if it is perceived because of relative motion between different body parts.

Figure 11 ABOUT HERE

The *z*-axis acceleration required to produce equivalent discomfort with all backrest inclinations also tended to increase with increasing frequency at the rate of 6 dB per octave. This suggests the W_d frequency weighting is suitable for evaluating *z*-axis backrest vibration with respect to comfort for all backrest inclinations. With the greatest inclinations of the backrest (i.e., 60° and 90°), the response is clearly dependent on the vibration magnitude, so that at low magnitudes the acceleration required to cause discomfort is almost independent of frequency below about 4 Hz (see Figure 5), consistent with contours for the longitudinal horizontal whole-body vibration of recumbent person (see Figure 10). Although the W_d frequency weighting may provide a useful prediction of the frequency-dependence of the discomfort with all inclinations of backrests it may be less precise for low frequencies with greater backrest inclinations (60° and 90°).

It might be assumed that the frequency weightings for the different directions of backrest vibration apply to geocentric axes (horizontal and vertical) rather than a basicentric coordinate system (axes defined relative to the contact surface and therefore approximately aligned with the biodynamic coordinate system, e.g. x_b and z_b). Vertical vibration of a backrest is solely in the *z*-axis of the body when the backrest is vertical, in both the *z*-axis and the *x*-axis of the body when the backrest is inclined, and entirely in the *x*-axis of the body when the backrest is fully reclined. Geocentric and basicentric coordinate systems give the same predictions of perception and comfort when a backrest is vertical but increasingly different predictions as a backrest reclines. In the extreme, when fully reclined, weighting W_c would be used in a geocentric system for evaluating horizontal vibration of a backrest along the *z*-axis of the body, whereas W_d would be used in a basicentric system. The greatest sensitivity to acceleration would be in the range 0.5 to 8 Hz in a geocentric system but 0.5 to 2 Hz in a basicentric system. The experimental results show sensitivity is primarily dependent on the direction of vibration relative to the body, rather than relative to gravity, so a basicentric system is more convenient. It follows that perception and comfort can be estimated directly from measurements at the interface between the back and a backrest without resolving the vibration into vertical and horizontal components.

5. CONCLUSIONS

Absolute thresholds for the perception of *z*-axis vibration of the back are frequency-dependent, with sensitivity to acceleration decreasing at 6 dB per octave from 2.5 to 25 Hz. The frequency-dependence of equivalent comfort contours is similar to the frequency-dependence of the thresholds. The frequency-dependence of perception and discomfort is not greatly dependent on backrest inclination, but there is evidence of artefactual lowering of thresholds at low-frequencies (less than about 4 Hz) due to relative motion between moving and stationary contacts with the body. The equivalent comfort contours are also dependent on the magnitude of vibration, especially with fully upright and fully reclined backrests.

The results show that it is reasonable to use the W_d frequency weighting (as defined in current standards) to predict the frequency-dependence of both absolute thresholds and the discomfort of *z*-axis vibration of the backs of seated people. However, with great inclination of a backrest, particularly with a fully reclined backrest, the weighting for evaluating low frequencies (less than 4 Hz) requires further consideration.

The results suggest that the vibration on backrests can be measured at the interface between a backrest and the back (e.g. using a SIT-pad located between the backrest and the back) so that the direction of measurement varies with the backrest inclination, and that the vibration can evaluated without correcting for the backrest inclination.

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FIGURE LEGEND

Figure 1 Test rig setup for *z*-axis vibration of the back with different backrest angles: (a) upright backrest (0°), (b) inclined backrests (e.g. 30°), (c) fully reclined backrest (90°). The posture of the hand on the handle bar for common reference (i.e. vertical hand vibration) within each backrest angles are shown beneath.

Figure 2 Example trial of perception threshold test, showing peaks and troughs formed as a result of one ‘no’ response and two consecutive ‘yes’ responses (1-up and 2-down algorithm).

Figure 3 Median and inter-quartile ranges of absolute thresholds for perception with: (a) upright backrest (0°), and comparison with (b) backrest inclined at 30°, (c) 60° and (d) fully reclined backrest (90°).

Figure 4 Median rate of growth of discomfort with (a) upright backrest (0°), (b) backrest inclined at 30°, (c) 60° and (d) fully reclined backrest (90°).

Figure 5 Median absolute threshold for the perception of *z*-axis vibration of the back, and median equivalent comfort contours at nine sensation magnitudes (ψ = 40 to 250) within each of four backrest inclinations: indicating the *z*-axis vibration of the back required to produce discomfort equivalent to 40% to 250% of that produced by 8-Hz *z*-axis vibration of the back at 0.65 ms^{-2} r.m.s.

Figure 6 Median ‘rescaled’ equivalent comfort contours showing the relative discomfort between backrest inclinations. Each point on the contours indicates the acceleration of *z*-axis vibration of the backrest required to produce discomfort equivalent to that produced by the common reference vibration (i.e., 8-Hz vertical hand vibration at 2.0 ms^{-2} r.m.s.).

Figure 7 Principal locations of discomfort arising from exposure to middle and highest vibration magnitudes when sitting with: (a) upright backrest (0°), (b) backrest inclined at 30°, (c) 60° and (d) fully reclined backrest (90°).

Figure 8 Acceleration thresholds for *z*-axis vibration of the fully reclined backrest (90° or recumbent) in the present study compared to average thresholds with longitudinal horizontal vibration of the back and whole-body vibration.

Figure 9 Equivalent comfort contours with the upright backrest (0°) in the present study compared to discomfort with a full upright backrest equivalent to that caused by 0.8 ms^{-2} r.m.s. of 10-Hz vertical seat vibration, and the inverted realisable W_d frequency weighting.

Figure 10 Equivalent comfort contours for *z*-axis vibration of the fully reclined backrest (90° or recumbent) in the present study compared to contours for longitudinal horizontal whole-body vibration of recumbent subjects.

Figure 11 Acceleration thresholds and equivalent comfort contours for nine sensation magnitudes (ψ = 40 to 250) inverted and normalised to the same value as the realisable W_d frequency weighting at the reference frequency (at 8 Hz W_d = 0.253) and compared with the realisable W_d frequency weighting.

TABLE LEGEND

Table 1 Median exponent (*n*), constant (*k*) and absolute threshold (φ_0) for perception of *z*-axis vibration of the back with upright backrest (0°), backrest inclined at 30° and 60° and fully reclined backrest (90° or recumbent). Median equivalent comfort contours can be constructed from the median *n* and *k* and are similar to the median equivalent comfort contours calculated from the 12 individual equivalent comfort contours as shown in Figure 5.

