Journal of Sound and Vibration (2000) **229**(5), 1077–1095
doi:10.1006/jsvi.1999.2598, available online at http://www.idealibrary.com on IDEAL®

TRANSMISSION OF YAW SEAT VIBRATION TO THE HEAD

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(*Received* 8 *January* 1999, *and in final form* 16 *July* 1999)

The transmission of yaw-axis vibration to the heads of seated subjects has been investigated at frequencies below 5 Hz. The variability between and within subjects and the effects of backrest contact, visual environment and the position of the centre of rotation have been investigated. The subjects sat on a rigid flat seat and were exposed to random motion at a magnitude of 1·0 rad/s^2 r.m.s. (root-mean-square) for 2 min. Head motion was measured in six axes using a light-weight bite-bar held between the teeth. Twelve male subjects participated in a study of the effect of backrest contact and visual conditions and one male subject participated in a repeatability study. A "back-on" posture (subject's back in contact with the seat backrest) increased the frequency of maximum transmissibility from 2 to 3 Hz compared with a "back-off" posture. There was little change in transmissibility with the subjects sitting with their eyes open compared to their eyes closed. With increasing separations between a subject and the centre of rotation (at six distances from 0 to 500 mm with the subject facing outwards) there were large increases in lateral acceleration at the head.

1. INTRODUCTION

The human body experiences rotation about the vertical axis (i.e., yaw-axis motion) during self-induced movements (e.g., ballet dancing and sports activities) and when travelling in vehicles. The head may compensate for the rotations of the body, so as to maintain a stable line of sight; alternatively, the head may be turned independently of body movement towards a fixed point, or moved to follow a moving point. Yaw movements of the body may have various effects on the comfort, well-being and performance of observers and operators in vehicles, yet there have been few investigations of how these effects depend on vibration frequency or how the motions are transmitted through the body.

Perception thresholds for yaw acceleration have been investigated using various low-frequency waveforms (e.g., references [1–4]). Perception thresholds for oscillation in the yaw axis have been reported to be lower when visual cues are present compared with when no cues are present over the frequency range 0·05–6·3 Hz [5] and female subjects have been reported to be slightly more sensitive to yaw-axis oscillation compared to male subjects over the range

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0·02–10 Hz [6]. Subjective responses to higher magnitudes of yaw oscillation have been reported from 2·5 to 8 Hz [7], from 0·05 to 6·3 Hz [5], from 1 to 31·5 Hz [8] and from 3·15 Hz to 8 Hz [9]. British Standard BS 6841 [10] defines a frequency weighting for use when assessing the discomfort of seated persons exposed to yaw-axis whole-body vibration. These experimental studies and recommendations mainly suggest that sensitivity to yaw-axis acceleration decreases with increasing frequency above about 1 Hz. The effects of rotational oscillation on vision have also been investigated (e.g., at 0·04 Hz [11], from 0·05 to 10 Hz [12], from 0·05 to 2 Hz [4]). Oscillation of the body about the yaw-axis can also cause motion sickness, by several possible mechanisms [13].

Compared with biodynamic studies of the transmission of whole-body translational motion to the heads of seated and standing subjects, there has been little investigation of the transmission of rotational seat vibration. Barnes and Rance [14] exposed eight seated subjects to yaw-axis motion and measured head motion in three rotational axes (roll, pitch and yaw) using a bite-bar (weighing 250 g). Subjects were exposed to sinusoidal oscillations at 16 frequencies in the range 0·5–20 Hz with a peak-to-peak magnitude of 20 rad/s^2 (7·07 rad/s^2 r.m.s. (root-mean-square)). The subjects sat with their eyes closed in two conditions: unrestrained (sitting upright with an erect back, no backrest, no harness) and restrained (leaning against a backrest, shoulder harness, lateral support). Transmissibilities between yaw seat acceleration and the three rotational axes of head motion showed most motion in the yaw-axis, with a peak at about 2 Hz for the unrestrained condition and rapid attenuation for frequencies above 4 Hz. There were no peaks in the yaw-axis transmissibility data when the subjects sat in the restrained condition: the transmissibilities decreased with increasing frequency. A greater attenuation in transmissibility was seen for the unrestrained condition (transmissibility of about 0·006 at 20 Hz) compared with the restrained condition (transmissibility of about 0·205 at 20 Hz).

The transmission of yaw vibration from the feet to the heads of standing subjects has been reported by Benson [12]. Ten male subjects stood in “relaxed” and “tensed” postures while exposed to sinusoidal motion at discrete frequencies over the range 0·5–10 Hz with a peak acceleration of 280°/s^2 (3·46 rad/s^2 r.m.s.). The acceleration of the head was found to decrease rapidly at frequencies above 5 Hz. Tensing the body increased the acceleration transmitted to the head over the frequency range.

This paper reports on experiments designed to investigate factors affecting the transmission of yaw seat vibration to the head. The variation in transmissibility within and between individuals, and the effects of sitting posture, visual feedback and the location of the centre of rotation along the fore-and-aft direction of the subject have been studied.

2. EQUIPMENT AND PROCEDURE

The experiments were conducted on a yaw-axis turntable consisting of a 2120 mm diameter platform resting on air bearings. The turntable was capable of producing oscillatory motion at frequencies up to 5 Hz. The whole apparatus was deemed safe for the exposure of human subjects to vibration.

A rigid seat with flat surfaces was used for the studies of intra-subject variability, inter-subject variability and the effect of the visual environment. The supporting surface of the seat was inclined backwards at an angle of 3° to the horizontal and was 470 mm above the turntable on which subjects rested their feet. A rigid flat backrest was inclined at an angle of 6° to the vertical and had its lower and upper edges 90 and 480 mm, respectively, above the seat surface. A seat with the same dimensions but of lighter construction was used to investigate the effect of the location of the centre of rotation on seat-to-head transmissibility. Both seats were rigid over the frequency range studied in these experiments (i.e., up to 5 Hz). A thin layer of high stiffness, high friction rubber was glued to the seat and the backrest surfaces to reduce relative motion between the subject and the seat due to sliding. A lap strap was worn by all subjects for safety purposes; it was worn loosely so as to have no influence on the head motion. The location of the centre of rotation was at the point of intersection between a line joining the subject's ischial tuberosities and their mid-sagittal plane. Thus, the position of the seat was adjusted for each subject. Two sitting postures were investigated: "back-on" (leaning slightly against the rigid seat backrest) and "back-off" (no contact with the seat backrest). The subjects sat in a comfortable upright posture for each exposure with their heads in a normal upright forward facing orientation.

