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WHOLE-BODY VIBRATION AND AIRCREW PERFORMANCE

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Final Report on Research Agreement No. AT/2040/0180 between the University of Southampton and the Ministry of Defence covering the period February 1976 to August 1985.

ABSTRACT

A programme of experimental research concerned with the effects of aircraft vibration on vision and manual control performance has been completed. Twenty-eight experiments were conducted, 16 investigating effects on vision and 12 investigating effects on manual control performance. Short summaries of the objectives, methods and findings of all 28 experiments are presented. References to publications providing full reports of each experiment are also provided.

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1.0 INTRODUCTION

This report summarises work carried out in the Human Factors Research Unit of the Institute of Sound and Vibration Research under Research Agreement AT/2040/0180 between the University of Southampton and the Ministry of Defence during the period February 1976 to August 1985. The research culminated in the production of two Design Guides, which may be used to minimise the disruptive effects of vibration on visual performance and manual activity in aircraft environments.

It has been well documented that vibration may interfere with aircrew activities involving visual perception or hand control. Experiments were conducted to provide information on how visual performance and manual control can be degraded by vibration. The research studies yielded fundamental scientific information not otherwise available. In addition, all studies provided data which may be applied and the results have been used in the formulation of the Design Guides.

Twenty-eight experiments have been completed: 16 investigated effects of vibration on vision and 12 concerned effects of vibration on manual control. The research has involved the compilation of several literature reviews of the effects of vibration on performance, three PhD theses, two Design Guides and many scientific papers.

Section Two of this report summarises the principal experiments. Brief details of the aims, methods, results and conclusions of each experiment are provided. The published reference is also given.

Section Three refers to the contents of literature reviews, PhD theses and Design Guides.

2.0 EXPERIMENTAL WORK

2.1 VISION

Summary of experiments on vision

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Previous studies have shown that vibration can have a disruptive effect on vision. However, there have been few systematic investigations of the many variables which combine to influence the effects. In consequence it has not been possible to reliably predict the effect of aircraft vibration on vision or to offer proven guidance on means of reducing the effects.

The prime objective of the studies which have been conducted was to make it possible to offer practical guidance based on sound experimental evidence. Sixteen investigations were conducted. They are summarised in the following sections.

2.1.1 Eye motion during vertical whole-body vibration

Aim

This study was conducted to determine whether the minimum magnitudes of vertical whole-body vibration likely to cause decrements in visual performance would produce rotational or translational motion of the eye. If vibration produces predominantly rotational eye motion the movement of the retinal image will be independent of the distance at which a target is viewed. If eye movements are translational the image motion will be inversely proportional to the viewing distance.

Experimental Details

Independent Variables:	vibration frequency, viewing distance.
Subjects:	six males.
Task:	adjust vibration magnitude to level at which visual blur of point light source was just perceptible. Viewing distance = 1.2 and 6.0 metres.
Vibration:	vertical (z-axis) sinusoidal vibration at frequencies of 7, 15, 30 and 60 Hz (six replications).
Dependent variables:	minimum magnitude of head motion at which subjects perceived any definite blurring or movement of the light source.

The magnitude of head vibration required to produce visual blur at frequencies between 7 and 60 Hz did not decrease with a change in viewing distance from 6.0 to 1.2 metres. Thus the effective eye motion causing visual blur was shown to be rotational. Consequently, the magnitudes of vibration which produce visual blur of images located at distances greater than about 1 metre are independent of viewing distance. In some vibration environments a reduction in viewing distance will, therefore, often improve vision since it will increase the size of the retinal image of an object without significantly increasing the retinal image displacement due to whole-body vibration.

Published Reference

Griffin M J (1976)

Eye motion during whole-body vertical vibration. Human Factors 18(6), 601-606.

2.1.2 Vibration frequency and reading performance

Aim

This experiment determined contours of vertical (z-axis) vibration resulting in equal degradation of a reading task. These 'equal performance contours' describe the variations in sensitivity of the visual task with vibration frequency and may be used as frequency-weighting functions for the evaluation of vibration spectra.

Experimental Details

Independent variables:	vibration frequency, vibration magnitude.
Subjects:	ten males.
Task:	numeral reading of hard-copy characters subtending 4.5 min arc at 0.75 metres.
Vibration:	vertical (z-axis) sinusoidal. Vibration frequencies of 2.8 to 63.0 Hz spaced at 1/2 octave intervals. Vibration magnitudes ranged from 0.5 to 2.5 ms^{-2} rms for the lowest frequency and from 1.6 to 2.8 ms^{-2} rms for the highest.
Dependent variables:	reading errors, reading times.

Results and Conclusions

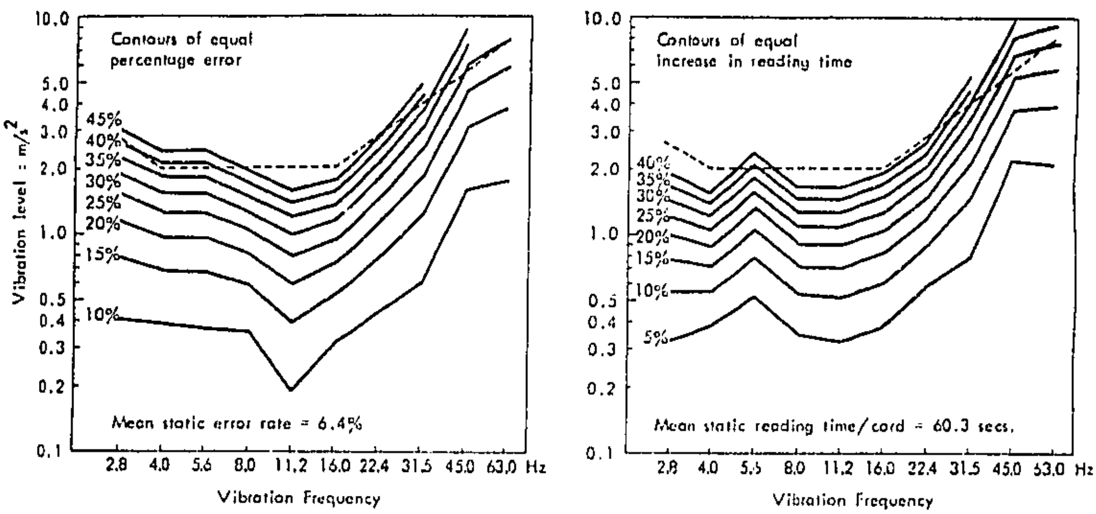
The effect of vibration magnitude on reading error was found to be significant at all frequencies except 45 and 63 Hz and there were significant linear trends at all other frequencies. The effect of vibration magnitude on reading time was significant at all frequencies except 31.5 Hz, 45 Hz and 63 Hz and there were significant linear trends at all frequencies except 63 Hz. The equal performance contours shown in the figure were calculated from the regression equation:

$$e = A_0 + A_1.V(f)$$

where e is the mean percentage reading error with vibration magnitude V, A_0 is the static reading error and A_1 the increase in reading error per unit increase in vibration of the seat. The performance contours indicate the visual task to be most sensitive to vertical vibration in the frequency region 8 Hz to 16 Hz.

Published Reference

Lewis C H (1977)
Frequency of whole-body vibration and reading performance. Paper presented at UK Informal Group Meeting held at Bostrom/MIRA, Northampton. 7-9 September.



Equal performance contours for reading error and reading time during exposure to z-axis sinusoidal vibration at frequencies from 2.8 to 63.0 Hz. (The dotted lines are the highest vibration levels presented in the experiment. Data above these lines are extrapolated).

2.1.3 Character size and display legibility

Aim

This experiment investigated the effect of changes in character size on the legibility of a numeral reading task during vertical (z-axis) whole-body vibration.

Experimental Details

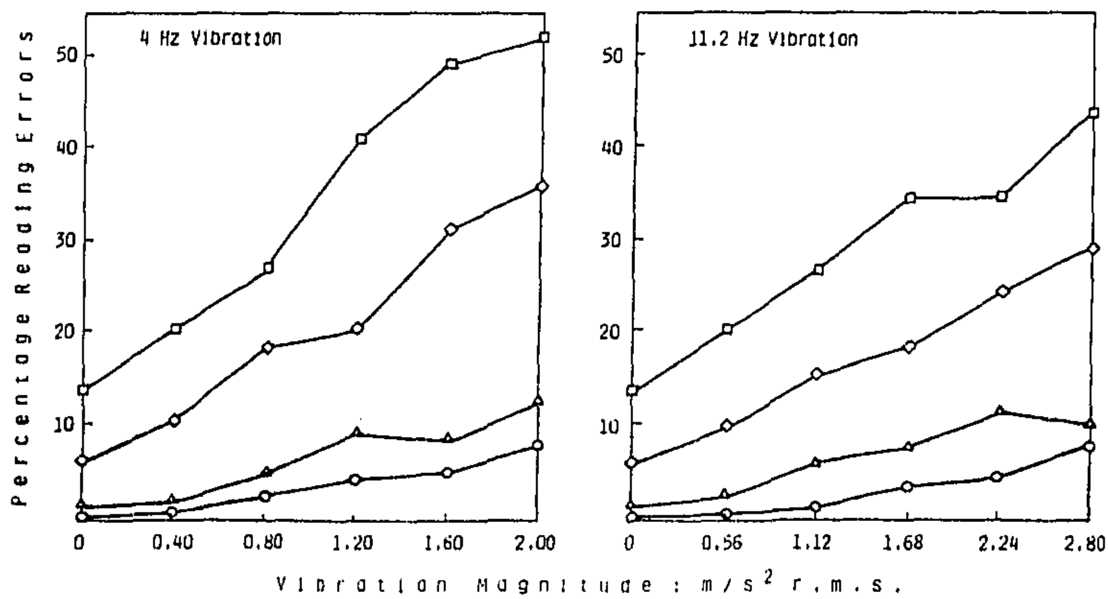
Independent variables:	vibration frequency, vibration magnitude, character size.
Subjects:	ten males.
Task:	paced numeral reading from a CRT display. Characters subtended 4.58, 5.73, 7.56 or 9.17 min arc at a constant viewing distance of 0.75 metres.
Vibration:	vertical (z-axis), vibration frequencies of 4.0 and 11.2 Hz. Vibration magnitudes of 0.4 to 2.0 ms^{-2} rms (4 Hz) and 0.56 to 2.8 ms^{-2} rms (11 Hz).
Dependent variable:	reading error.

Results and Conclusions

The mean results of the experiment are illustrated in the figure. Significant linear trends were present in the increasing reading errors with vibration magnitude at both frequencies at all except the largest character size (9.17 min arc). It can be seen from the figure that although the effects of vibration were not significant with numerals subtending 9.17 min arc, error rates of 8.2% and 8.0% still occurred at the highest magnitudes of 4 Hz and 11 Hz vibration. A large inter-subject variation indicated that, in an environment with similar conditions and numerals to those in the experiment, characters subtending an angular height of approximately 10 min arc could only be read with acceptable levels of error at vibration magnitudes less than the lowest presented in this experiment.