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FIGURE 1

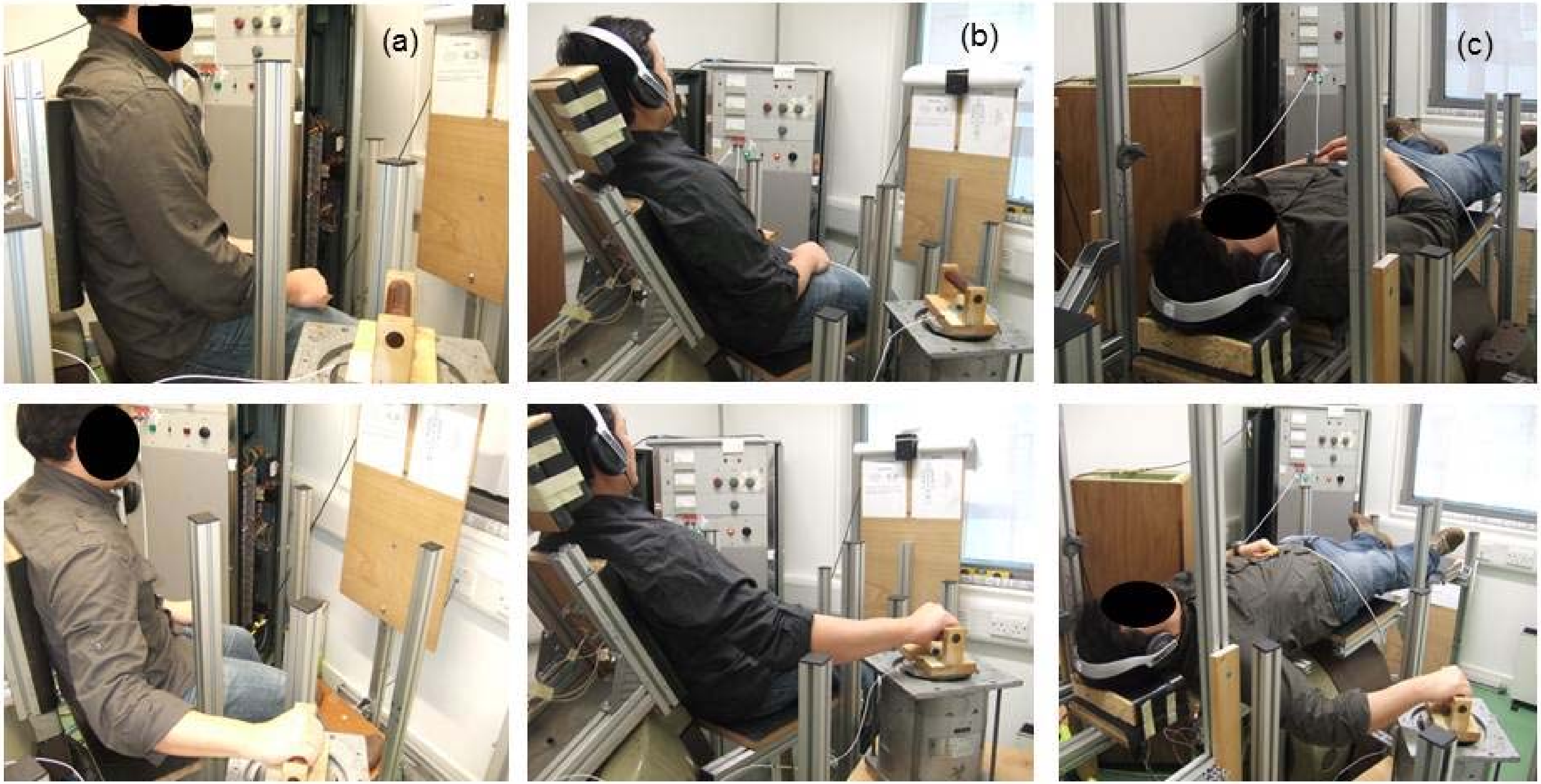

FIGURE 2

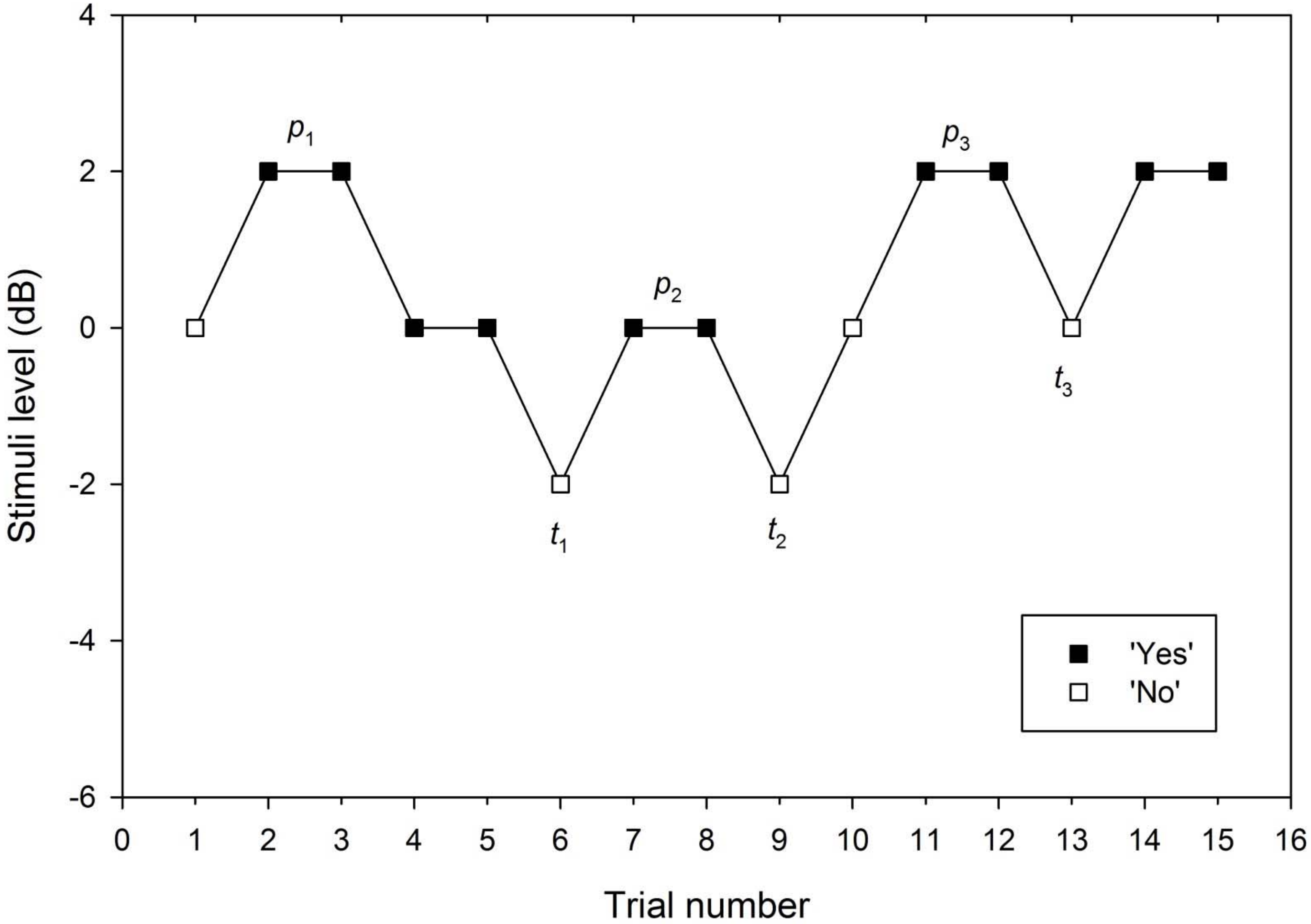
4
2
0
-2
-4
-6
Stimuli level (dB)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Trial number
p_1
p_2
p_3
t_1
t_2
t_3
'Yes'
'No'