Head motion was measured using light-weight bite-bars which the subjects held between their teeth. A simple bite-bar weighing 90 g was used to monitor fore-and-aft, lateral and yaw-axis acceleration of the head for the studies of intra-subject variability and the effects of the location of the centre of rotation. Two of the three translational accelerometers (Entran EGCSY-240D-10) were located on the bite-bar at mouth level and 60 mm to the left of the mid-sagittal plane. These transducers sensed fore-and-aft and lateral head acceleration. The third accelerometer (which measured fore-and-aft acceleration) was located similarly but to the right of the mid-sagittal plane. Yaw-axis head motion was obtained from the difference in the signals provided by the two fore-and-aft accelerometers.

The bite-bar used for the study of inter-subject variability and the effect of visual environment measured motion in all six axes (fore-and-aft, lateral, vertical, roll, pitch and yaw). The translational accelerations were measured at mouth level 100 mm to the left of the mid-sagittal planes of the subjects. The bite-bar had six miniature accelerometers (Entran type EGAX5) located and orientated so that all six axes of acceleration could be measured (see reference [15]). The total weight of this six-axis bite-bar was 135 g. Rotational acceleration on the platform (turntable) was measured using a translational accelerometer (Entran type EGCSY-240D-10) attached at a distance of 1·0 m from the centre of rotation.

A data acquisition and analysis system, *HVLab*, developed at the Institute of Sound and Vibration Research of the University of Southampton, was used to control the experiment and analyze the acquired data. A computer-generated random waveform having a nominally flat acceleration spectrum was used with a rotational acceleration magnitude of 1·0 rad/s^2 r.m.s. at the seat. The waveform was sampled at 32 samples per second and low-pass filtered at 5 Hz before being fed to the turntable. Acceleration signals from the bite-bar accelerometers (either 3 or 6 channels of vibration depending on the type of bite-bar) and the vibrator platform were passed through signal conditioning amplifiers and then low-pass filtered (30 dB/octave Butterworth) at 10 Hz. These signals were digitized into a computer at a sample rate of 32 samples per second. The duration of each vibration exposure was 120 s.

2.1. PROCEDURE

Subjects taking part in the experiments were given written instructions about the required postures of the head, body, arms, etc. (see Appendix A).

To investigate the effect of backrest contact and the visual environment, an experiment was conducted with 12 subjects. The effect of the visual environment was determined with the subjects sitting in a back-off posture with two visual conditions: “eyes open” and “eyes closed”. The order of presentation of the two postures and the two visual conditions was completely balanced across the subjects such that four subjects commenced with the back-on posture (eyes open), four subjects started with the back-off posture with their eyes open, and four subjects commenced with the back-off posture with their eyes closed. Intra-subject variability in the transmission of vibration to the head was determined with one subject who sat in a back-on posture (eyes open) and was exposed to the same vibration six times, with a 5 min pause between exposures.

To determine the influence of the position of the centre of rotation, the seat was moved away from the centre of the turntable along the subject’s fore-and-aft axis in increments of 100 mm, with the subject facing away from the centre of rotation. Six separation distances between the centre of rotation and the subject’s ischial tuberosities were investigated: 0 mm (subject sitting on the centre of rotation) to 500 mm (centre of rotation 500 mm behind the subject). The separation distance was successively increased between the consecutive runs. Therefore, apart from the first run in which he experienced pure yaw-axis vibration, the subject was exposed to a combination of yaw, lateral and fore-and-aft acceleration. During all vibration exposures, the subject sat in an upright forward facing back-off posture. The same subject took part in the intra-subject variability experiment described above.

2.2. SUBJECTS

One male subject took part in the intra-subject variability experiment. He was 45 years old, weighed 87 kg and was 1·89 m tall. This subject also took part in the experiment to investigate the effect of the location of the centre of rotation on the transmission of vibration from seat to head. A group of 12 male subjects participated in the inter-subject variability study, the effect of the visual environment and the investigation of the effect of sitting posture; their physical characteristics are summarized in Table 1. All subjects were fit and healthy, and complied with the medical contraindications specified in British Standard BS 7085

Table 1

Physical characteristics of subjects taking part in the experiments

	Age (yr)	Weight (kg)	Stature (m)
Minimum	22	65	1·68
Maximum	46	87	1·85
Mean	30	75	1·79
Standard deviation	7·1	5·4	0·05

[16]. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

3. ANALYSIS

Transfer functions between seat motion and head motion have been calculated using the "cross-spectral density function (c.s.d.) method". The transfer function, $H_c(f)$, was determined as the ratio of the cross-spectral density of seat and head motions, $G_{sh}(f)$, to the power spectral density of seat motion, $G_{ss}(f)$, that is

$$H_c(f) = \frac{G_{sh}(f)}{G_{ss}(f)}.$$

Transfer functions were also calculated using the "power spectral density function (p.s.d.) method". These transfer functions, $H_p(f)$, were determined as the square root of the ratio of the power spectral density of head motion, $G_{hh}(f)$, to the power spectral density of seat motion, $G_{ss}(f)$:

$$H_p(f) = \left[\frac{G_{hh}(f)}{G_{ss}(f)}\right]^{1/2}.$$

The transfer function calculated using the c.s.d. method $H_c(f)$, produces a complex output that can be used to resolve the transmissibility (i.e., modulus of the transfer function) and the phase between the input (seat motion) and the output (head motion). Transmissibility and phase are calculated as follows:

$$\text{transmissibility} = [(R(H_c(f)))^2 + (I(H_c(f)))^2]^{1/2},$$

$$\text{phase} = \tan^{-1}\left[\frac{I(H_c(f))}{R(H_c(f))}\right],$$

where $R(H_c(f))$ is the real part of the transfer function, and $I(H_c(f))$ is the imaginary part of the transfer function.

The c.s.d. transfer function only takes into account the linearly correlated proportion of the output motion with the input motion. The p.s.d. method $H_p(f)$, takes into account the total energy in the output signal, and thus produces a real output. The transmissibility calculated using the c.s.d. transfer function method will be equal to or less than that produced using the p.s.d. method.

Ordinary coherency can be calculated for the c.s.d. method. This provides an indication of the amount of motion at the output which is linearly correlated with the input motion. It can be calculated as

$$\text{ordinary coherency } \gamma^2_{sh}(f) = \frac{|G_{hh}(f)|^2}{G_{ss}(f)G_{hh}(f)}.$$

The coherency will show values between 0 and 1; a coherency of 0 would indicate no correlation between input and the output motions, whereas a value of 1 would imply perfect correlation between the two motions.

Transfer functions were calculated between yaw seat acceleration and the six axes of acceleration at the head. Transfer functions have been calculated for a position on the bite-bar at mouth level and either 60 or 100 mm (depending on the type of bite-bar) to the left of the mid-sagittal planes of the subjects. Frequency analysis was carried out with a resolution of 0·122 Hz, which gave 58 degrees of freedom (d.o.f.).