<u>Published Reference</u>

Lewis C H and Griffin M J (1979)
The effect of character size on the legibility of numeric displays during vertical whole-body vibration. Journal of Sound and vibration 76(4), 562-565.



The effect of vibration magnitude on the legibility of characters subtending 4.58 (□), 5.73 (◇), 7.56 (Δ) or 9.17 (O) min arc viewing angle. Mean data for 10 subjects.

2.1.4 Vibration frequency, axis, seating conditions and reading performance

Aim

This study sought to determine the effect of whole-body vibration on reading performance in each of three translational axes: x (fore-and-aft), y (lateral) and z (vertical). The influence of seating conditions and the feasibility of predicting performance decrements directly from head motion were also examined.

Experimental Details

Independent variables:	vibration frequency, vibration magnitude, vibration axis, seating.
Subjects:	ten males.
Task:	paced numeral reading from a CRT display. Characters subtended 5 min arc at 0.75 metres.
Vibration:	z-axis: 2.8 to 63 Hz, 0.56 to 8.0 ms^{-2} rms y-axis: 2.8 to 31.5 Hz, 0.40 to 8.0 ms^{-2} rms x-axis: 2.8 to 31.5 Hz, 0.40 to 5.6 ms^{-2} rms All stimuli sinusoidal, frequencies spaced at half-octaves, five vibration magnitudes per frequency. Seating conditions: i) rigid flat seat with backrest and attached foot rest (simulated helicopter seat) ii) rigid flat seat without backrest and with a stationary foot rest.
Dependent variables:	reading errors, reading time.

Results and Conclusions

With z-axis (vertical) vibration and the helicopter seat the effect of vibration on reading performance was significant ($p<0.05$) at all frequencies except 45 Hz and 63 Hz. With the flat seat the effect was significant only at frequencies up to and including 11.2 Hz.

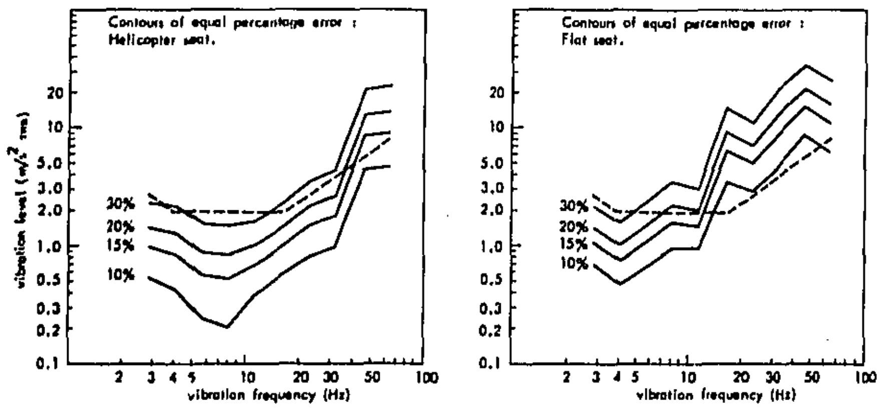
With x-axis (fore-and-aft) vibration of the helicopter seat, the effect of vibration magnitude was significant at 4.0, 5.6, 8.0, 11.2 and 16.0 Hz. With the flat seat the effect of x-axis vibration was not significant at any frequency with either seat.

The equal performance contours shown in the figures were derived from the regression equations describing the relationships between mean reading errors and vibration magnitude at each frequency. It can be seen that z-axis (vertical) vibration of the simulated helicopter seat extends the effects of vibration on reading performance to higher vibration frequencies compared with the flat seat. Vibration in the x-axis (fore-and-aft) up to 5.6 Hz with the helicopter seat resulted in performance degradations of a similar level to those caused by the same magnitude of z-axis motion. However there was little evidence of any effect of x-axis vibration with the flat seat with magnitudes of vibration presented in the experiment.

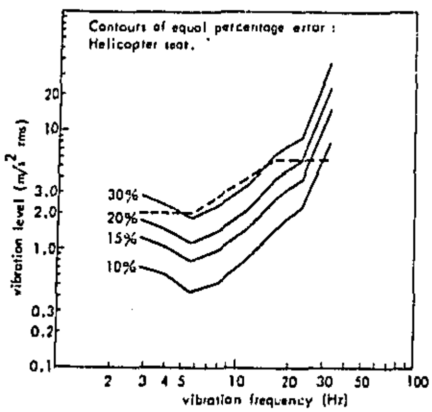
Measures of translational and rotational head motion were also made for each vibration axis and seat. Very little vibration was found to be transmitted to the head during x-axis vibration with the flat seat or y-axis vibration with either seat, in agreement with the small effect of vibration on reading performance in these cases. These results were combined with performance data and it was concluded that predicting performance decrements directly from head motion may be an effective predictive procedure.

Published Reference

Lewis C H and Griffin M J (1980)
Predicting the effects of vibration frequency and axis, and seating conditons on the reading of numeric displays. Ergonomics 23(5), 485-501.



z-axis vibration



x-axis vibration

Contours of magnitude of z-axis and x-axis vibration required to produce equal percentage reading errors (predicted from mean data). Points above the dashed lines are based on extrapolations. Top two figures for z-axis vibration, bottom figure for x-axis vibration.

2.1.5 Viewing distance and reading performance during vertical vibration

Aim

This experiment investigated the effect of viewing distance on reading performance during vertical whole-body vibration. Viewing distance is an important parameter of visual tasks presented in vibration environments. If eye motion arising from translational motion of the seat is predominantly rotational then the effects of vibration will be independent of viewing distance and improvements in the legibility of a display might be obtained by a reduction in the viewing distance (ie increasing the angular size of the visual targets). If however translational eye motion is the predominant cause of visual disturbance its effect will be inversely proportional to viewing distance and consequently a reduction in viewing distance may not improve legibility.

Experimental Details

Independent variables:	vibration frequency, vibration magnitude, viewing distance.
Subjects:	six males.
Task:	paced numeral reading of a hard-copy display. Characters were 1 mm, 2 mm and 4 mm high each subtending 4.5 min arc at distances of 0.75 m, 1.5 m and 3.0 m respectively.
Vibration:	vertical (z-axis) sinusoidal vibration at frequencies of 3.15 Hz and 16.0 Hz. Each frequency was presented at five vibration magnitudes ranging from 0.45 to 2.25 ms^{-2} rms (3.15 Hz) and from 0.40 to 2.00 ms^{-2} rms (16.0 Hz).
Dependent variables:	reading errors.

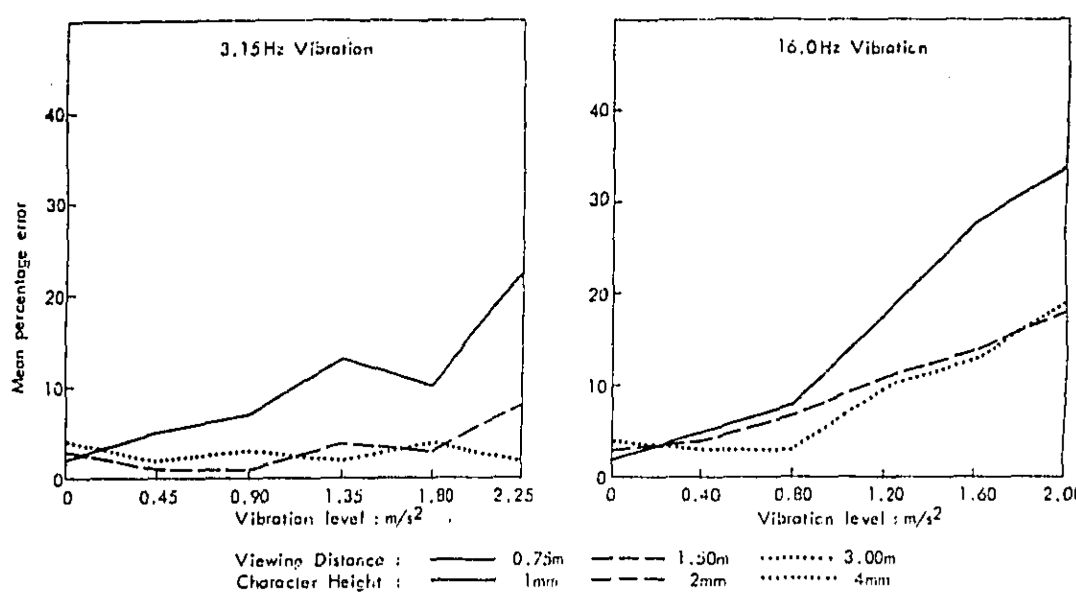
Results and Conclusions

The mean percentage reading errors shown in the figure indicate the effect of viewing distance on reading performance. At 3.15 Hz there is very little effect of vibration at the middle and far viewing distances. At 16 Hz reading errors are generally greater and the increase in reading error can be seen to be very similar for the 1.5 m and 3 m viewing distances.

This lack of effect of viewing distance for viewing distances greater than 1.5 m indicates that the effects are predominantly due to the rotational head and eye motions arising from the translational vibration of the seat. As the 3.15 Hz vibration conditions had no discernable effect on performance at the 1.5 m and 3 m viewing distances it can be concluded that very little rotational eye motion occurred at this frequency. This is probabily partially due to the vestibulo-ocular reflex compensating for rotational motion of the head. It can be inferred from the figure that the effects of translational eye motion become more significant between 0.75 m and 1.5 m: the head motions will be the same at both viewing distances but the reduction in viewing distance increases the angle subtended at the eye by the translational motion.

Published Reference

Lewis C H and Griffin M J (1980)
Predicting the effects of vertical vibration frequency, combinations of frequencies and viewing distance on the reading of numeric displays. Journal of Sound and Vibration. 70(3), 355-377.



The effect of magnitude of 3.15 Hz and 16.0 Hz whole-body vibration on 'reading errors' at three viewing distances.

2.1.6 Multiple frequency whole-body vibration and reading performance

Aim

To evaluate the effects of a vibration environment which is not characterised by discrete frequency sinusoidal motion it is necessary to understand how different vibration frequencies combine to produce a visual performance decrement. This study investigated the effects of combining different frequencies of sinusoidal vibration and predicting the resultant reading performance decrements.

Experimental Details

Independent variables:	vibration frequency, combinations of vibration frequencies, vibration magnitude.
Subjects:	ten males.
Task:	paced numeral reading of a hard-copy display. Characters subtended 4.5 min arc at 0.75 metres.
Vibration:	vertical (z-axis), whole-body sinusoidal vibration: frequencies of 3.15 Hz, 16 Hz and 25 Hz at five vibration magnitudes in the range 0.45 to 3.15 ms^{-2} rms. Complex (multiple frequency) vibration: 12 combinations of 3.15 Hz, 16.0 Hz and 25.0 Hz with component magnitudes ranging from 0 to 2.61 ms^{-2} rms.
Dependent variables:	reading errors.

Results and Conclusions

Predictions of reading performance were obtained by weighting the effects of the component motions (3.15, 16 and 25 Hz) and applying four separate predictive models:

i) the most severe weighted component
ii) the root-mean quad (rmq) of the weighted components
iii) the root-mean square (rms) of the weighted components
iv) the arithmetic sum of the weighted components.