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FIGURE 3

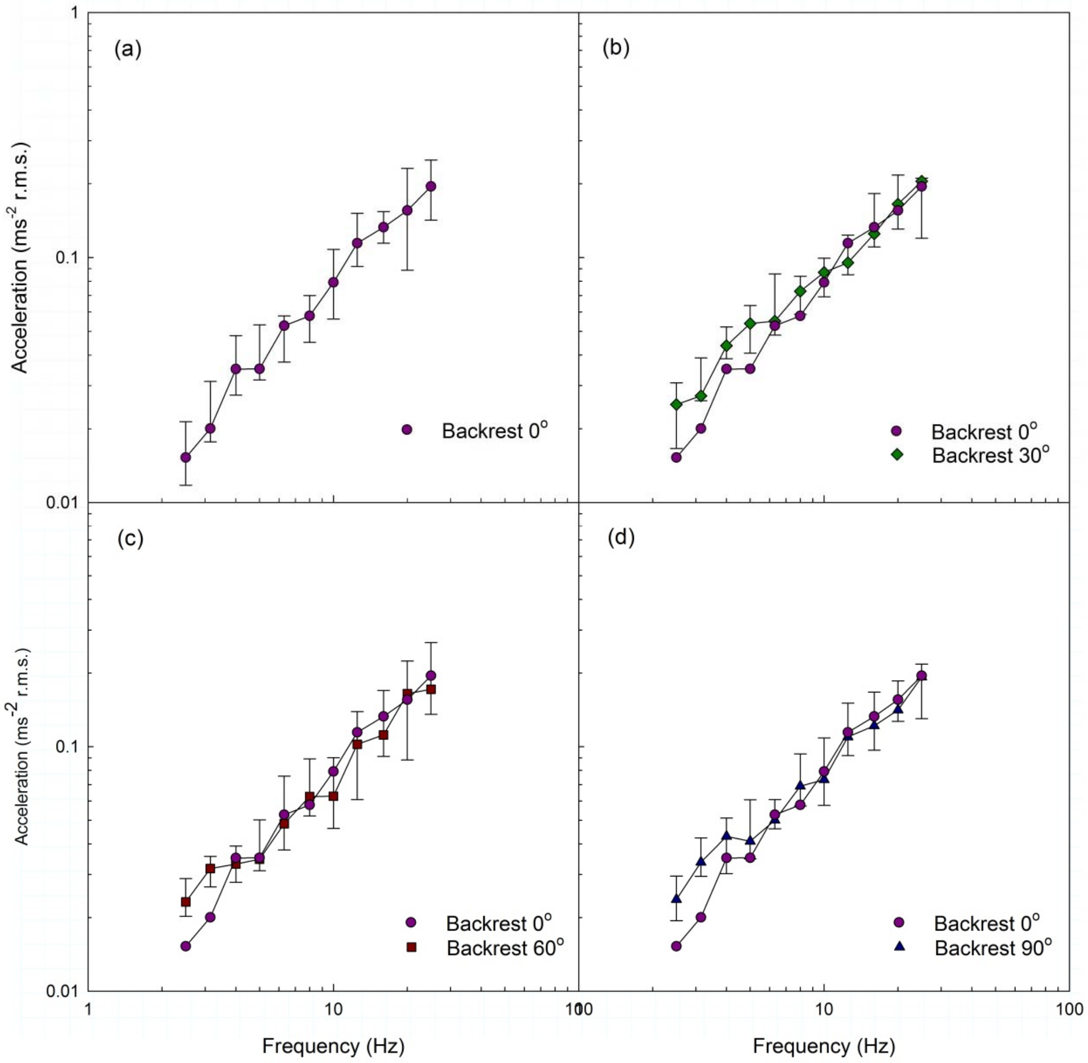

FIGURE 4

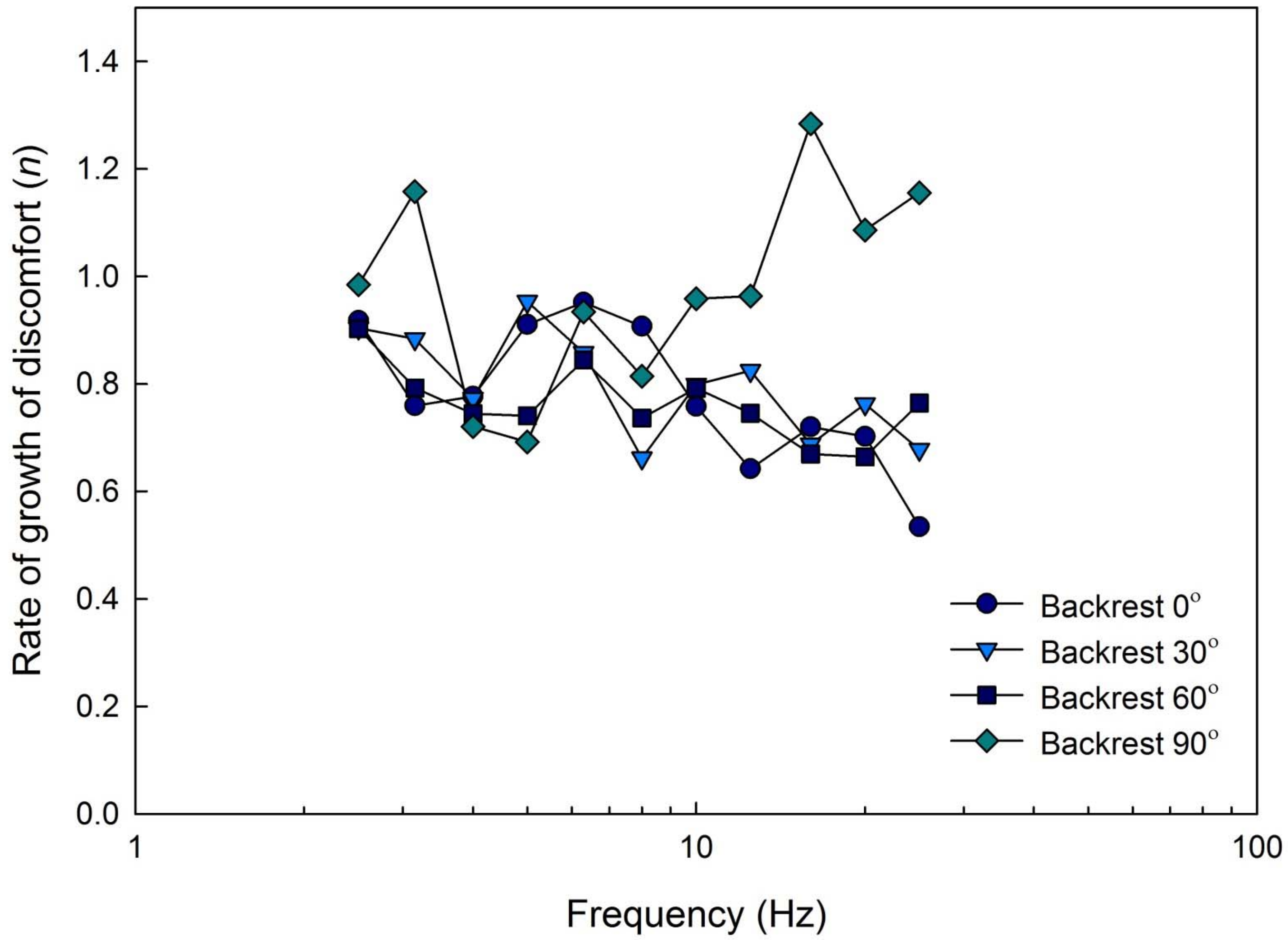
Rate of growth of discomfort (n)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
10
100
Frequency (Hz)