4. RESULTS

4.1. INTRA- AND INTER-SUBJECT VARIABILITY

Transmissibilities between yaw seat acceleration and three axes of acceleration (fore-and-aft, lateral and yaw) at the head are shown in Figure 1 for the subjects

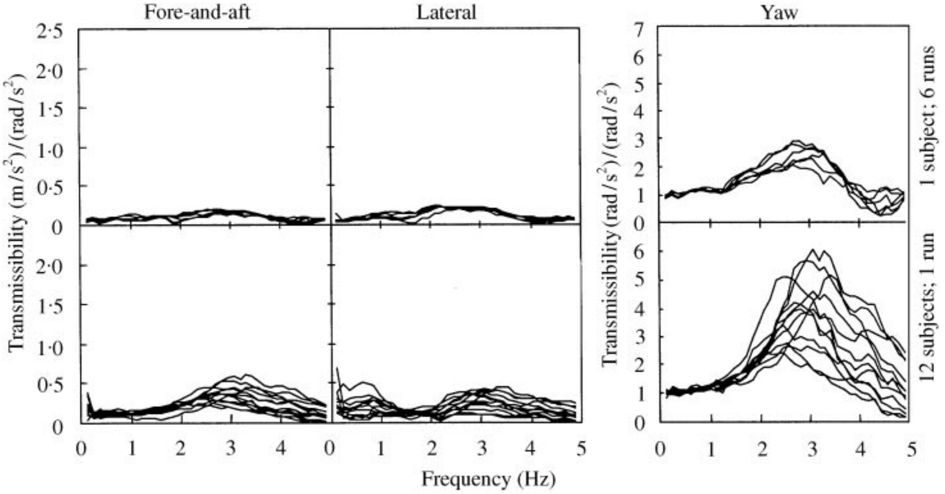

Figure 1. Transmissibilities for subjects sitting in a back-on posture during exposure to yaw seat vibration (0·122 Hz resolution, 58 d.o.f.).

sitting with a back-on posture at the centre of rotation. The data shown are for the 1 subject who took part in the intra-subject variability study (top part of figure) and the 12 subjects taking part in the inter-subject variability study (lower part of figure).

The data from the repeated exposure of 1 subject show a peak in yaw-axis transmissibility at about 2·8 Hz. Motion of the subject's head in the horizontal axes (fore-and-aft and lateral) showed low values, although with a consistent pattern.

Transmissibilities for the 12 subjects also show low values for translational motion in the fore-and-aft and lateral axes, with a maximum of about 0·5 $(m/s^2)/(rad/s^2)$ at 3 Hz. Yaw-axis transmissibilities show a peak in the range 2–3·5 Hz with large variations between subjects at frequencies greater than about 1·5 Hz. The percentage difference between the minimum and maximum yaw response at any frequency tended to increase with increasing frequency, indicating greater inter-subject variability at higher frequencies. At 5 Hz, the yaw transmissibility was 0·1 $(rad/s^2)/(rad/s^2)$ for 1 subject but 2·2 $(rad/s^2)/(rad/s^2)$ for another.

4.2. EFFECT OF SITTING POSTURE

Figures 2 and 3 show transmissibilities to the six axes of head motion during exposure to pure yaw-axis motion with the 12 subjects sitting in back-on and back-off postures, respectively.

The effect of sitting posture on the transmission of yaw seat vibration to the head is seen in the median transmissibilities shown in Figure 4. There is a reduction in the frequency of maximum transmissibility from about 3 to 2 Hz in the fore-and-aft, lateral and yaw axes as the posture changed from back-on to back-off. A higher resonance frequency is consistent with the backrest stiffening the response of the

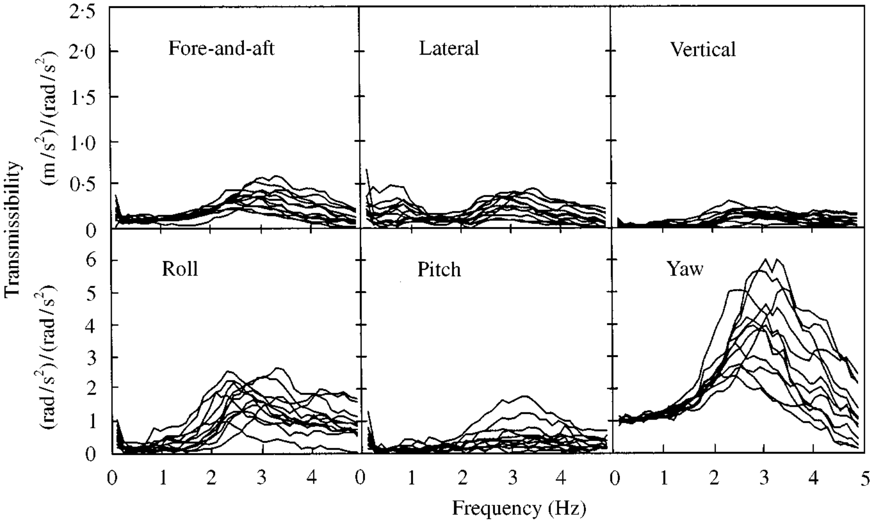

Figure 2. Transmissibilities for 12 subjects in a back-on posture during exposure to yaw seat vibration (0·122 Hz resolution, 58 d.o.f.).

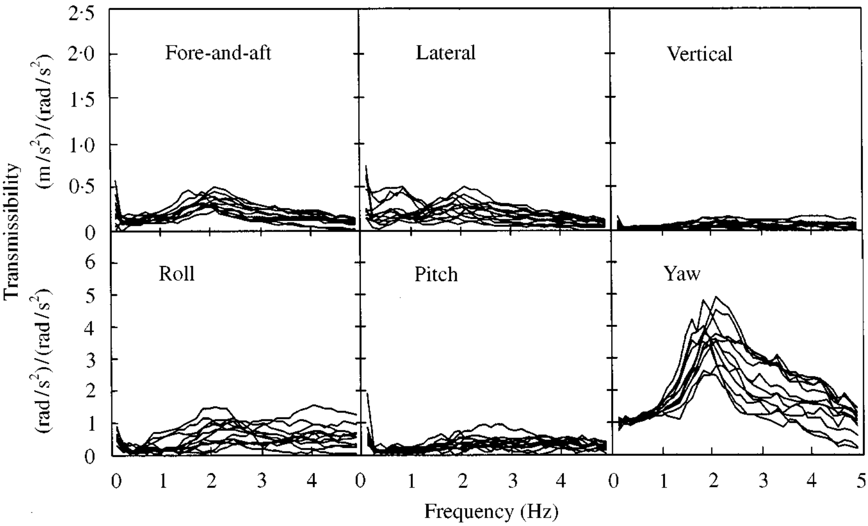

Figure 3. Transmissibilities for 12 subjects in a back-off posture during exposure to yaw seat vibration (0·122 Hz resolution, 58 d.o.f.).