The most accurate predictions of reading error were obtained using the most severe weighted component method. However it was concluded that the rmq method, although slightly less accurate, is a more appropriate method of evaluation due to the relative ease (compared to the most severe weighted component method) with which it can be applied. In general, reading errors produced by the six subjects during multiple frequency vibration were less than those produced with the most severe weighted component alone - a result which is consistent with previous studies using complex vibration of a visual target.

Published Reference

Lewis C H and Griffin M J (1980)
Predicting the effects of vertical vibration frequency, combinations of frequencies and viewing distance on the reading of numeric displays. Journal of Sound and Vibration 70(3), 355-377.

2.1.7 Seating conditions, head motion and reading performance during vertical vibration

Aim

It is generally accepted that seating and postural variables may significantly influence reading performance by modifying the vibration transmitted to the head (see Section 2.1.4). This experiment sought to quantify the effects of several different seating conditions on reading performance and relate them to measurements of head vibration.

Experimental Details

Independent variables:	vibration frequency, seating conditions:
Seating conditions:	a) rigid flat seat, backrest contact, stationary footrest b) rigid flat seat, no backrest contact, stationary footrest c) rigid flat seat, no backrest contact, stationary footrest d) rigid flat seat, backrest contact, attached footrest, helmet worn e) real helicopter seat, backrest contact, stationary footrest f) real helicopter seat, no backrest contact, stationary footrest
Subjects:	twelve males.
Task:	paced numeral reading of a CRT display. Characters subtended 5 min arc at 0.75 metres.
Vibration:	fifteen vertical (z-axis) sinusoidal stimuli with frequencies ranging from 2.5 Hz to 63 Hz spaced at one-third octave intervals. Vibration magnitudes ranged from 2.5 ms^{-2} rms for the lowest frequency to 8.0 ms^{-2} rms.
Dependent variables:	reading errors.

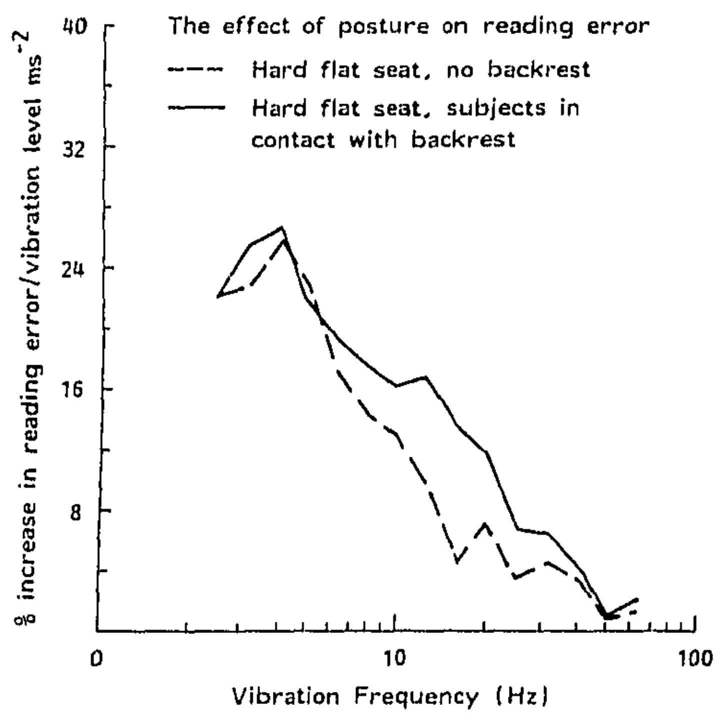
Results and Conclusions

One of the clearest examples of the effects of seating conditions on visual performance is shown in the figure. This figure illustrates the effect of backrest contact on reading performance for subjects seated in a rigid flat seat with attached footrest. Reading errors are notably reduced in the 'back-off' condition between 6.3 Hz and 40 Hz and this appears to be correlated with a decrease in seat-to-head transmissibility for this condition.

The effect of the other seating and postural variations were less dramatic although in many instances significant positive correlations between reading performance and seat-to-head transmissibility were obtained.

Published Reference

Moseley M J, Lewis C H and Griffin M J (1981)
Paper presented at the UK Informal Group Meeting on Human Response to Vibration held at Heriot-Watt University, Edinburgh.



The effect of a backrest on reading error during exposure to z-axis whole-body vibration at frequencies from 2.5 to 63 Hz.

2.1.8 A comparison of the effects of sinusoidal and random whole-body vibration on reading performance

Aim

Previous comparisons of the effects of sinusoidal and random whole-body vibration had failed to give a clear indication of the relative severity of these stimuli. This experiment compared one-third octave-band random and sinusoidal vibration stimuli equated for acceleration magnitude. Reading performance was also determined during exposure to broad-band random stimuli. The reading errors obtained with these stimuli were compared with predictions based on rms and rmq averaging procedures using a Fourier weighting procedure.

Experimental Details

Independent variables:	vibration stimulus type, vibration frequency.
Subjects:	twelve males.
Task:	paced numeral reading from a CRT display. Characters subtended 5 min arc at 0.75 metres
Vibration:	vertical (z-axis), sinusoidal and one-third octave-band random, 2.5 Hz to 31.5 Hz; broad-band random, 1, 2 and 3 octave with centre frequencies in range 4 to 16 Hz; vibration magnitudes 1.8 to 4 ms^{-2} rms.
Dependent variables:	reading error (corrected to increase in percentage reading error per unit vibration magnitude).

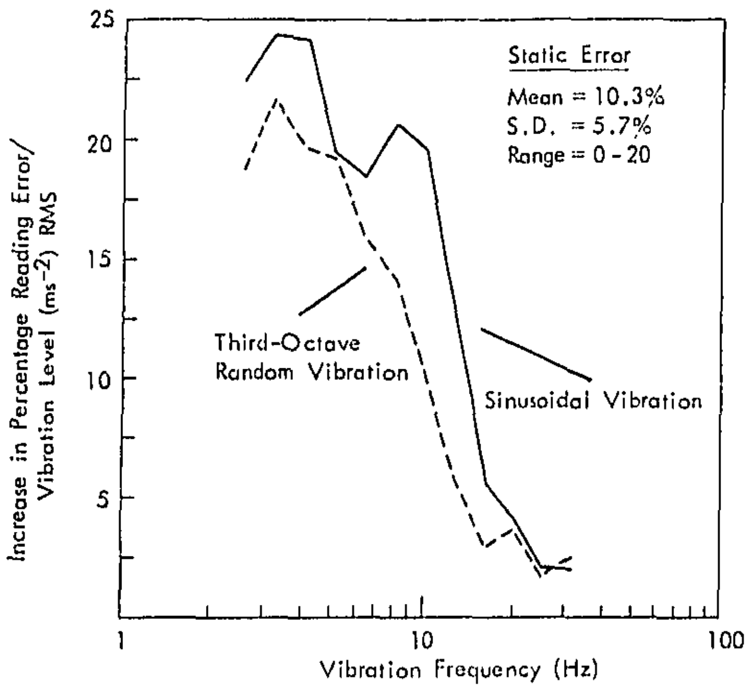
Results and Conclusions

The figure illustrates the mean level of reading performance during exposure to sinusoidal and one-third octave-band random vibration. At most frequencies the least reduction in performance occurs with the random vibration stimuli. An explanatory model based on the differences in the probability distibutions of image velocity was developed to account for these findings: random vibration produced a higher probability of low image velocity compared to sinusoidal vibration. Support for this model was derived from measures of rotational (pitch) head motion obtained from a single subject.

The predictive procedures indicated that both rms and rmq averaging can provide accurate estimates of reading performance during exposure to broad-band random vibration.

<u>Published Reference</u>

Moseley M J, Lewis C H, and Griffin M J (1982)
Sinusoidal and random whole-body vibration: comparative effects on visual performance. Aviation Space and Environmental Medidine 53(10), 1000-1005.



The effect of one-third octave-band and sinusoidal vibration on reading error rate. (mean values for 12 subjects)

2.1.9 Character font, dot-matrix symbol definition and display legibility

Aim

This experiment was conducted in order to compare the legibility of the Lincoln Mitre and Huddleston fonts during whole-body vibration. The effect of symbol definition (ie dot-matrix size) was also examined by determining the legibility of each font at both 5 x 7 and 7 x 9 symbol definitions.

Experimental Details

Independent variables:	character font, symbol definition.
Subjects:	eight males.
Task:	alphanumeric reading of a CRT display. All characters subtended 12 min arc at 0.63 metres. Each of the independent variables - Huddleston font (5 x 7), (7 x 9) and Lincoln Mitre font (5 x 7), (7 x 9) - were presented in separate presentations of the task.
Vibration:	a single vertical (z-axis) vibration stimulus: 4 Hz at 2.8 ms^{-2} rms.
Dependent variables:	reading errors, reading times.

Results and Conclusions

The number of errors and reading times recorded for each of the four combinations of character font and symbol definition were compared using the Tukey 't' test. Under no conditions were there any differences in the legibility of the Lincoln Mitre and Huddleson fonts defined with 7 x 9 pixels. During vibration, both 7 x 9 fonts produced fewer reading errors and shorter reading times compared to the 5 x 7 fonts (see figure). Also during vibration, the 5 x 7 Huddleston font demonstrated superior legibility to the 5 x 7 Lincoln Mitre font (reading errors), although reading times were not significantly different.

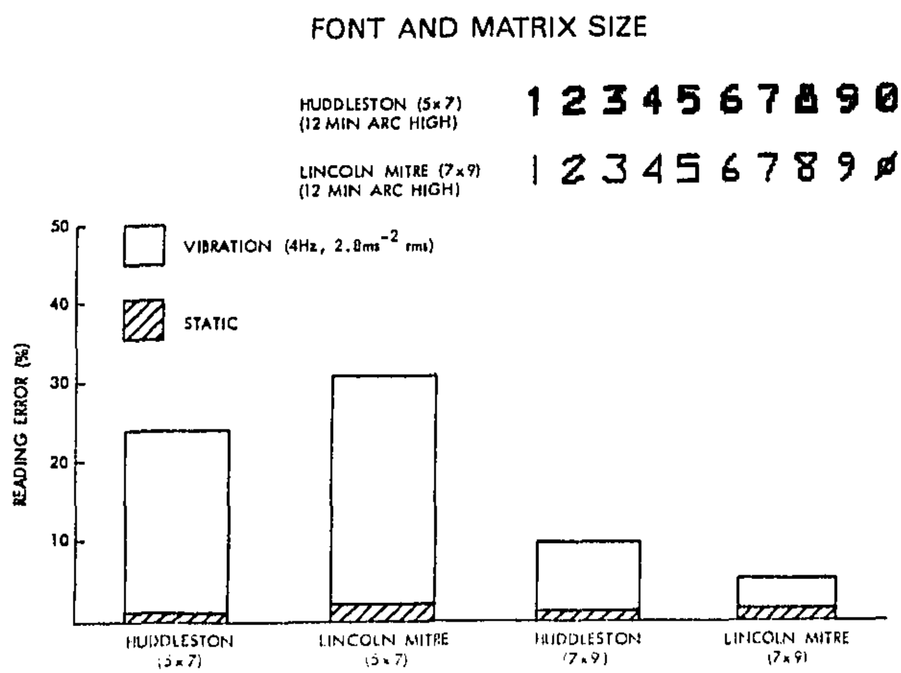
These findings suggest that a 7 x 9 or larger matrix size is more appropriate than a 5 x 7 matrix size if display legibility is likely to be degraded by vibration.