Backrest 0°
Backrest 30°
Backrest 60°
Backrest 90°

FIGURE 5

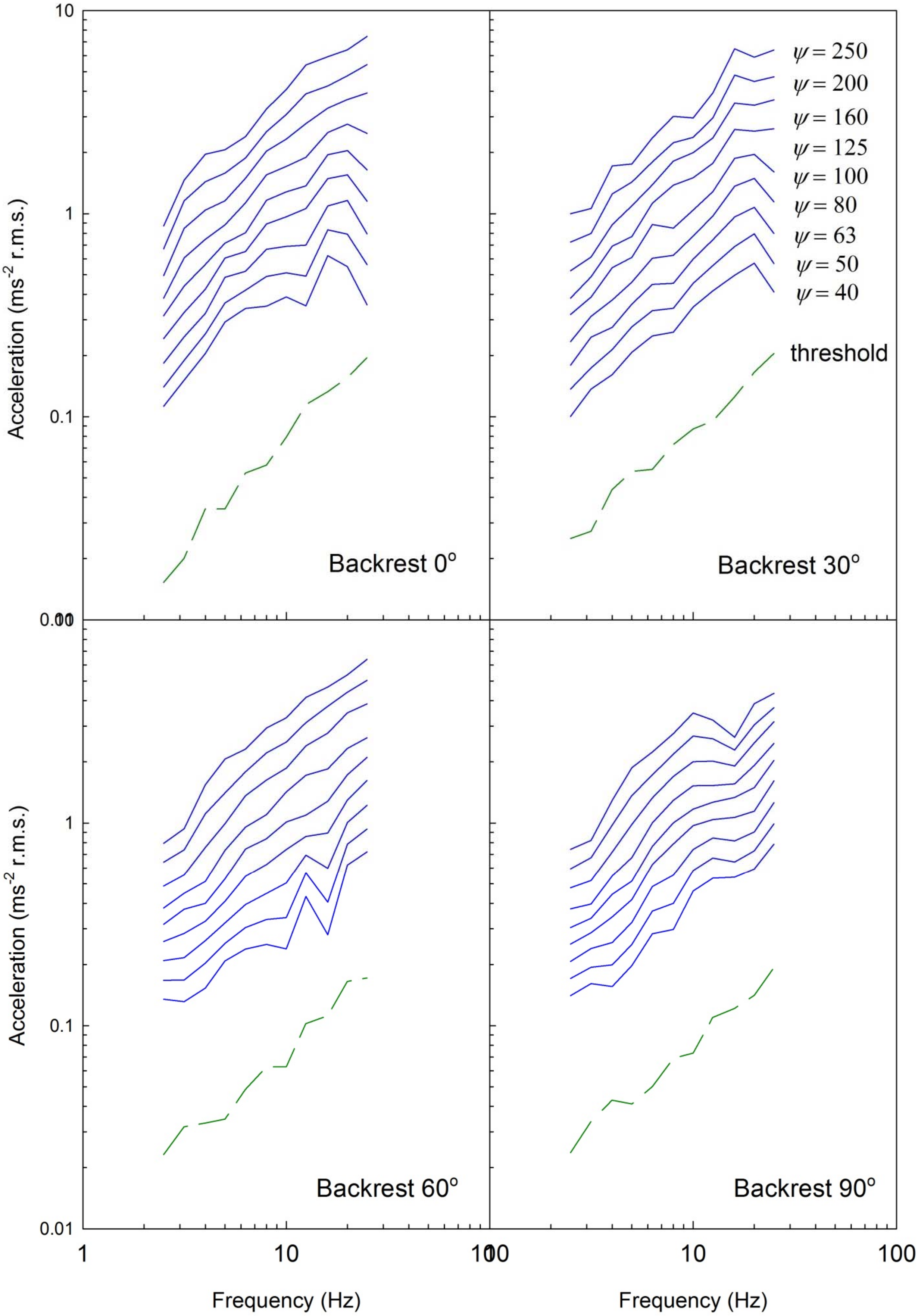
Acceleration (ms-2 r.m.s.)
Frequency (Hz)
ψ = 250
ψ = 200
ψ = 160
ψ = 125
ψ = 100
ψ = 80
ψ = 63
ψ = 50
ψ = 40
threshold
Backrest 0°
Backrest 30°
Backrest 60°
Backrest 90°