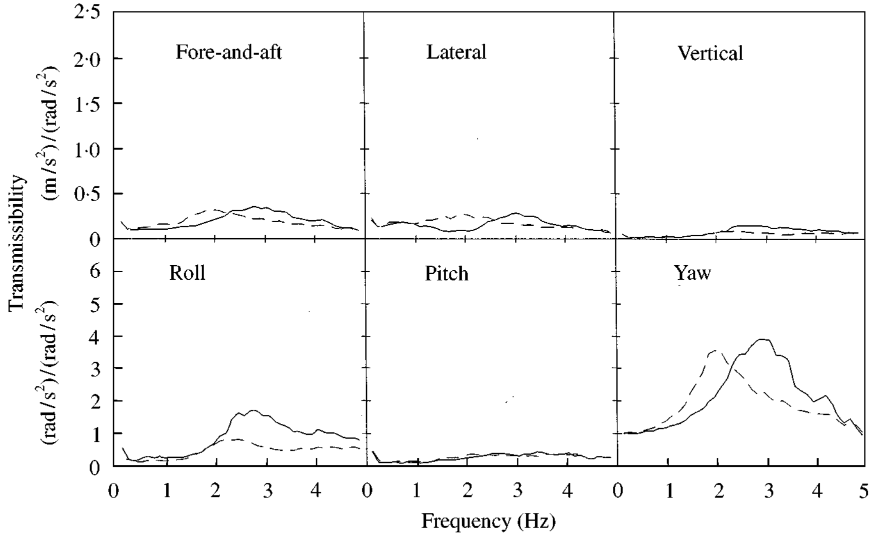

Figure 4. Median transmissibilities for 12 subjects seated in back-on (——) and back-off (- - - -) postures during exposure to yaw seat vibration (0·122 Hz resolution, 58 degrees of freedom).

body. For head motion in the translational axes, the differences in transmissibility caused by backrest contact were statistically significant (i.e., fore-and-aft and lateral axes: 0·5–2 Hz and 2·5–4·3 Hz; vertical axis: 2·3–4·1 Hz; $p < 0.05$, Wilcoxon matched-pairs signed ranks test, [17]). Roll transmissibilities showed a significant reduction in motion for frequencies above 2·3 Hz with the back-off posture ($p < 0.01$). Sitting posture had no significant effect on pitch-axis transmissibilities.

There was a significant effect of the backrest on yaw transmissibilities from 0·7 to 2 Hz and from 2·6 to 4·2 Hz ($p < 0{\cdot}01$).

4.3. EFFECT OF VISUAL ENVIRONMENT

Small differences between the median transmissibilities obtained with the eyes open and with the eyes closed were not statistically significant in any of the six axes of head motion, apart from the yaw-axis where there was slightly more head motion in the range 2·4–3·5 Hz with the eyes closed (Figure 5, $p < 0{\cdot}05$, Wilcoxon matched-pairs signed ranks test).

4.4. PHASE FOR SITTING POSTURE AND VISUAL ENVIRONMENT

The phases calculated using the cross-spectral density method for the 12 subjects seated in the two backrest conditions (i.e., back-on and back-off) and with the two visual conditions (i.e., eyes open and eyes closed) are shown in Figure 6. There was a significant difference in phase for frequencies from 1 to 5 Hz between the subjects sitting in back-on and back-off postures with their eyes open ($p < 0{\cdot}01$, two-tail, Wilcoxon matched-pairs signed ranks test). There were no distinct differences in phase with changes in visual condition (sitting in a back-off posture with eyes open and eyes closed).

4.5. EFFECT OF LOCATION OF THE CENTRE OF ROTATION

There was a large and consistent increase in lateral head motion at frequencies below about 2 Hz as the separation distance between the subject and the centre of

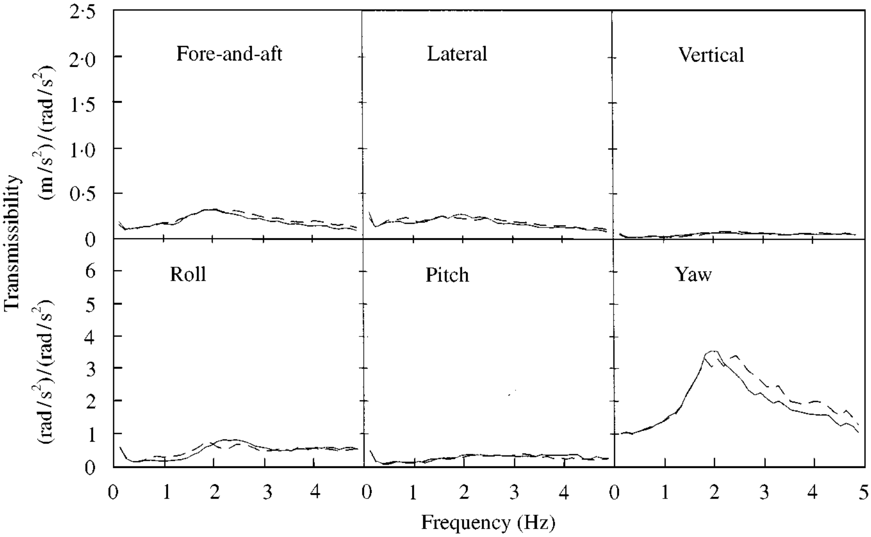

Figure 5. Median transmissibilities for 12 subjects seated in a back-off posture with their eyes open (——) and eyes closed (- - - -) during exposure to yaw seat vibration (0·122 Hz resolution, 58 d.o.f.).

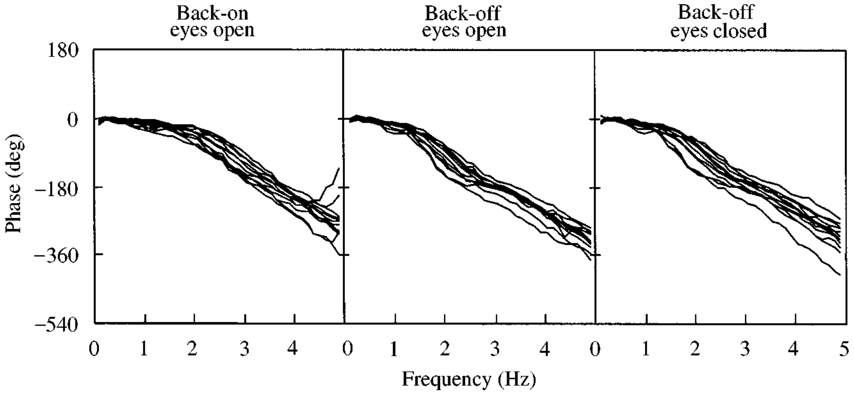

Figure 6. Phases between yaw seat vibration and yaw head motion for 12 subjects seated in different postures and visual conditions (0·122 Hz resolution, 58 d.o.f.).