In vibration-degraded viewing conditions both the Huddleston and Lincoln Mitre fonts appear equally legible at the larger symbol definition but the Huddleston font is to be preferred at the smaller 5 x 7 definition.

Published Reference

Moseley M J (1982)

The legibility of dot-matrix character fonts viewed under conditions of whole-body vibration. Paper presented at the United Kingdom Informal Group Meeting on Human Response to Vibration held at the Health and Safety Executive, Cricklewood, London. 16-17 September.



Effects of character font and definition on reading errors.

2.1.10 Contrast and display legibility

Aim

This study was conducted to determine the relationship between display contrast and legibility during whole-body vibration. Previous research had suggested that increasing display contrast may not improve display legibility in a simple predictable manner.

Experimental Details

Independent variables:	display contrast.
Subjects:	eight males.
Task:	numeral reading of a CRT display. Characters subtended 12 min arc at a 0.75 metre viewing distance. Contrast of display externally manipulated by controlling incident ambient illumination. Range of contrast from 20% to 99% (Michelson).
Vibration:	A single vertical (z-axis) stimulus: 4 Hz at 2.8 ms^{-2} rms.
Dependent variable:	reading errors, reading times.

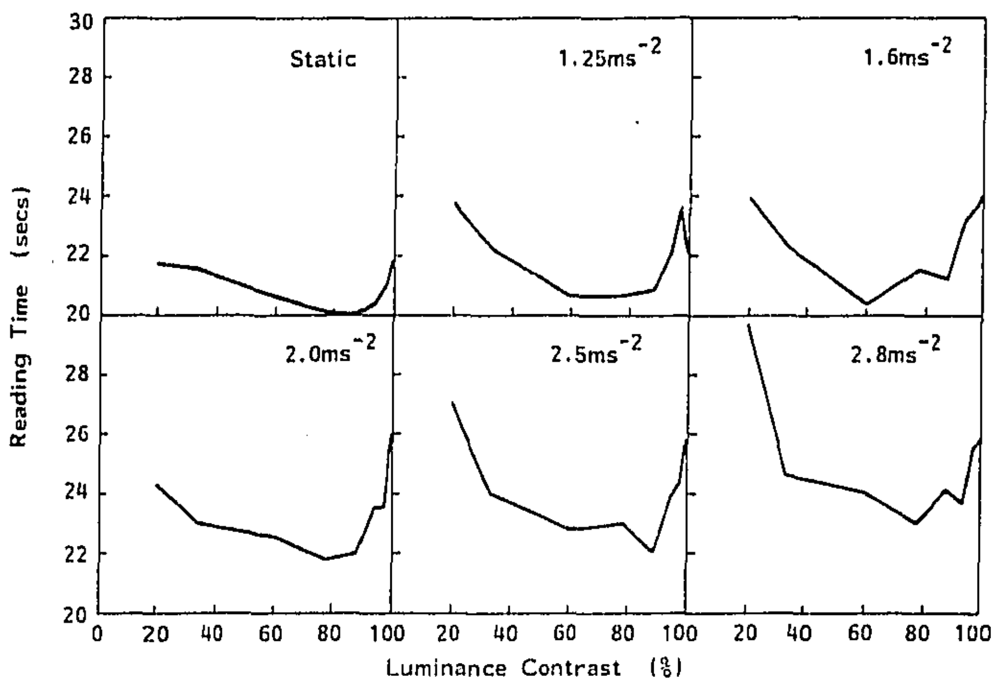
Results and Conclusions

Mean reading time data are shown in the figure. The graph illustrates the effect of luminance contrast on reading performance under static conditions and at each vibration magnitude. Generally, the relationship between contrast and legibility appears non-monotonic or 'U'-shaped (and this was statistically confirmed by quadratic trend analysis). Optimum reading performance is obtained with values of contrast in the mid-range (60% to 88%).

The basis of the relationship demonstrated in this experiment has not been resolved although it has been suggested that both 'raised retinal receptor gain' during whole-body vibration and 'contour interaction' may be responsible.

Published Reference

Moseley M J (1983)
The effect of contrast variation on the legibility of a CRT display during observer whole-body vibration. Paper presented at the UK Informal Group Meeting on Human Response to Vibration held at NIAE, Silsoe on 14-16 September.



The effect of luminance contrast on reading time.

2.1.11 Vertical character separation and display legibility

Aim

This study examined the effect of five vertical character separations on the legibility of a numeral reading task performed during vertical whole-body vibration.

Experimental Details

Independent variables:	vibration frequency, vibration magnitude, character size, vertical character separation.
Subjects:	twelve males.
Task:	numeral reading of a CRT display. Characters subtended 5 min arc and 12 min arc at 0.75 metres Characters were formed from a 5 x 7 dot-matrix with vertical character separations of 4 (57.1%), 15 (214.3%), 26 (371.4%), 37 (528.6%) and 48 (685.7%) pixels.
Vibration:	vertical (z-axis) sinusoidal: 3.15, 4 and 5 Hz at 1.6 ms^{-2} rms and 2.8 ms^{-2} rms
Dependent variables:	reading errors, reading times.

Results and Conclusions

Mean data illustrating the effect of vertical separation for characters subtending 5 min and 12 min arc are shown in the figure. Statistical analysis using the Tukey 't' test indicated that for characters subtending 5 min arc significantly greater errors occurred with 4 (57.1%) pixels spacing than at each of the larger separations. With characters subtending 12 min arc a significantly greater number of errors occurred with the closest spacing but only at the largest vibration magnitude.

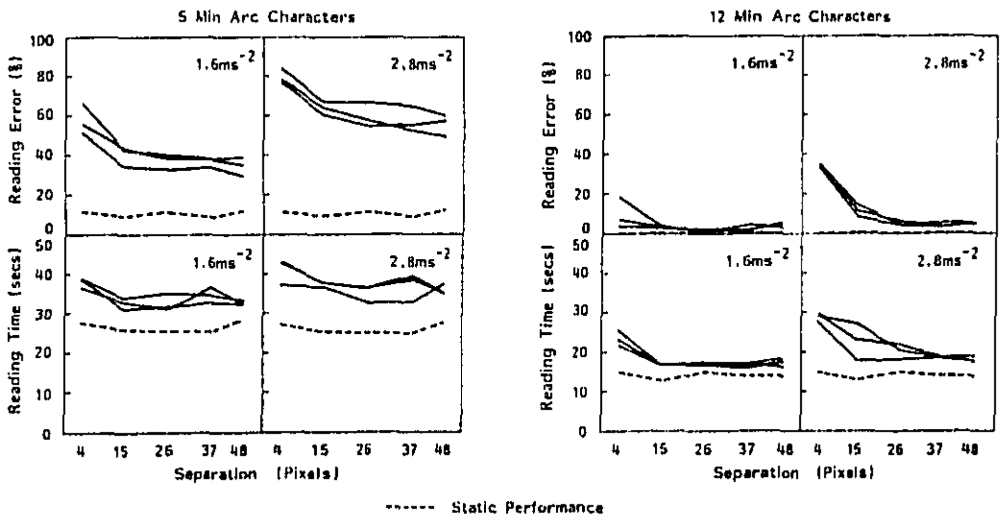
Characters subtending 12 min arc are likely to be found on displays situated in operational environments where vibration may be present. In these circumstances the experimental results indicate that a vertical character separation in excess of 57.1% may be required in order that maximum legibility is achieved.

Published Reference

Moseley M J (1986)

The effects of vibration on visual performance and display legibility.

Ph.D Thesis. University of Southampton. (In preparation.)



Effect of vertical character separation on reading performance (Mean for 10 subjects)

2.1.12 Horizontal character separation and display legibility

Aim

This study examined the effect of three different horizontal character separations on the legibility of a numeral reading task performed during vertical whole-body vibration. No previous attempts to establish guidelines for horizontal character separation for displays viewed in vibration environments had been reported.

Experimental Details

Independent variables:	vibration frequency, vibration magnitude, character size, horizontal character separation.
Subjects:	twelve males.
Task:	numeral reading of a CRT display. Characters subtended 5 min arc and 12 min arc at 0.75 metres. Characters were formed from a 5 x 7 dot-matrix with horizontal separations of 3, 11 and 19 pixels.
Vibration:	Vertical (z-axis) sinusoidal: 3.15, 4 and 5 Hz at 1.6 ms^{-2} rms and 2.8 ms^{-2} rms.
Dependent variables:	reading errors, reading times.

Results and Conclusions

Statistical analysis revealed that horizontal character separation did not influence the legibility of characters subtending 12 min arc at either of the vibration magnitudes investigated. However, for characters subtending 5 min arc, significantly fewer errors occurred at each vibration magnitude with 11 pixels separation than with spacings of either 3 or 19 pixels.

These findings suggest that an optimum character separation exists for fine resolution (ie 5 min arc) visual tasks performed during whole-body vibration. The separation of 11 pixels for 5 x 7 dot matrix characters resulted in approximately 10% fewer reading errors and may therefore provide substantial improvements in legibility if adopted as a recommendation for displays situated in vibration environments.

Published Reference

Moseley M J (1986)
The effects of vibration on visual performance and display legibility. PhD Thesis. University of Southampton. (In preparation.)

2.1.13 A comparison of display, whole-body and simultaneous whole-body-and-display vibration on reading performance

Aim

Most previous investigations of reading performance during vibration had been concerned with examining the effects of vibration in only one of the three possible viewing conditions, ie display, whole-body or simultaneous whole-body and display vibration. This experiment compared the effects of all three conditions within the framework of a single experiment.

Experimental Details

Independent variables:	vibration frequency, vibration magnitude, viewing condition - display vibration, whole-body vibration simultaneous whole-body and display vibration.
Subjects:	fifteen males.
Task:	numeral reading of a CRT display. Characters subtended 5 min arc and 12 min arc at 0.75 metres.
Vibration:	11 vertical (z-axis), sinusoidal stimuli in the frequency range 0.5 to 5 Hz at each of five magnitudes ranging from 1.0 to 2.5 ms^{-2} rms.
Dependent variables:	reading errors, reading times.