FIGURE 6

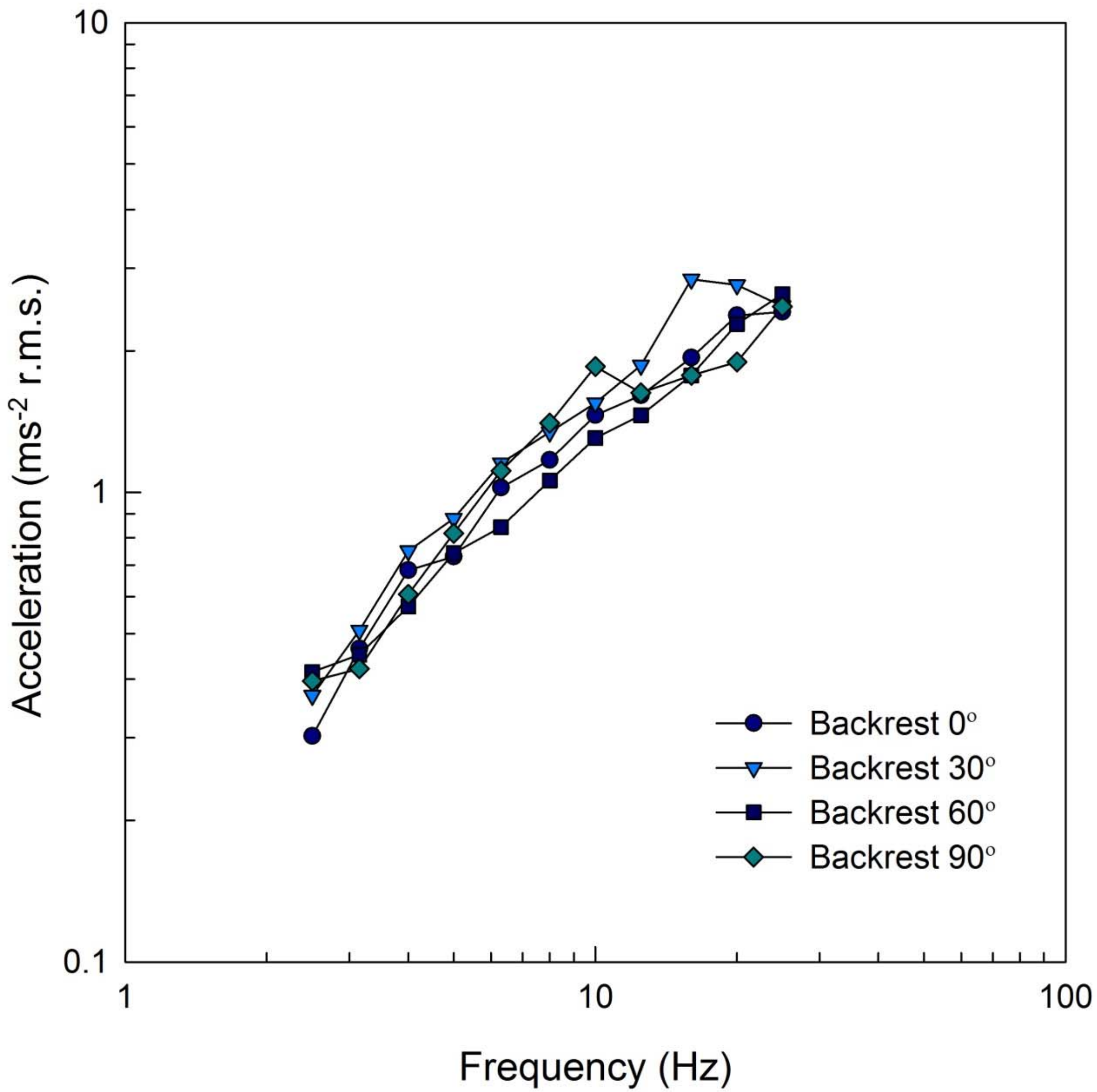
10
1
0.1
1
10
100
Acceleration (ms-2 r.m.s.)
Frequency (Hz)
Backrest 0°
Backrest 30°
Backrest 60°
Backrest 90°

FIGURE 7

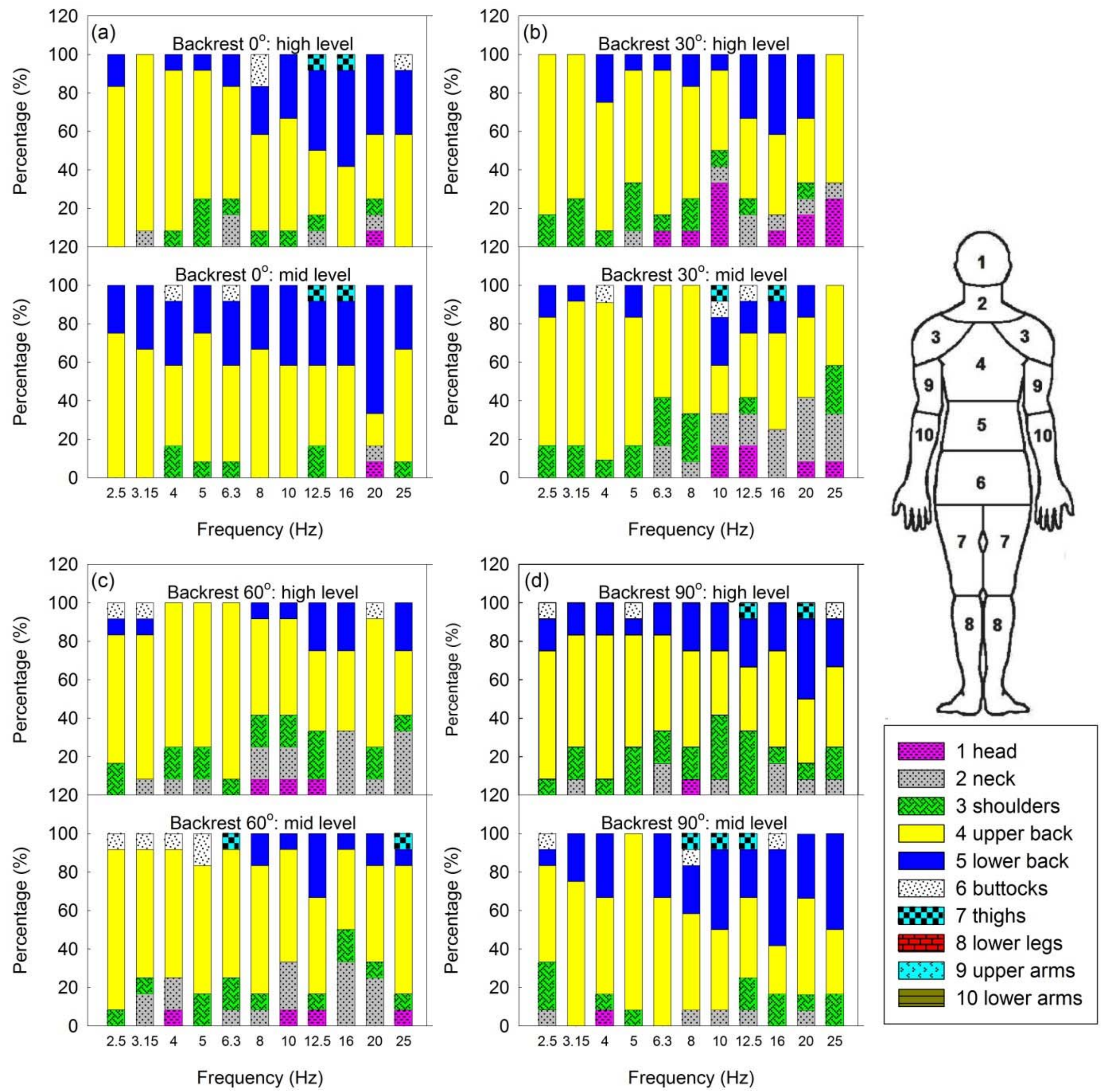
(a) Backrest 0°: high level
Backrest 0°: mid level
(b) Backrest 30°: high level
Backrest 30°: mid level
(c) Backrest 60°: high level
Backrest 60°: mid level
(d) Backrest 90°: high level
Backrest 90°: mid level
Percentage (%)
Frequency (Hz)
2.5 3.15 4 5 6.3 8 10 12.5 16 20 25
1 head
2 neck
3 shoulders
4 upper back
5 lower back
6 buttocks
7 thighs
8 lower legs
9 upper arms
10 lower arms