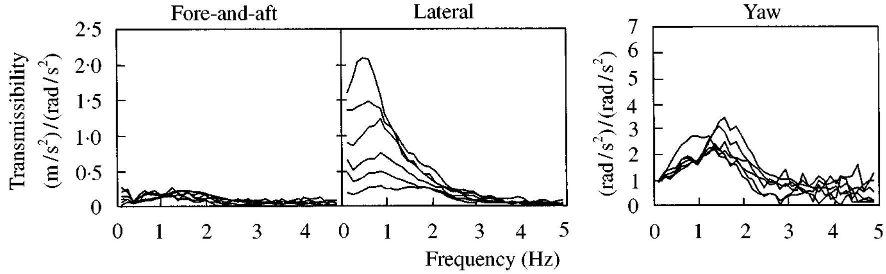

Figure 7. Transmissibilities for one subject in a back-off posture during exposure to yaw seat vibration with various locations for the centre of rotation along the fore-and-aft axis (0·122 Hz resolution, 58 d.o.f.).

rotation increased (Figure 7). This is consistent with the increase in lateral acceleration occurring on the seat. There were no consistent trends in the fore-and-aft or yaw axes of head motion with increasing distance between the subject and the centre of rotation when using the c.s.d. method of analysis. (The effect of varying separation distances on transmissibility is more clearly seen in the data when using the p.s.d. method of analysis as presented in Figure 10, below.)

5. DISCUSSION

Median and inter-quartile ranges of the yaw-axis transmissibilities shown in Figure 1 are illustrated in Figure 8 for both intra- and inter-subject variability. It is clear that inter-subject variability with 12 subjects was much greater than the variability occurring during repeat measures with 1 subject. The variability between and within subjects has been compared by the relative variability (i.e., the ratio of the inter-quartile range across subjects to the inter-quartile range within subjects, see reference [18]). The relative variability in yaw-axis transmissibility for the data presented in Figure 8 shows that at 3·6 Hz, the variation between subjects was up to about 19 times the variation found within one individual.

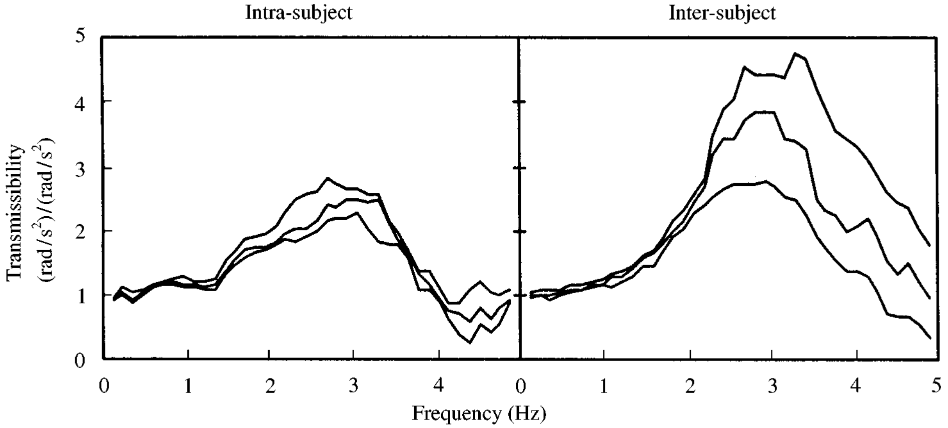

Figure 8. Median and inter-quartile transmissibilities for subjects sitting in a back-on posture during exposure to yaw seat vibration (0·122 Hz resolution, 58 d.o.f.).

In a study involving 1 subject, Paddan and Griffin [19] showed that contact with the seat backrest increased the frequency of maximum motion of yaw-axis head motion from 1·6 Hz (back-off posture) to 2·8 Hz (back-on posture). In the present study, transmissibilities obtained from 12 subjects showed this trend in the fore-and-aft, lateral and yaw axes (Figure 4), with a significant decrease in frequency ($p < 0{\cdot}05$, Wilcoxon matched-pairs signed ranks test) from about 3 Hz (for the back-on posture) to 2 Hz (for the back-off posture). With the subjects sitting in a back-off posture, the input motion to the body was solely at the seat, with vibration being transmitted through the torso and the upper body to the head. In the back-on posture, the input motion was additionally transmitted by the seat backrest to the shoulders. The backrest may also have served to support and stiffen the response to the upper body. Numerical values of median transmissibilities for yaw-axis head motion are shown in Appendix B for the two sitting postures so as to assist comparison with future studies and biodynamic models (other tabulated transmissibility data are available elsewhere [20]).

Barnes and Rance [14] measured yaw-axis transmissibilities in a darkened room with the subject's eyes closed to eliminate visual feedback. In the present experiment, the effect of the visual environment on seat-to-head transmissibility was small: in a back-off posture, eyes open and eyes closed conditions gave similar transmissibilities (see Figure 5). If changes in the visual environment were to affect transmissibility, the effects would have been more likely to occur with the subjects sitting in the back-off posture than in the back-on posture, where additional tactile cues and postural support from the backrest might help to control head motion. If visual feedback was to affect head motion, a yaw transmissibility lower than unity might have been expected at low frequencies, but this is not evident in the data. A similar study reported elsewhere has found that visual feedback had no effect on seat-to-head transmissibility during exposure to either roll or pitch seat vibration [21]. These findings might depend on the type of motion employed in addition to the visual conditions and the subject instructions.

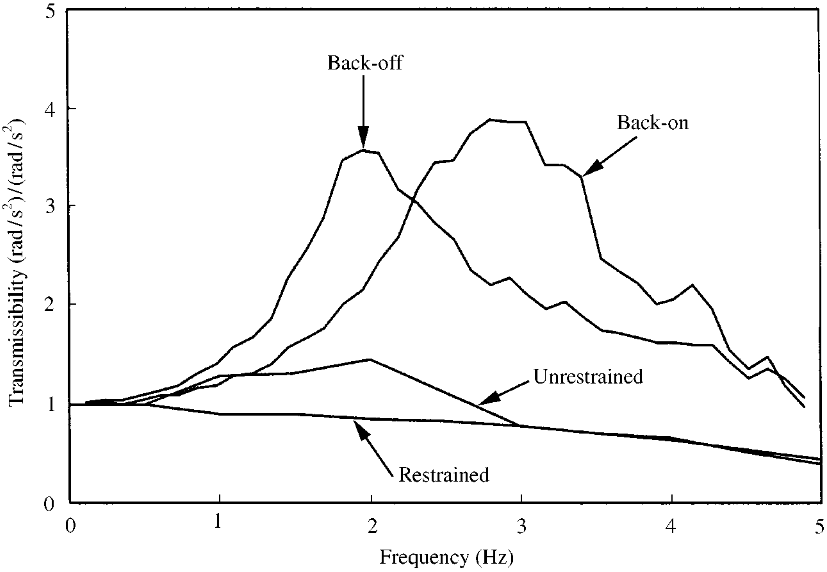

Figure 9. Comparison of median (back-on and back-off for present data) and mean (restrained and unrestrained from Barnes and Rance [14]) transmissibilities for subjects sitting during exposure to yaw seat vibration.