Results and Conclusions

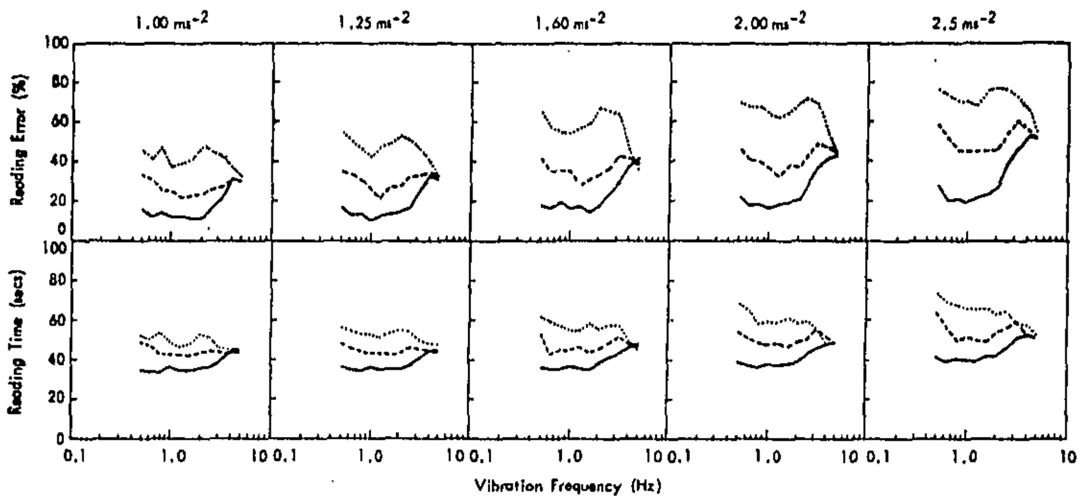
Mean reading performance data are shown in the figure illustrating the sensitivity of the visual task to vibration for each viewing condition. These data indicate that for frequencies below 4 Hz, display vibration is responsible for the largest performance decrement. Whole-body-and-display vibration produced the least effect on performance. Whole-body vibration with a stationary display was found to produce significantly worse performance than whole-body-and-display vibration but significantly better performance than with display vibration alone. An explanation of these findings involving the pursuit and vestibular-ocular reflexes, the transmission of vibration to the head and the geometry of the viewing conditions was described.

Published Reference

Moseley M J and Griffin M J (1986)

Effects of display vibration and whole-body vibration on visual performance.

Submitted to Ergonomics.



Mean percentage reading errors and reading times for display vibration (......), whole-body vibration (------) and simultaneous whole-body-and-display vibration (———). Static performance = 6.2%, 27.8 seconds.

2.1.14 The prediction of visual performance during random and simulated aircraft vibration

Aim

This study examined a previous suggestion that a velocity-based model could accurately predict visual performance during vibration (see 2.1.8). Two experiments were conducted using display vibration. In the first experiment the relative performance decrements due to five simulated aircraft motions were related to their velocity probability density distributions. In a second experiment visual performance was determined for each of five random motions having identical velocity distributions but differing in frequency content.

Experimental Details

Independent variables:	Experiment I: probability of low image velocity. Experiment II: frequency content of random vibration.
Subjects:	ten males.
Task:	paced reading of a numeric display (CRT). Characters subtended 5 min arc at 0.75 metres.
Vibration:	Experiment I: five pairs of simulated fixed-wing and helicopter vibration with frequency bandwidths of 1 to 31.5 Hz, 2 to 31.5 Hz, 4 to 31.5 Hz, 8 to 31.5 Hz and 16 to 31.5 Hz. The subjects were not vibrated. All at vibration magnitudes of 1.6 ms^{-2} rms. Experiment II: five, one-octave-band random stimuli with centre frequencies of 0.5, 1.0, 2.0, 4.0 and 8.0 Hz. Each motion having identical velocity probability density distributions and presented at 0.125, 1.25, 1.5, 1.0, and 2.0 ms^{-2} rms. The subjects were not vibrated.
Dependent variables:	reading errors.

Results and Conclusions

In the first experiment significantly fewer reading errors occurred with the motions having the greatest probability of low image velocity. In the second experiment, motions centred on 2.0, 4.0 and 8.0 Hz resulted in similar performance decrements whilst fewer errors occurred with motions centred on 0.5 Hz and 1 Hz.

Taken together the results of these experiments indicate that the probability of low-image velocity is a useful predictor of visual performance. Future refinements of this method will have to take into account the frequency dependence identified in the second experiment which occurs as a result of the eye's ability to pursue a moving target at low frequency (<2 Hz).

Published Reference

Moseley M J (1984)
The prediction of visual performance during random and simulated aircraft vibration of a numeric display. Paper presented at the UK Informal Group on Human Response to Vibration held at Heriot-Watt University, Edinburgh. 21-22 September.

2.1.15 The effect of vibration on visual performance: spatial filtering contrast sensitivity

Aim

This experiment was conducted to determine if changes in contrast thresholds due to whole-body vibration could predict reading performance. The experiment also investigated how the spatial frequency content of alphanumeric characters influences their legibility during vibration.

Experimental Details

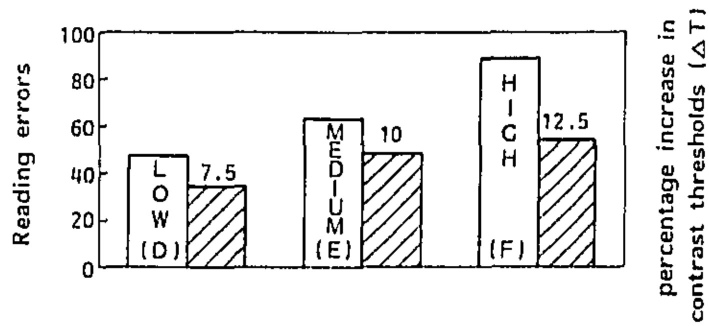
Independent variables:	grating spatial frequency (7.5, 10 and 12.5 $cdeg^{-1}$). Spatial frequency content of alphanumeric characters (low, medium, high).
Subjects:	twelve males.
Task:	threshold detection of sinusoidal gratings. Alphanumeric reading performance. Characters subtended 12 min arc at 1 metre and were formed from a 7 x 9 dot-matrix (Huddleston font).
Vibration:	vertical (z-axis) sinusoidal, 4 Hz at 2.5 ms^{-2} rms.
Dependent variables:	Reading errors, contrast thresholds.

Results and Conclusions

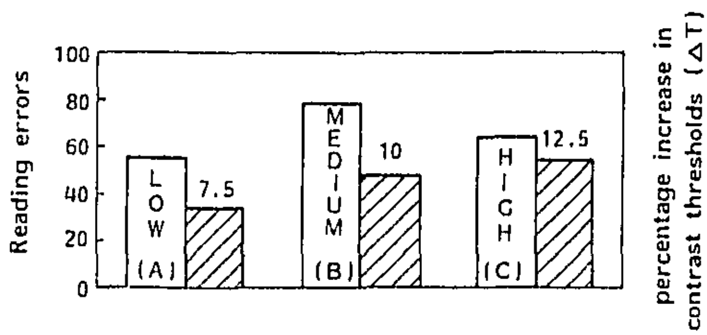
Data shown in the figure illustrate the mean percentage increase in contrast thresholds and reading errors for alphanumeric characters. These data are for horizontally oriented gratings (ie orthogonal to the vibration axis) and for alphanumeric characters defined as being of either low, medium or high vertical spatial complexity. As grating spatial frequency increases significant increases in contrast thresholds occur. Similarly, as spatial complexity of alphanumeric characters increases, (ie increasing high spatial frequency content) reading performance declines. These findings, at least for the vibration stimulus used in the experiment, suggest that the effects of vibration may be predicted by low-pass spatial filtering. Thus it may eventually be feasible to simulate the effects of vibration by image processing using spatial filter routines.

Published Reference

Moseley M J and Griffin M J (1986)
Whole-body vibration and visual performance, an examination of spatial filtering and time-dependancy. (Awaiting publication).



Vertical character complexity : Horizontal (90°) gratings



The effect of vibration on contrast thresholds and reading errors. (□ Reading errors, ▨ Mean percentage increase in grating thresholds (7.5, 10 and 12.5 c deg^{-1})

2.1.16 Time-dependency and visual performance during whole-body vibration

Aim

This study was conducted to determine if time-dependent effects of whole-body vibration exert a significant influence on visual performance. Previous investigations had suggested that small time-dependent decrements in visual acuity may occur independent of changes in arousal and motivation.

Experimental Details

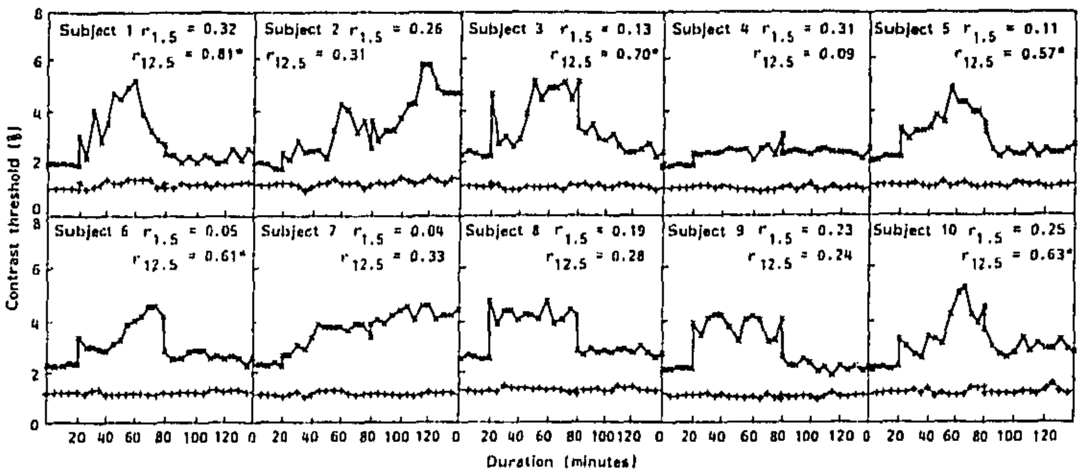
Independent variables:	vibration exposure duration.
Subjects:	ten males.
Task:	contrast thresholds for sinusoidal gratings subtending 1.5 and 12.5 $cdeg^{-1}$. Viewing distance = 1.0 metre. Thresholds determined at 5 minute intervals.
Vibration:	experiments consisted of three periods - a 20 minute pre-exposure (no vibration), a 60 minute exposure to vertical whole-body vibration of 20 Hz at 1.7 ms^{-2} rms, a 60 minute post-exposure period (no vibration).
Dependent variables:	contrast thresholds. Translational head vibration.

Results and Conclusions

Individual subject data shown in the figure illustrate the time dependent changes in contrast sensitivity, vertical head vibration and correlations between vertical head vibration and contrast thresholds.

<u>Published Reference</u>

Moseley M J and Griffin M J (1986)
Whole-body vibration and visual performance, an examination of spatial filtering and time-dependency. (Awaiting publication).



The effect of vibration exposure duration on contrast thresholds (+++++ 1.5 c deg^{-1}, xxxx 12.5 c deg^{-1}). Vibration exposure onset at 20 minutes, termination at 80 minutes. * Indicates significant positive correlation between magnitude of vertical head vibration and contrast thresholds.

2.2 MANUAL CONTROL

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Previous studies have investigated effects of whole-body vibration on manual control performance. However, due to the complexity of manual control systems and of the effects observed under vibration, relatively little has been known about either the way that individual variables interact to produce effects or the fundamental mechanisms which mediate the vibration-induced disruption. It has not therefore been possible to offer specific guidance on whether a particular task would be disrupted by vibration, or on the ways in which any disruption might be minimised.