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FIGURE 8

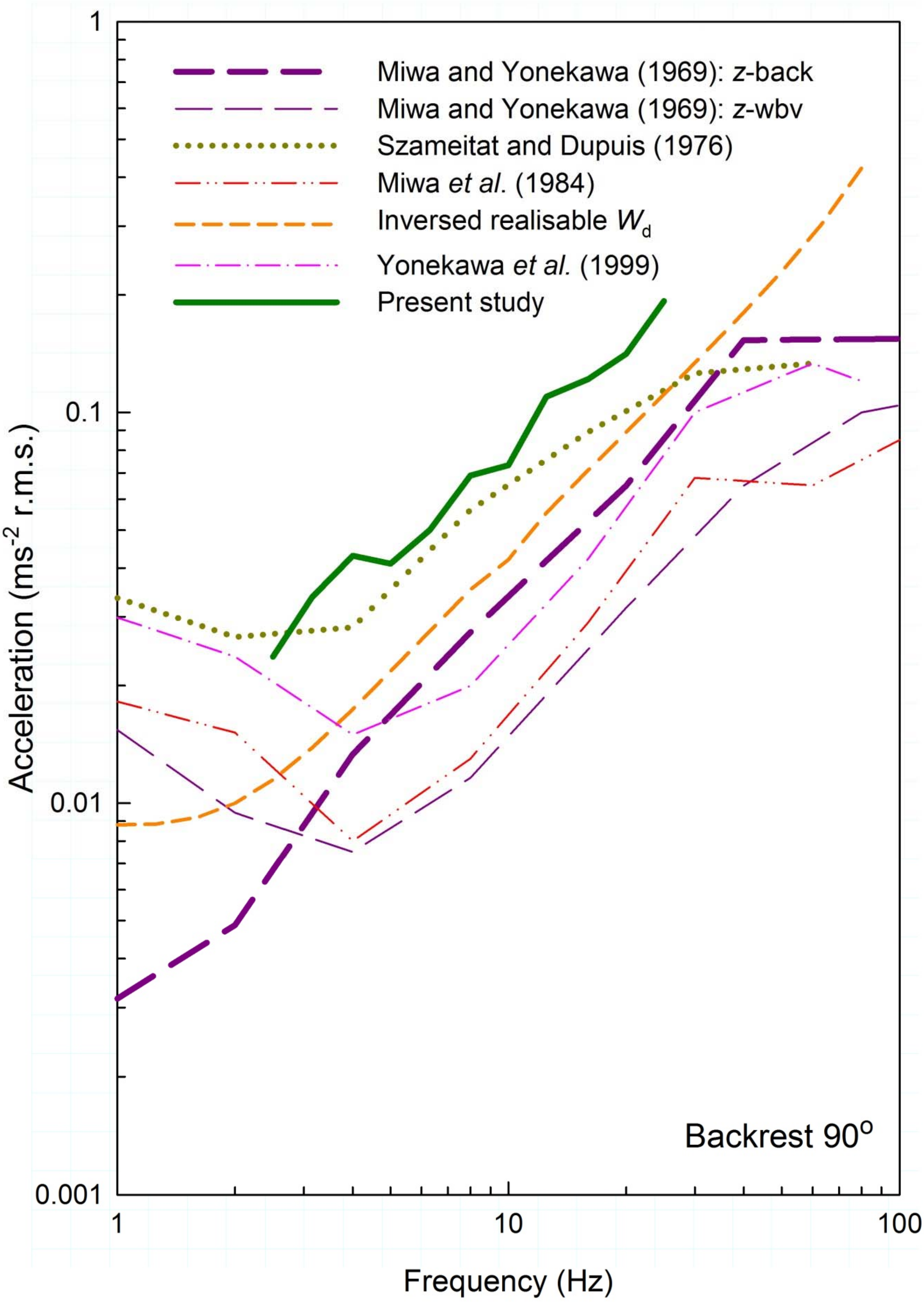

FIGURE 9

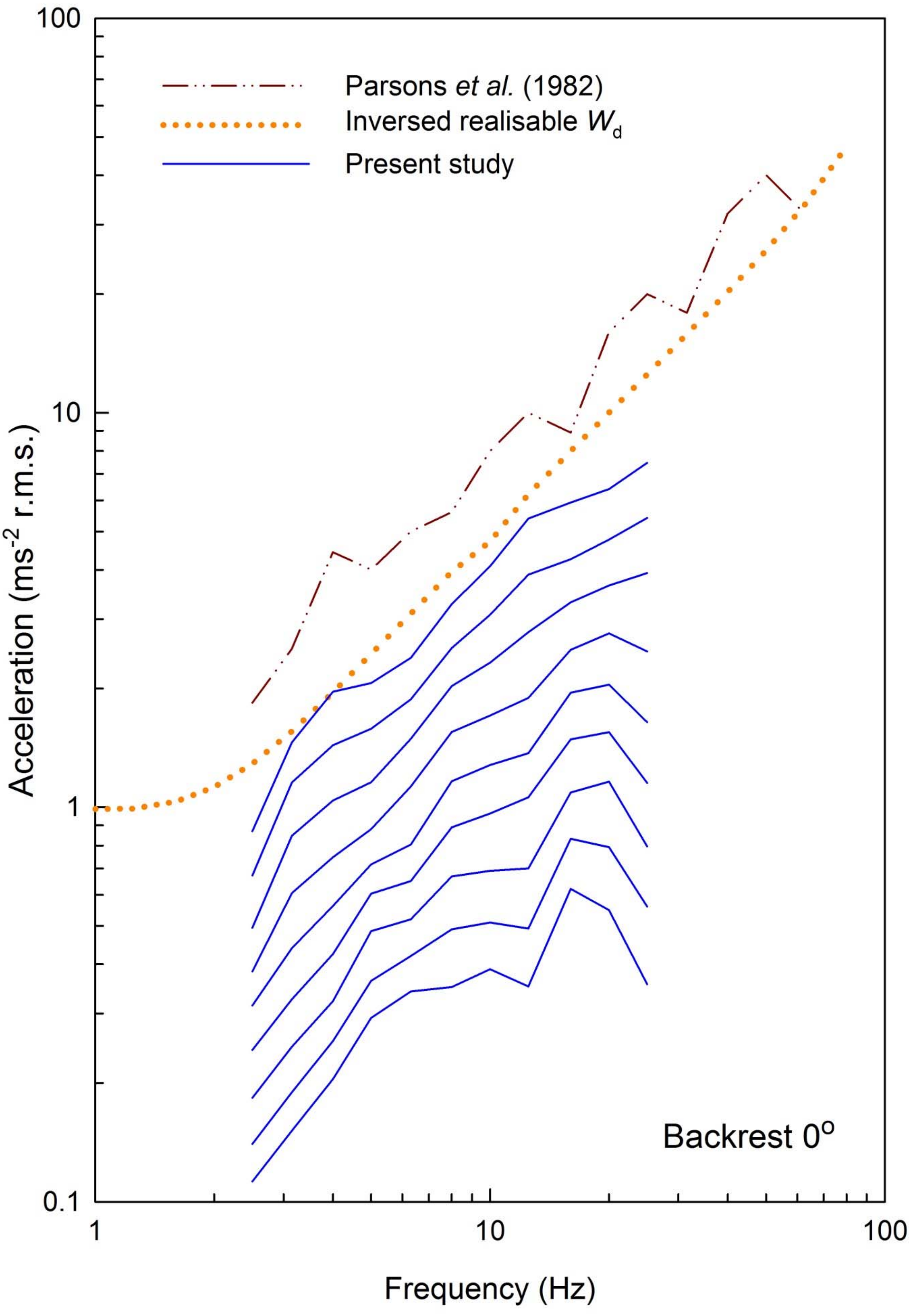
Parsons et al. (1982)
Inversed realisable W_d
Present study
Backrest 0°
Acceleration (ms^{-2} r.m.s.)
Frequency (Hz)