The transmissibilities presented in the various figures were calculated for motion occurring at the point of measurement on the bite-bars (two different bite-bars were used, see sections 2 and 3). One bite-bar was capable of measuring head motion in six axes (fore-and-aft, lateral, vertical, roll, pitch and yaw axes) while the other bite-bar was used to measure motion in only three axes (fore-and-aft, lateral and yaw axes). The data from the six-axis bite-bar can be used to calculate the motion of the head at any chosen anatomical landmark; the procedure has been demonstrated elsewhere (see reference [22]). The procedure involves various assumptions. Transmissibilities reported for the fore-and-aft and the lateral axes would be affected by changing the point of measurement. The peak transmissibilities in the fore-and-aft and lateral axes in Figures 4 and 5 occur at the same frequency as the peak in the yaw transmissibility and so it is expected that these peaks would be less evident at a point closer to the centre of yaw of the head.

Figure 9 compares the transmissibilities between yaw-axis seat motion and yaw-axis head motion obtained in two studies: median transmissibilities for back-on and back-off postures from the present study (as presented in Figure 4) and mean transmissibilities for "restrained" and "unrestrained" postures presented by Barnes and Rance [14]. There are significantly lower transmissibilities and less evidence of resonance in the data from Barnes and Rance. At 2 Hz there is a peak in the transmissibility from both studies with the less constrained posture (i.e., back-off posture and unrestrained posture). However, the median transmissibility for the back-off posture (about 3·6) is much greater than the mean transmissibility for the unrestrained posture (about 1·5). The large differences between the two studies suggest that the subjects used by Barnes and Rance were much more tightly constrained to the seat than in the present experiments. In the restrained posture this may have been achieved by the shoulder harness and lateral support.

With a subject seated at a position on the turntable other than at the centre of rotation, there is combined yaw, lateral and fore-and-aft oscillation. When, as in the experiment, the centre of rotation was behind the seat, the subject received lateral acceleration proportional to both the yaw acceleration and the distance from the centre of rotation to the seat. The fore-and-aft acceleration was proportional to this distance and the square of the yaw velocity. When using the c.s.d. method of analysis as described above, the yaw acceleration at the seat was the “input”. Any head acceleration linearly correlated with either the yaw acceleration of the seat or the lateral acceleration of the seat will have contributed to the calculated transmissibilities shown in Figures 1–8. However, any head acceleration that was linearly correlated with the fore-and-aft seat acceleration (i.e., centripetal acceleration) will not have greatly contributed to the transmissibilities. This may be expected to have artificially reduced the transmissibilities to the fore-and-aft direction of the head since this direction of movement is the most likely motion to be caused by fore-and-aft seat acceleration [23]. The identification of the full response of the body when sitting away from the centre of rotation might appear to require analysis of the body response as a three-input six-output system, but two of the inputs (yaw and lateral acceleration) are correlated. The influence of the fore-and-aft seat acceleration can be estimated by calculating transmissibilities using the p.s.d. method. This method shows the ratio of head acceleration to the input acceleration (i.e., yaw acceleration) irrespective of whether the head acceleration is linearly correlated with the input. The transmissibilities given by this method will therefore be either the same as, or higher than, those obtained using the c.s.d. method. A difference between the two transmissibilities illustrates the extent to which motion at the head is not correlated with the yaw acceleration on the turntable. With the subject sitting away from the centre of rotation most of this motion may be expected to be caused by fore-and-aft acceleration of the turntable, but “noise” sources will also contribute. Comparisons between the c.s.d. and the p.s.d. transmissibilities at various distances from the centre of rotation are shown in Figure 10. The total motion in the fore-and-aft axis at the head gradually increased with increasing distance from the centre of rotation (i.e., transmissibilities calculated using the p.s.d. method). In contrast, the linearly correlated motion at the head in the fore-and-aft direction remained almost constant with increasing separation distance (i.e., transmissibilities calculated using the c.s.d. method). Transmissibilities for lateral acceleration at the head show small differences between the two methods of calculation, indicating that most of the acceleration at the head in the lateral axis was probably caused by either yaw or lateral acceleration of the turntable. As there was a gradual increase in the lateral transmissibilities with increasing distance between the centre of rotation and the seat, it can be concluded that this increase was due to the lateral acceleration of the seat. There are large differences between the two types of transmissibility for yaw-axis acceleration of the head at frequencies above about 2 Hz; the difference appears to increase with increasing distance from the centre of rotation. This implies that much of the yaw head acceleration at frequencies above 2 Hz was

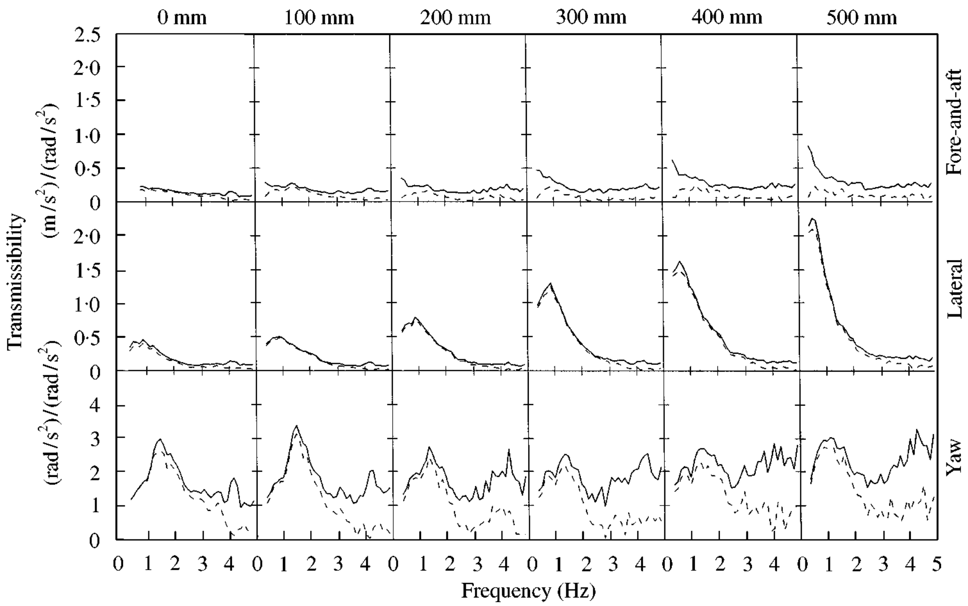

Figure 10. Transmissibilities for one subject in a back-off posture during exposure to yaw seat vibration with various locations from the centre of rotation along the fore-and-aft axis (—— p.s.d. method, – – – – c.s.d. method; 0·122 Hz resolution, 58 d.o.f.).

not correlated with the yaw motion of the turntable. This uncorrelated yaw acceleration of the head might be due to noise (i.e., head motion uncorrelated with any input motion) or the direct influence of fore-and-aft seat acceleration.