The program of research summarised in this section consisted of a series of fundamental investigations of the effects of vibration on manual control performance. A major aim was to elucidate the mechanisms which produce the vibration effects. The experiments also investigated the contribution of vibration and system variables in determining the sensitivity of manual control systems to disruption by vibration. Twelve experiments are summarised in this section.

2.2.1 Control stiffness

Aim

This study investigated the effect of varying control stiffness on the sensitivity of a simple tracking task to disruption by whole-body vibration. A taxonomic model of human operator processes contributing to performance provided a framework for the investigation.

Experimental Details

Independent variables:	control stiffness, vibration magnitude.
Subjects:	twelve males.
Task:	zero-order pursuit tracking. Side-arm control with no arm-rest. 1.1 m viewing distance. Control stiffness of 0 (S1), 0.08 (S2), 0.16 (S3) kg cm^{-1}. (All 3 levels allowed substantial displacement).
Vibration:	z-axis. Equal acceleration amplitude sinusoidal components at 3, 5 and 8 Hz. Magnitudes of 0 (V1), 0.43 (V2), 0.87 (V3), 1.73 (V4) ms^{-2} rms.
Dependent variables:	mean square tracking error. Tracking error spectra. Channel capacity.

Results and Conclusions

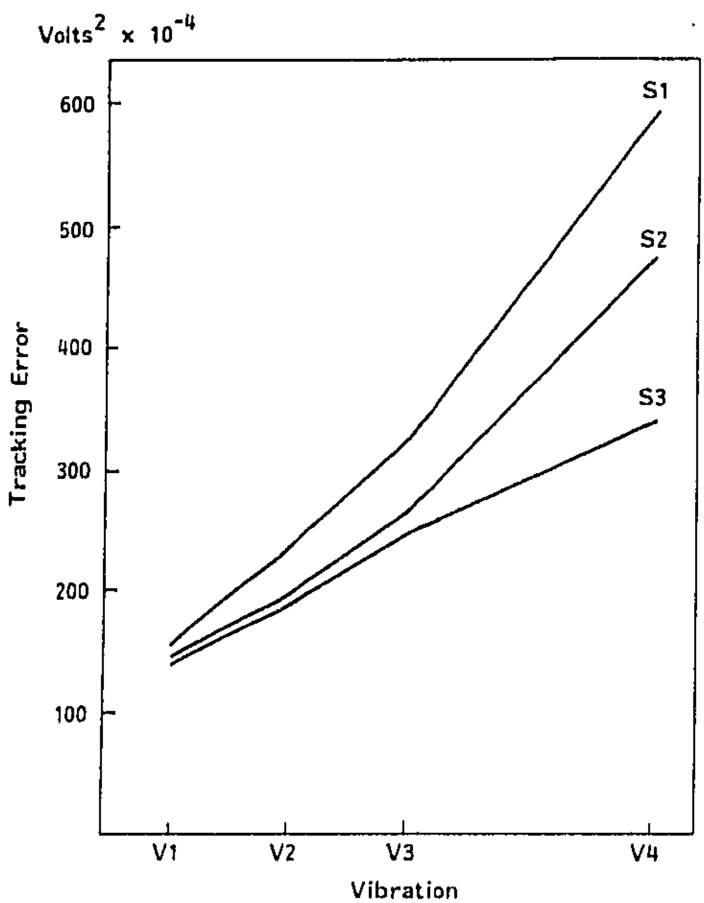
The figure shows total mean square tracking error as a function of vibration magnitude for each control stiffness. There was no significant difference between performance at the three stiffness levels with no vibration. Increasing the stiffness reduced the disruption due to vibration. Vibration breakthrough contributed only a small proportion of total error, greatest disruption occurred at tracking frequencies below 1 Hz. Increasing control stiffness significantly increased channel capacity during vibration but not in the absence of vibration.

The effect of vibration on performance therefore depends upon the stiffness of the control. With controls which allow significant displacement, increasing the stiffness reduces the effect of vibration. A discussion of the possible mechanisms of disruption was included.

Published Reference

Lewis C H and Griffin M J (1976)

The effect of vibration on manual control performance. Ergonomics 19(2), 203-216.



The effect of control stiffness on tracking error with increasing magnitudes of z-axis whole-body vibration. (See 'experimental details' for key)

2.2.2 Vibration frequency at the limb-control interface

Aim

This experiment tested the hypothesis that interference with kinaesthetic feedback mechanisms involved in neuromuscular control loops is a principal means by which vibration degrades manual control performance. It also investigated the dependence of these effects on vibration frequency and control type.

Experimental Details

Independent variables:	frequency of control vibration, control type.
Subjects:	four males.
Task:	zero-order pursuit tracking in one axis. Isotonic, Isometric and spring-centred side-arm controls with no arm-rests.
Vibration:	z-axis, sinusoidal vibration of the control at frequencies of 4, 8, 16, 32 and 64 Hz at acceleration magnitudes of 1.2, 2.4 , 4.8 and 9.6 ms^{-2} rms. (1 hour FDP boundaries from ISO 2631 (1974)).
Dependent variables:	total mean-square tracking error, vibration-correlated error, input-correlated error and remnant.

Results and Conclusions

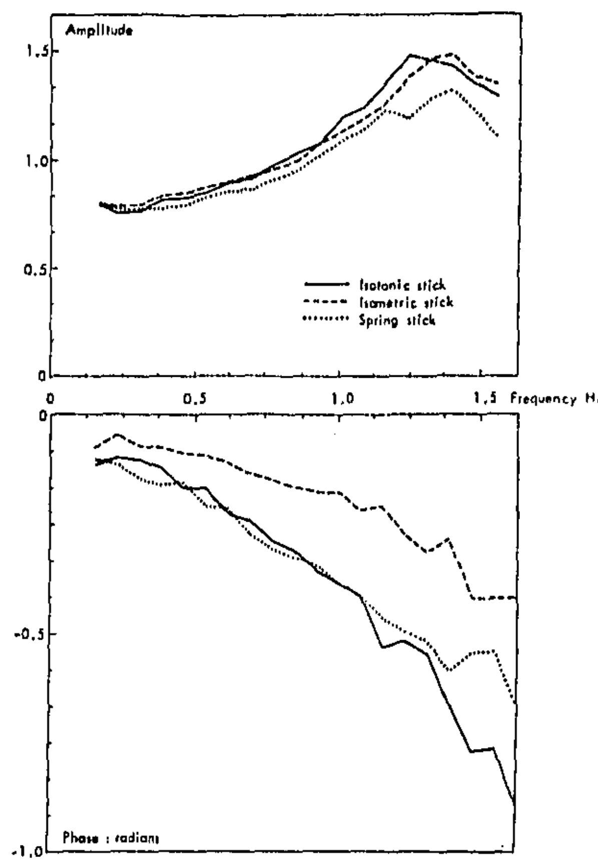
Increases in total error and remnant occurred with both the isotonic and the isometric controls. Statistical significance was only achieved for remnant with the isotonic control at 4, 8 and 64 Hz, and for the isometric control at 64 Hz. There were considerably larger phase lags with the isotonic and spring-centred controls than with the isometric stick without vibration, due to the inertia and friction inherent in moving controls. The figure shows closed-loop human operator transfer functions for the three controls without vibration.

Results at lower frequencies were interpreted as showing either visual confusion caused by vibration-induced oscillations of the controlled element or interference with kinaesthetic feedback mechanisms. The effect of 64 Hz vibration was attributed to direct interference with neuro-muscular actuation mechanisms.

Published Reference

Lewis C H and Griffin M J (1979)

Mechanisms of the effects of vibration frequency, level and duration on continuous manual control performance. Ergonomics, 22(7), 855-889.



Mean closed-loop transfer functions (4 subjects; static conditions) for isotonic, isometric and spring stick dynamics.

2.2.3 Vibration magnitude

Aim

This study further tested the hypotheses, suggested in 2.2.2, that low frequency vibration either caused visual confusion or affected neuromuscular feedback mechanisms. It also determined changes in tracking error components and transfer function parameters for two control types with increasing vibration magnitudes.

Experimental Details

Independent variables:	whole-body or control vibration, vibration magnitude, control type, 'apparent' vibration of controlled element.
Subjects:	four males.
Task:	zero-order pursuit tracking in one axis. Isotonic and Isometric side-arm joystick controls with no arm-rest.
Vibration:	4 and 16 Hz z-axis sinusoidal vibration at 0.35 to 2.0 ms^{-2} rms applied either to the subjects seat or to the control. 'Apparent' sinusoidal vibration of the controlled element on the display of 0, 2, 4 or 6 mm rms.
Dependent variables:	mean square tracking error and components, closed-loop human operator transfer functions.

Results and Conclusions

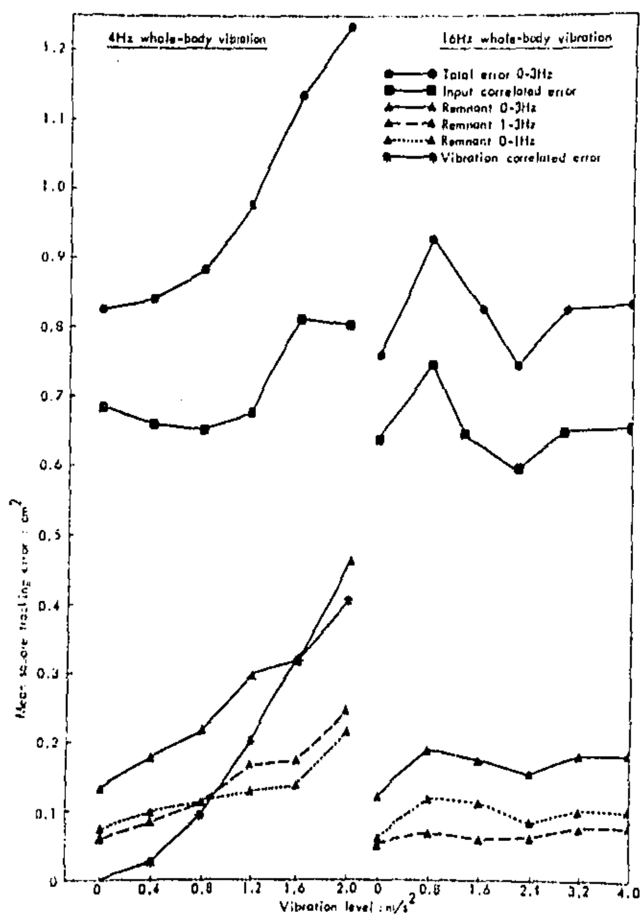
Increases in remnant were highly correlated with actual, or 'apparent', vibration-induced disturbance of the controlled element. The observed effect on remnant was therefore attributed to perceptual confusion arising from the reduced clarity of the displayed information. With whole-body vibration, increases in total error, vibration-correlated error and remnant were linearly related to increases in vibration magnitude at 4 Hz. The rate of increase for each component was greater with the isotonic stick than with the isometric stick. The figure shows the effect of increasing magnitude of whole-body vibration at 4 and 16 Hz with the isotonic control.

Human operator transfer functions showed slight, but significant, reductions in response lags during vibration at high transfer function frequencies. These may be caused by either adaptive changes in subject response strategy, or by increased arousal.