100
10
1
0.1
1
10
100

FIGURE 10

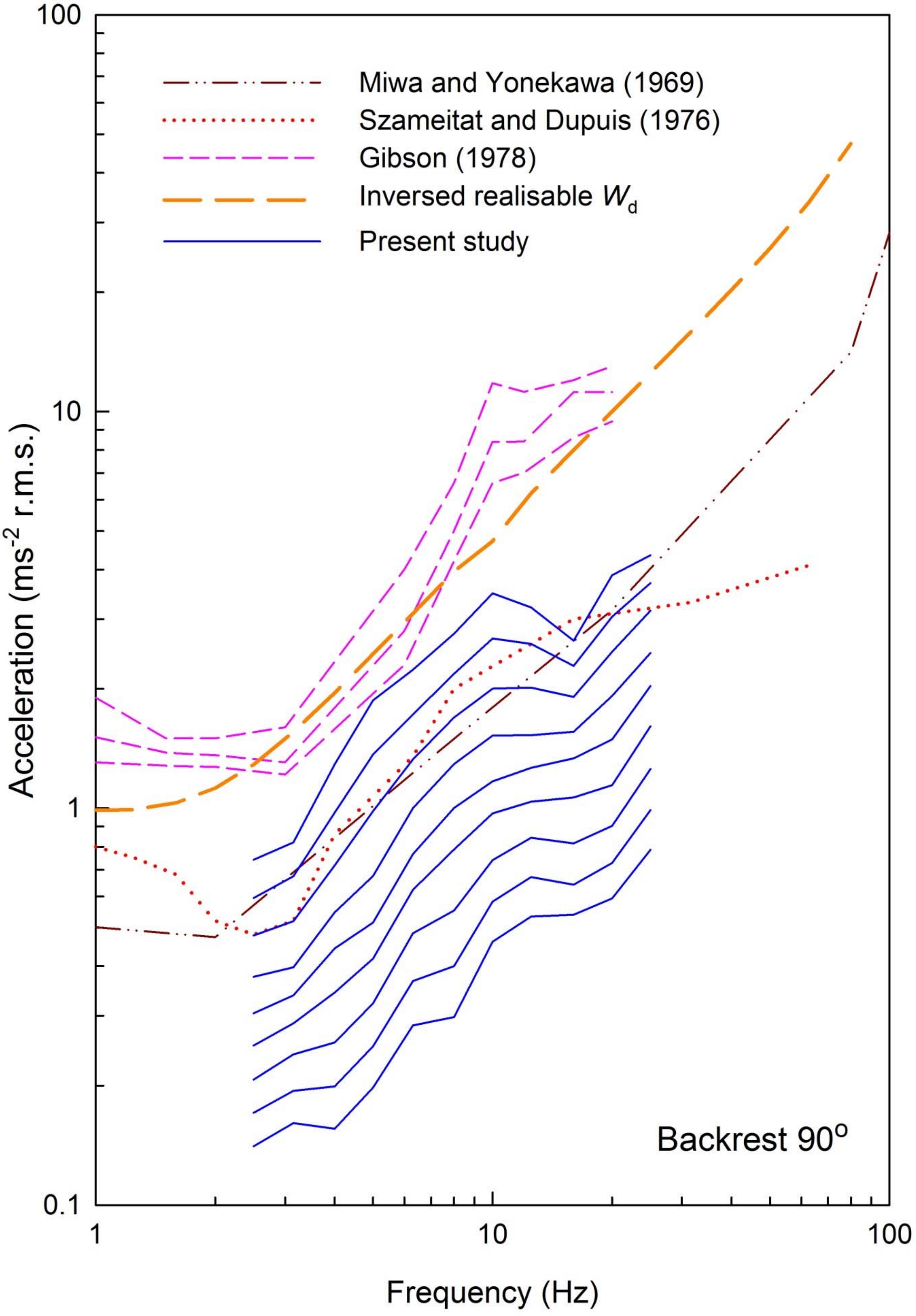
100
10
1
0.1
Acceleration (ms^{-2} r.m.s.)
1
10
100
Frequency (Hz)
Miwa and Yonekawa (1969)
Szameitat and Dupuis (1976)
Gibson (1978)
Inversed realisable W_d
Present study
Backrest 90^o