Ordinary coherencies illustrate the amount of correlation between the input motion (i.e., seat motion) and the output motion (i.e., head motion). It was seen in Figure 10 that, for motions in the fore-and-aft axis and the yaw axis, the difference between the transmissibilities calculated using the c.s.d. and the p.s.d. methods increased with increasing distance from the centre of rotation. These differences in the transmissibilities are reflected in the coherencies, shown in Figure 11, between seat motion and head motion for varying separation distances. Coherencies for both axes show a decrease with increasing distance from the centre of rotation.

When seated at the radius of a large turntable with the centre of rotation behind the subject, the dominant motion caused by small angles of oscillation will be lateral acceleration. Transmissibilities to the head will then be expected to be almost solely due to lateral acceleration of the seat. The amount of lateral acceleration occurring at the seat can be calculated from the rotational acceleration. Figure 12 compares transmissibilities between lateral seat acceleration and lateral head acceleration in an earlier study (reference [23]: back-off posture, median for 12 subjects), and lateral head acceleration caused by the lateral acceleration component produced by the yaw motion of the turntable (at a separation distance of 500 mm; see Figure 10). The transmissibilities for lateral motion of the head are similar for frequencies above about 2 Hz. Frequencies below

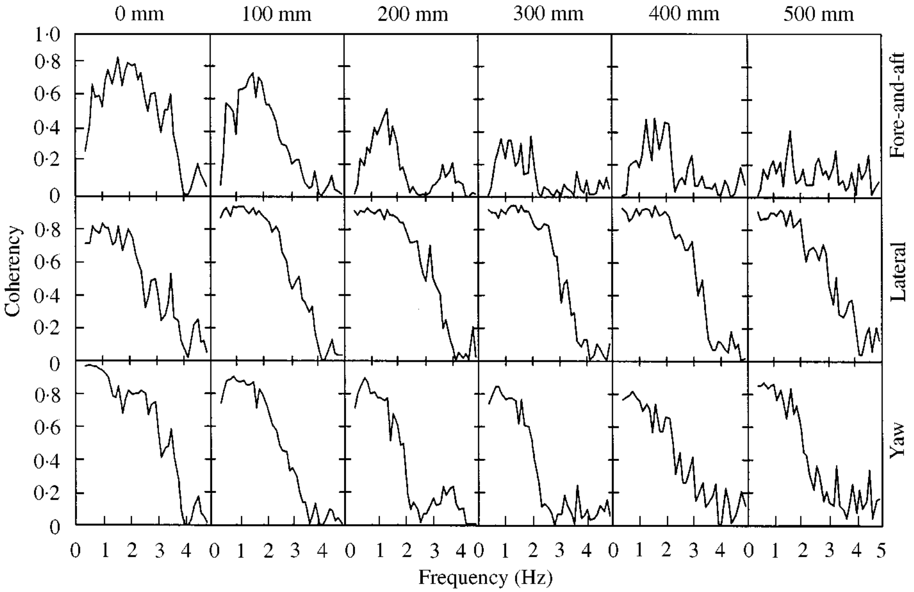

Figure 11. Coherencies for 1 subject in a back-off posture during exposure to yaw seat vibration with various locations from the centre of rotation along the fore-and-aft axis (0·122 Hz resolution, 58 d.o.f.).

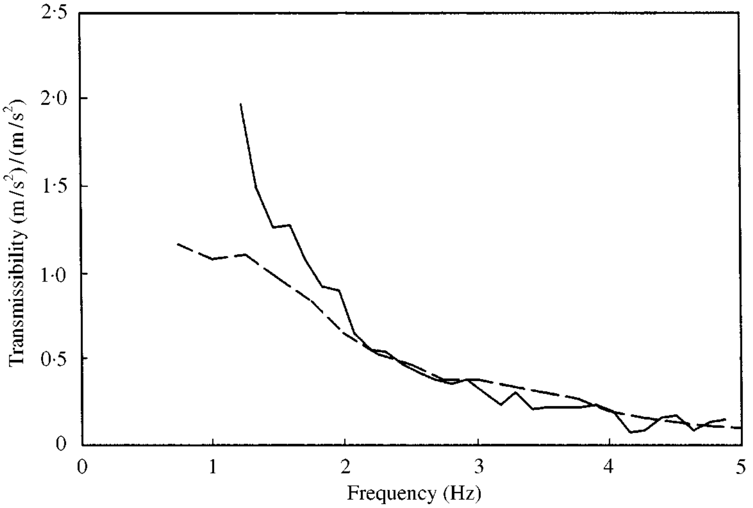

Figure 12. Comparison of yaw seat to lateral head transmissibilities for one subject with a separation distance of 500 mm (——) with lateral seat to lateral head transmissibilities for 12 subjects (- - - -, from Paddan and Griffin [22]).

2 Hz show higher transmissibilities for the subject seated on the turntable and exposed to combined lateral and yaw motion. Transmissibilities calculated for the other separation distances (i.e., 100, 200, 300 and 400 mm) also showed an increase in lateral head acceleration at low frequencies compared to that during exposure to pure lateral seat vibration.

The effects of subject characteristics (age, weight and height) on transmissibility in each axis of head motion were investigated using Kendall's tau [17]. At frequencies between 0·122 and 5 Hz, using frequency steps of 0·122 Hz, no significant correlations were found, apart from a few isolated correlations (such as a correlation at the 5% level of significance between stature and pitch axis transmissibility over the frequency range 2·7–4·2 Hz with the subjects seated in a back-on posture with their eyes open). Previous studies of the transmission of vibration to the head have found that body characteristics are not prime determinants of head motion but that body posture has larger effects (e.g., references [15, 24]).

6. CONCLUSIONS

There was an increase in the frequency of greatest transmission of yaw seat motion to yaw head motion (from 2 to 3 Hz) when contact was made with a backrest (i.e., back-on as opposed to back-off). A change in the visual conditions (from eyes open to eyes closed) had no effect on the transmission of yaw seat vibration to the head. Head acceleration in the lateral direction increased with increasing distance from the centre of rotation for subjects facing radially outwards. During exposure to yaw-axis seat vibration, head motion was not correlated with the body characteristics of the subjects.

ACKNOWLEDGMENTS

This work has been carried out with the support of the U.K. Ministry of Defence under an extramural research agreement with the Centre for Human Sciences, DERA Farnborough.