Published Reference

Lewis C H and Griffin M J (1979)

Mechanisms of the effect of vibration frequency, level and duration on continuous manual control performance. Ergonomics, 22(7) 855-889.



The effect of magnitude of sinusoidal z-axis whole-body vibration at 4 Hz and 16 Hz on the components of tracking error. Isotonic stick. Mean data for 4 subjects.

2.2.4 Control gain

Aim

To investigate the effect of changing the gain of the control on a zero-order tracking task, and to establish optimum gain conditions for four different controls in both vibration and no-vibration environments. The study also investigated the interaction between control gain and the components of tracking error.

Experimental Details

Independent variables:	control gain, control type, vibration.
Subjects:	four males.
Task:	zero-order pursuit tracking in one axis. Isometric and isotonic joysticks and knobs with gains from 12.5-50 cm/radian for isotonic controls and 2.5-10 cm/kg for isometric controls.
Vibration:	static and 4 Hz sinusoidal z-axis whole-body vibration at 0.75 ms^{-2} rms.
Dependent variables:	total mean square tracking error and components.

Results and Conclusions

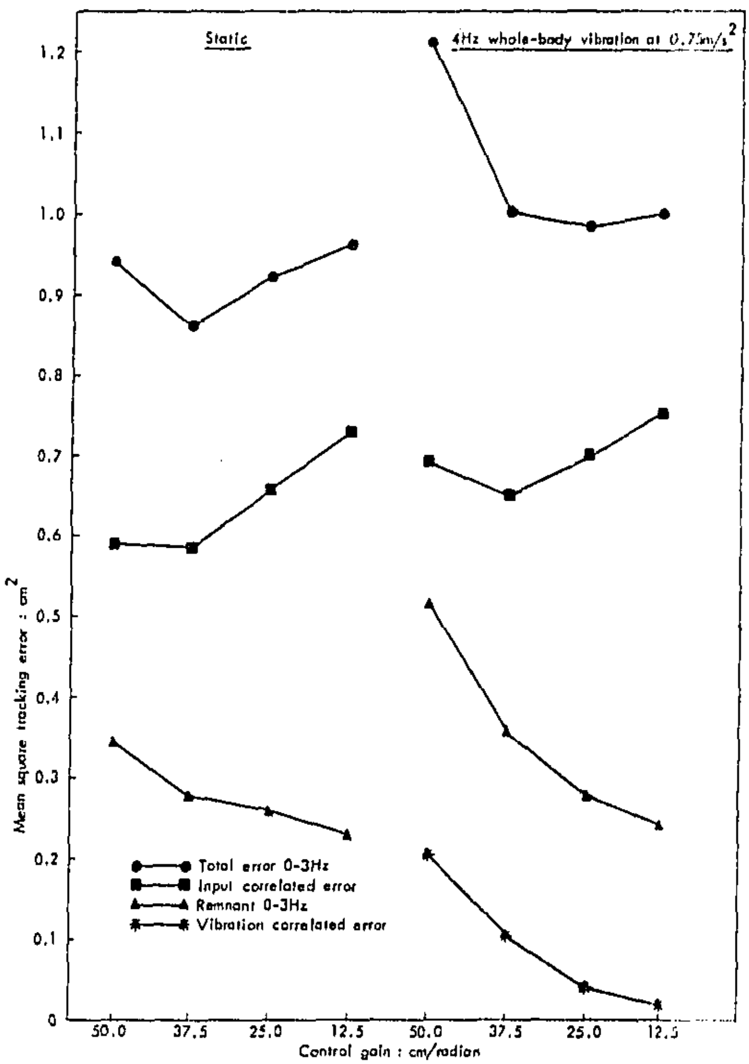
The figure shows the average mean square tracking error and its components for the isotonic joystick. With all four controls, decreasing the control gain reduced both the remnant and the vibration breakthrough. However, breakthrough was as great with the rotary knobs as with the joysticks. There was a significant interaction between control gain and vibration: the optimum gain was lower with vibration than without. With the isotonic controls, decreasing the gain, thereby increasing the size of control movements, produced increased response lags and some reduction in the operators gain at high transfer function frequencies.

There was a considerable interaction between the effects of vibration and control gain. The form of the interaction may differ between controls and vibration environments. Control gains should be optimised for the experimental or operational environment to be encountered.

Published Reference

Lewis C H and Griffin M J (1977)

The interaction of control gain and vibration with continuous manual control performance. J. Sound Vib. 55(4) 553-562.



The effect of control gain on tracking error components without vibration and during exposure to z-axis whole-body sinusoidal vibration at 4.0 Hz. Isotonic stick. Mean data for 4 subjects.

2.2.5 The interaction of control dynamics and display type with vibration frequency

Aim

To investigate the relative effects of vibration frequencies from 2.5 to 12.5 Hz on pursuit and compensatory tracking with zero and first-order system dynamics. The study also investigated the contribution of vibration-induced motion of the controlled element on overall disruption in each condition.

Experimental Details

Independent variables:	control order, display type, vibration frequency.
Subjects:	four independent groups of 8 subjects each, one group for each control order x display type condition.
Task:	two axis pursuit or compensatory tracking of a zero or first-order system using an isotonic side-arm control. No arm-rest.
Vibration:	sinusoidal z-axis whole-body vibration at each preferred 1/3rd octave centre frequency between 2.5 and 12.5 Hz. Acceleration magnitude dependent upon frequency - 1.5 ms^{-2} rms between 4.0 and 8.0 Hz. Induced 5 mm rms distrubance of target or display at each frequency with no motion of body.
Dependent variables:	increase in root-mean-square vector tracking error per unit acceleration magnitude, and components

Results and Conclusions

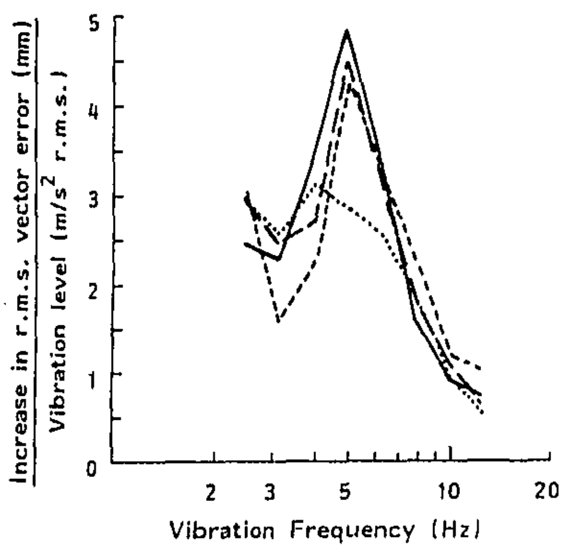
The figure shows the frequency sensitivity of the task to whole-body vibration in each display and control order condition. Differences between tasks were small, especially as different groups of subjects performed each task. The mean increase in total r.m.s error for all four tasks could be predicted by one average sensitivity function with an accuracy of not less than 50%, and considerably greater accuracy at many frequencies.

Although the total increase in rms tracking error was approximately the same with each task, the error components differed considerably. First-order tasks attenuated vibration breakthrough by one half for every doubling in frequency. However, first-order tasks are more susceptible to other forms of disruption.

Errors without vibration were considerably greater for the more difficult first-order tasks. The relative increase in error during vibration was therefore greater with the easier, zero-order tasks.

<u>Published Reference</u>

Lewis C H (1980)
The interaction of control dynamics and display type with the effect of vibration frequency on manual tracking performance. Paper presented at the UK Informal Group Meeting on Human Response to Vibration. Swansea.



The effect of sinusoidal z-axis vibration frequency on manual control performance with zero-and first-order systems and with pursuit and compensatory displays.
(——— zero-order pursuit, – – – zero-order compensatory, ------- first-order pursuit, ... first-order compensatory)

2.2.6 Effect of duration up to 75 minutes

Aim

To determine whether effects of vibration observed in previous studies (2.2.1 to 2.2.5) would be dependent upon the duration of exposure to vibration.

Experimental Details

Independent variables:	control type, duration, vibration.
Subjects:	two independent groups of four subjects each. One group for each control type.
Task:	continuous zero-order pursuit tracking in one axis for 75 minutes, using isotonic or isometric side-arm controls with no arm supports.
Vibration:	static or 4 Hz sinusoidal whole-body vibration at an acceleration magnitude of 1.2 ms^{-2} rms for 60 minutes followed by no vibration for the remaining 15 minutes.
Dependent variables:	mean square tracking error and components. Human-operator closed-loop transfer functions.

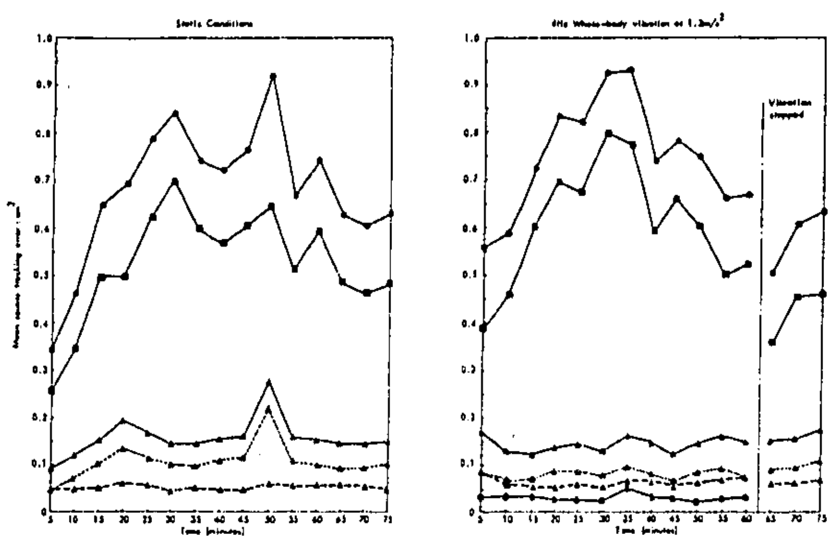
Results and Conclusions

Results showed large increases in overall error variance over the 75 minute runs in both static and vibration conditions. These were caused by large increases in response lags and suppression of coherent responses. Vibration did not alter the overall effect of duration. Observations and discussions with subjects indicated that they had considerable difficulty maintaining arousal and attention. Tests for trends in individual subjects' data suggested that error variance was more likely to increase with time in static conditions than with vibration.

As in previous studies, the only significant changes in error components during vibration ocurred for vibration-correlated error and remnant. However, effects were not time dependent.

<u>Published Reference</u>

Lewis C H and Griffin M J (1979)
Mechanisms of the effect of vibration frequency, level and duration on continuous manual control performance. Ergonomics, <u>22</u>(7) 855-889.



The effect of duration on tracking error components without vibration and during exposure to z-axis sinusoidal whole-body vibration at 4.0 Hz. Isometric stick. Mean data for 4 subjects. ●——● Total error 0-3 Hz ■——■ Input correlated error ▲– – –▲ Remnant 0-3 Hz ▲-----▲ Remnant 1-3 Hz ♦——♦ Vibration correlated error

2.2.7 Predicting the effects of dual-frequency vibration

Aim

It may be possible to predict the effects of complex vibration environments from a knowledge of the effects of individual frequencies. The effect of dual frequency whole-body vibration was measured and compared with three methods of predicting effects from a knowledge of the influence of single frequencies.