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FIGURE 11

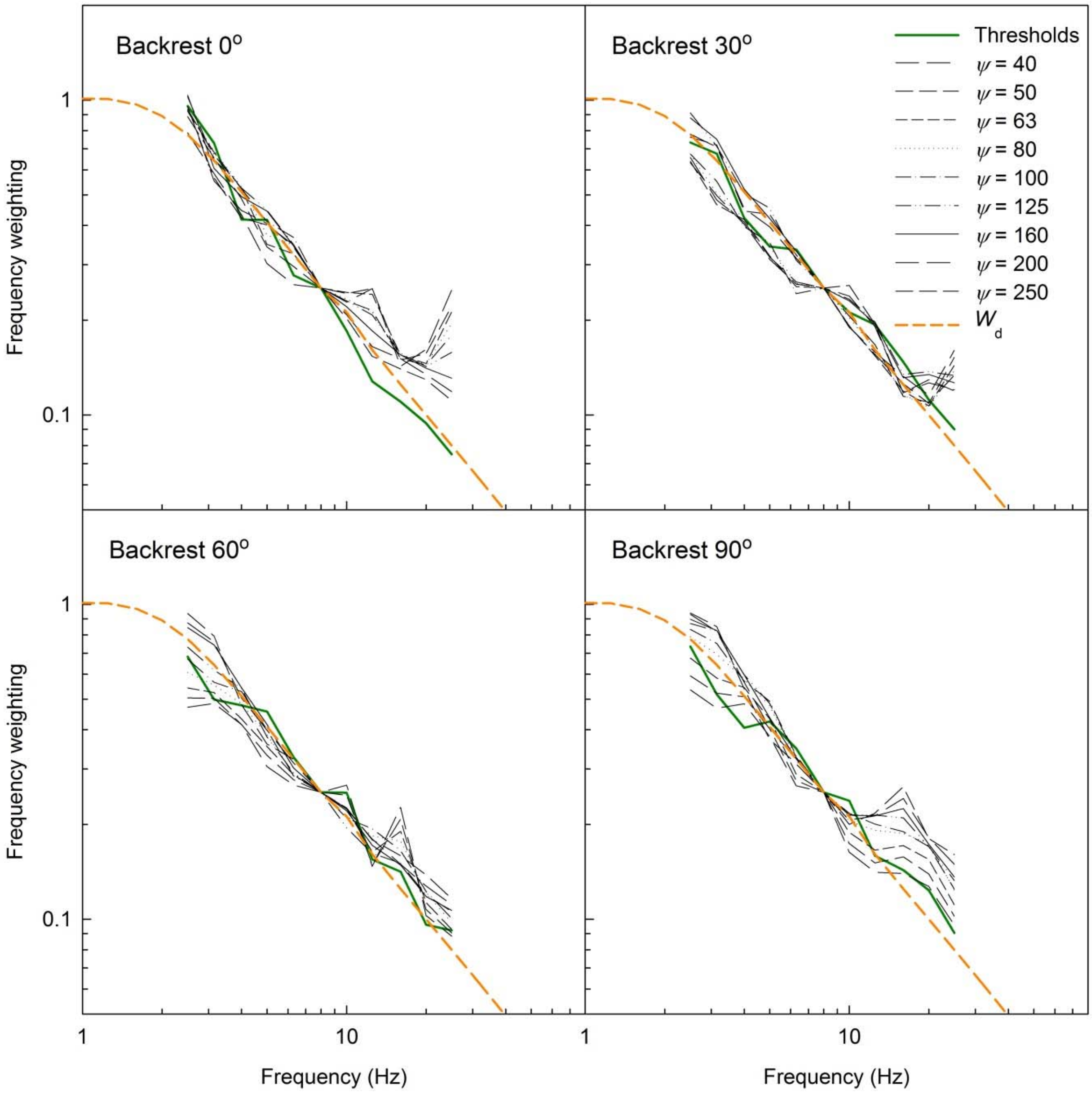

TABLE 1

Frequency	Exponent (*n*)				Constant (*k*)				Thresholds			
	0°	30°	60°	90°	0°	30°	60°	90°	0°	30°	60°	90°
2.5	0.918	0.799	1.058	1.028	284.08	255.06	312.79	322.92	0.015	0.025	0.023	0.024
3.15	0.759	0.813	0.885	1.158	177.44	237.34	265.03	323.29	0.020	0.027	0.032	0.034
4	0.777	0.755	0.798	0.794	156.63	172.21	188.25	204.96	0.035	0.044	0.033	0.043
5	0.911	0.784	0.794	0.747	139.32	150.18	160.84	161.60	0.035	0.054	0.035	0.041
6.3	0.952	0.884	0.851	0.934	115.96	110.12	130.31	124.79	0.053	0.055	0.048	0.050
8	0.907	0.757	0.755	0.814	88.95	106.63	117.97	98.64	0.058	0.073	0.063	0.069
10	0.771	0.799	0.792	0.958	82.31	98.50	99.10	82.89	0.079	0.087	0.063	0.073
12.5	0.685	0.825	0.845	1.012	76.62	82.02	89.40	76.10	0.114	0.095	0.102	0.110
16	0.720	0.688	0.696	1.284	58.56	64.64	86.44	75.13	0.133	0.125	0.112	0.122
20	0.702	0.763	0.860	1.093	57.04	59.22	62.76	71.24	0.156	0.165	0.165	0.141
25	0.534	0.678	0.893	1.156	72.11	73.66	52.51	51.08	0.195	0.205	0.172	0.193