REFERENCES

1. B. Clark and J. D. Stewart 1962 *Aerospace Medicine* **33**, 1426–1432. Perception of angular acceleration about the yaw axis of a flight simulator. Thresholds and reaction latency for research pilots.
2. B. Clark and J. D. Stewart 1968 *Journal of American Psychology* **81**, 207–216. Comparison of three methods to determine thresholds for perception of angular acceleration.
3. B. Clark and J. D. Stewart 1970 *Acta Otolaryngolica* **69**, 231–238. Thresholds for perception of angular acceleration about the three major body axes.
4. A. J. Benson, E. C. B. Hutt and S. F. Brown 1989 *Aviation, Space, and Environmental Medicine* **60**, 205–213. Thresholds for the perception of whole body angular movement about the vertical axis.
5. A. W. Irwin 1981 *Journal of Sound and Vibration* **76**, 481–497. Perception, comfort and performance criteria for human beings exposed to whole body pure yaw vibration and vibration containing yaw and translational components.
6. A. W. Irwin and T. Goto 1984 *United Kingdom Informal Group Meeting on Human Response to Vibration, Heriot-Watt University, Edinburgh*. Human perception, task performance and simulator sickness in single and multi-axis low frequency horizontal linear and rotational vibration.

7. R. W. Shoenberger 1980 *Aviation, Space, and Environmental Medicine* **51**, 759–762. Psychophysical comparison of vertical and angular vibrations.
8. K. C. Parsons and M. J. Griffin 1982 *Ergonomics* **25**, 631–644. Vibration and comfort. II. Rotational seat vibration.
9. R. W. Shoenberger 1986 *Aviation, Space, and Environmental Medicine* **57**, 1075–1081. Subjective effects of combined-axis vibration: III. Comparison of y-axis and y-plus-yaw vibrations.
10. British Standards Institution 1987 BS 6841. Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.
11. A. J. Benson and F. E. Guedry Jr 1971 *Aerospace Medicine* **42**, 593–601. Comparison of tracking-task performance and nystagmus during sinusoidal oscillation in yaw and pitch.
12. A. J. Benson 1972 *Annual Scientific Meeting of Aerospace Medical Association, FL*, 8–11 May, 43–44. Effect of angular oscillation in yaw on vision.
13. M. J. Griffin 1991 *Motion Sickness: Significance in Aerospace Operations and Prophylaxis. AGARD Lecture Series LS*-175, *Paper* 3. ISBN 92-835-0634-0. Physical characteristics of stimuli provoking motion sickness.
14. G. R. Barnes and B. H. Rance 1974 *Aerospace Medicine* **45**, 411–416. Transmission of angular acceleration to the head in the seated human subject.
15. G. S. Paddan and M. J. Griffin 1988 *Journal of Biomechanics* **21**, 191–197. The transmission of translational seat vibration to the head—I. Vertical seat vibration.
16. British Standards Institution 1989 BS 7085. Guide to safety aspects of experiments in which people are exposed to mechanical vibration and shock.
17. S. Siegel and N. J. Castellan Jr 1988 *Nonparametric Statistics for the Behavioral Sciences*. New York: McGraw-Hill, second edition. ISBN 0-07-100326-6.
18. G. S. Paddan and M. J. Griffin 1994 *ISVR Technical Report No.* 236, *Institute of Sound and Vibration Research, University of Southampton, Southampton, Hampshire*. Individual variability in the transmission of vertical vibration from seat to head.
19. G. S. Paddan and M. J. Griffin 1991 *Ergonomics Society Annual Conference, "Ergonomics—Design for Performance", University of Southampton*, 16–19 April (E. J. Lovesey, editor), 38–42. London: Taylor and Francis. ISBN 0-74840-007-9. Transmission of yaw seat vibration to the head of a seated subject.
20. G. S. Paddan and M. J. Griffin 1993 *ISVR Technical Report No.* 218, *Institute of Sound and Vibration Research, University of Southampton, Southampton, Hampshire*. Transmission of vibration through the human body to the head: a summary of experimental data.
21. G. S. Paddan and M. J. Griffin 1994 *Ergonomics* **37**, 1513–1531. Transmission of roll and pitch seat vibration to the head.
22. G. S. Paddan and M. J. Griffin 1992 *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* **206**, 159–168. The transmission of translational seat vibration to the head: the effect of measurement position at the head.
23. G. S. Paddan and M. J. Griffin 1988 *Journal of Biomechanics* **21**, 199–206. The transmission of translational seat vibration to the head—II. Horizontal seat vibration.
24. A. J. Messenger and M. J. Griffin 1989 *ISVR Technical Report No.* 172, *Institute of Sound and Vibration Research, University of Southampton, Southampton, Hampshire*. Effects of anthropometric and postural variables on the transmission of whole-body vertical vibration from seat-to-head.

APPENDIX A

Subject instructions

Following are instructions that were given to subjects taking part in the experiments on the transmission of rotational yaw seat vibration to the head.

Instructions to subjects

The aim of this experiment is to monitor the motion of the heads of seated persons during exposure to rotational yaw seat vibration.

In order to minimize the effect of the other variables, it is important that you maintain a "comfortable upright posture" throughout the experiment. If you are instructed to make use of the backrest, then lean but not push against the backrest. If you are instructed to keep off the backrest, then your back should be approximately 150 mm in front of the backrest. Keep your feet and legs together and your lower legs vertical. Place your hands together in your lap and avoid movements of either the arms or legs.

Just prior to the start of each run, which the experimenter will indicate, you are to place the bite-bar in your mouth and adjust your head to a normal upright forward facing position. This position is to be kept during all runs. Avoid voluntary movements of the head. Ensure that a normal bite grip is kept on the bite-bar.

You are free to terminate the experiment at any time by pressing the red STOP button.

Thank you for taking part in this experiment.

APPENDIX B: MEDIAN TRANSMISSIBILITIES

Presented below are median transmissibilities between yaw-axis seat vibration and yaw-axis head motion for 12 subjects sitting at the centre of rotation in "back-on" and "back-off" postures. Units for the transmissibilities are $(\mathrm{rad/s^2})/(\mathrm{rad/s^2})$.

Frequency (Hz)	Back-on	Back-off
0·00	—	—
0·12	—	—
0·24	1·01	1·04
0·36	0·98	1·02
0·48	1·04	1·08
0·61	1·08	1·13
0·73	1·09	1·18
0·85	1·16	1·31
0·97	1·18	1·39
1·09	1·27	1·56
1·22	1·30	1·65
1·34	1·40	1·86
1·46	1·57	2·27
1·58	1·67	2·57
1·70	1·76	2·88
1·83	1·99	3·46
1·95	2·15	3·56
2·07	2·44	3·53

2·19	2·67	3·17
2·31	3·17	3·01
2·44	3·44	2·83
2·56	3·45	2·65
2·68	3·72	2·35
2·80	3·86	2·21
2·92	3·83	2·27
3·05	3·85	2·09
3·17	3·42	1·96
3·29	3·40	2·02
3·41	3·28	1·89
3·54	2·47	1·74
3·66	2·33	1·72
3·78	2·21	1·67
3·90	1·99	1·62
4·02	2·05	1·61
4·15	2·19	1·60
4·27	1·95	1·59
4·39	1·55	1·41
4·51	1·34	1·26
4·63	1·47	1·35
4·76	1·18	1·26
4·88	0·97	1·05
5·00	0·81	0·94