Experimental Details

Independent variables:	vibration frequency, vibration magnitude, prediction procedure - three prediction procedures were a) rms sum of weighted components b) most severe weighted component and c) arithmetic sum of weighted components.
Subjects:	eight males.
Task:	zero-order pursuit tracking in two axes using an isotonic side-arm control. No arm rest.
Vibration:	3.15 and 5.0 Hz sinusoidal z-axis whole-body vibration at acceleration magnitudes of 0, 0.4, 0.8, 1.2, 1.6 and 2.0 ms^{-2} rms. Ten dual frequency combinations of 3.15 and 5.0 Hz at varying magnitudes.

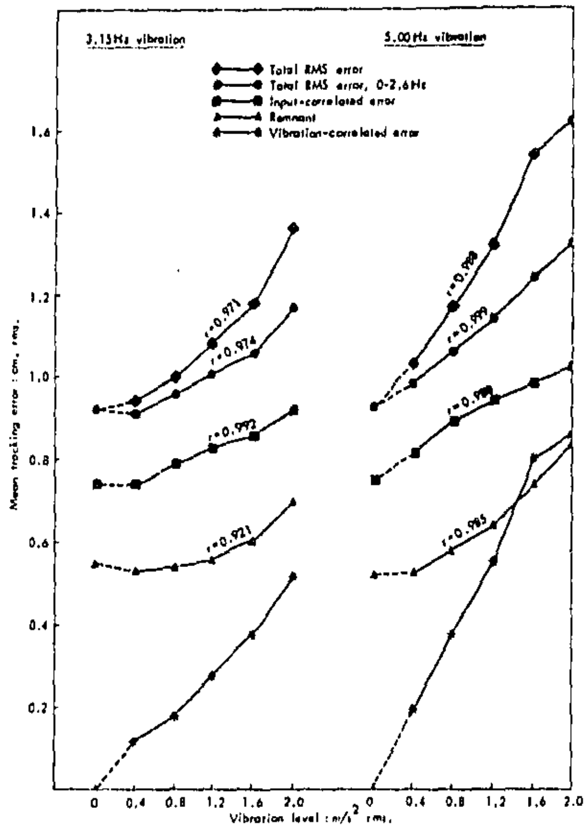
Results and Conclusions

The best predictions of overall performance in dual frequency environments were obtained using prediction procedure a): - the rms sum of the weighted frequency components. Measured values of total rms error were within 95% confidence limits of predicted error using this method. However this procedure over-estimated the input-correlated, or linear, component of the error and under-estimated the remnant, or non-linear, component. Caution should therefore be exercised when applying this conclusion.

Results showed strong linear relationships between increasing error and increasing acceleration magnitude. The slope of the relationship depends upon both the vibration frequency and the axis of the tracking task. The figure shows tracking error in the vertical display axis against acceleration magnitude at 3.15 and 5.0 Hz.

Published Reference

Lewis C H and Griffin M J (1978)
Predicting the effect of dual-frequency vertical vibration on continuous manual control performance. Ergonomics 21(8) 637-650.



The effect of magnitude of z-axis sinusoidal whole-body vibration at 3.15 Hz and 4.0 Hz on tracking error components. Mean performance for 8 subjects.

2.2.8 Predicting the effect of broad-band random vertical vibration

Aim

The aim of this study was to extend the prediction procedure evaluated for dual frequency motions in 2.2.7 to broad-band random vibration. A comparison was also made between the accuracy of predictions based on sensitivity functions derived from sinusoidal and one-third octave random vibration. Root-mean-square tracking error during broad-band random vibration was predicted from:

$$e_p = e_o + \left(\int_{\omega} s^2(f).G_{vv}(f).df\right)^{1/2}$$

where: e_p is the predicted error

e_o is the error with no vibration

$s(f)$ is the sensitivity function (ie frequency weighting)

$G_{vv}(f)$ is the power spectrum of the seat vibration, and

ω is the bandwidth of the vibration

Experimental Details

Independent variables:	vibration frequency, vibration waveform.
Subjects:	eight males.
Task:	two-axis zero-order pursuit tracking using an isometric side-arm control. No arm rest.
Vibration:	z-axis (vertical) whole-body vibration. Sinusoidal and one-third octave band random vibration with centre frequencies at 2.5, 3.15, 4.0, 5.0, 6.3, 8.0, 10.0 and 12.5 Hz at an acceleration magnitude of 1.5 ms^{-2} rms. Also random vibration of 1 octave bandwidths centred on 4.0 and 8.0 Hz, and 2 octave bandwidth centred on magnitudes of 2.0 ms^{-2} rms.
Dependent variables:	rms tracking error and components.

Results and Conlusions

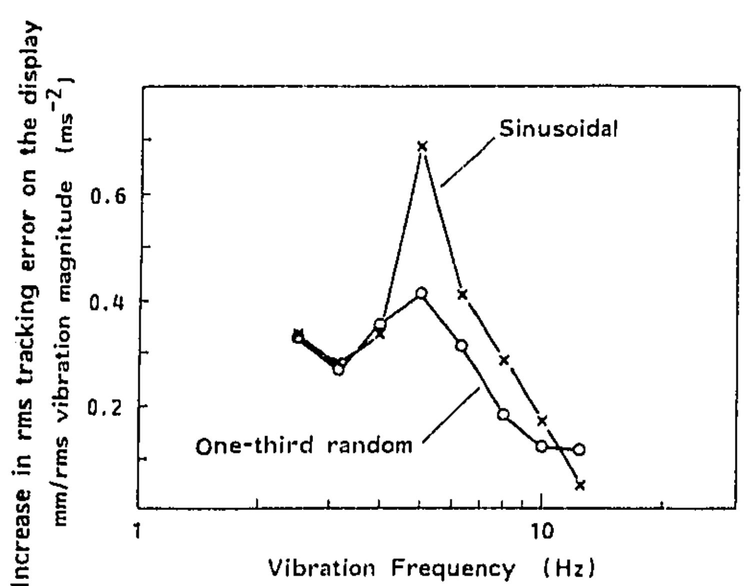
Good predictions of r.m.s tracking error during each random vibration were obtained

Results and Conlusions

Good predictions of r.m.s tracking error during each random vibration were obtained from sensitivity functions based on response to either sinusoidal or one-third octave-band vibration. The figure shows that slightly greater disruption occurred with the sinusoidal vibration than with the one-third octave-band motions. The sinusoidal sensitivity functions generally produced better predictions of the effect of broad band vibration. However, differences between predictions using either waveform were not large. Sensitivity curves for individual subjects were broadly similar to the results averaged over all subjects.

Published Reference

Lewis C H (1981)
A comparison of the effects of sinusoidal and random whole-body vibration on manual tracking performance. UK Informal Group Meeting, Edinburgh.



Pursuit tracking performance during sinusoidal and one-third octave-band random z-axis whole-body vibration.

2.2.9 Vibration frequency from 0.5 to 5.0 Hz and performance of a complex task.

Aim

This study used dynamics broadly representative of modern high-performance aircraft. An analogue computer simulation resolved two axis control inputs into 'airframe' rotations in roll, pitch and yaw. Subjects performed a complex task involving continuous pursuit tracking with simultaneous discrete target acquisition by pressing a button when 'on target'. The objectives were to investigate, i) whether this complex task would be sensitive to disruption by whole-body vibration and ii) whether there would be any frequency dependence in the effects.

Experimental Details

Independent variable:	vibration frequency.
Subjects:	eight males.
Task:	two-axis pursuit tracking with button pressing to indicate when on target. Isometric side-arm control with no arm-rest.
Vibration:	z-axis whole-body sinusoidal vibration at preferred one-third octave centre frequencies between 0.5 and 5.0 Hz, at an acceleration magnitude of 2.0 ms^{-2} rms.
Dependent variables:	probability of being on target - p(on) -, of pressing the button while on target - p(hit/on) - and of pressing the button while off target - p(press/off).

Results and Conclusions

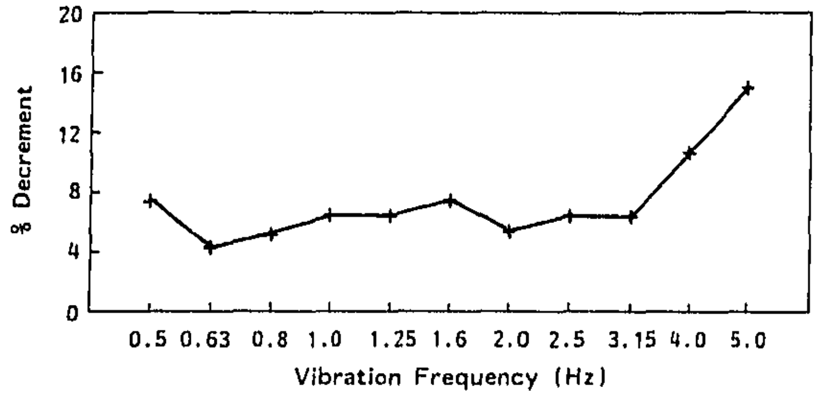
The figure shows the percentage reduction in p(on) at each vibration frequency relative to performance with no vibration. Disruption was approximately constant at about 5% from 0.5 to 3.15 Hz and increased to 15% at 5 Hz. Discrete task performance showed that subjects adopted a more cautious strategy during vibration; they were less likely to press the button while off target. The effect of vibration on discrete task performance was independent of vibration frequency. Analysis of tracking error spectra showed little evidence of vibration-correlated tracking error.

Data obtained during this study demonstrated the importance of ensuring that subjects are adequately trained in both vibration and no vibration environments before obtaining experimental data on the effects of vibration on performance.

Published Reference

McLeod R W and Griffin M J (1986)

Performance of a complex manual control task during vertical whole-body vibration between 0.5 and 5.0 Hz. In preparation.



The effect of vibration frequency on the probability of being on target with a complex manual control task.

2.2.10 Display collimation at vibration frequencies between 2.5 and 5.0 Hz

Aim

To investigate the hypothesis that the effect of vibration observed in 2.2.9 at frequencies above 2.5 Hz was caused by visual blurring arising from translational motion of the subjects' eyes relative to the display. A convex lens placed in front of the display placed the image of the display, viewed through the lens, at optical infinity. Effects caused by translational motion of the eye relative to the display were therefore expected to be removed.

Experimental Design

Independent variables:	vibration frequency, viewing condition.
Subjects:	six males (all took part in 2.2.9)
Task:	two axis pursuit tracking with simulated aircraft dynamics plus button pressing to indicate when on target. Isometric side-arm control with no arm-rest.
Vibration:	z-axis whole-body sinusoidal vibration at 2.5, 3.15, 4.0 and 5.0 Hz at an acceleration magnitude of 2.0 ms^{-2} rms. Display stationary.
Dependent variables:	p(on), p(hit/on) and p(press/off) (see 2.2.9).

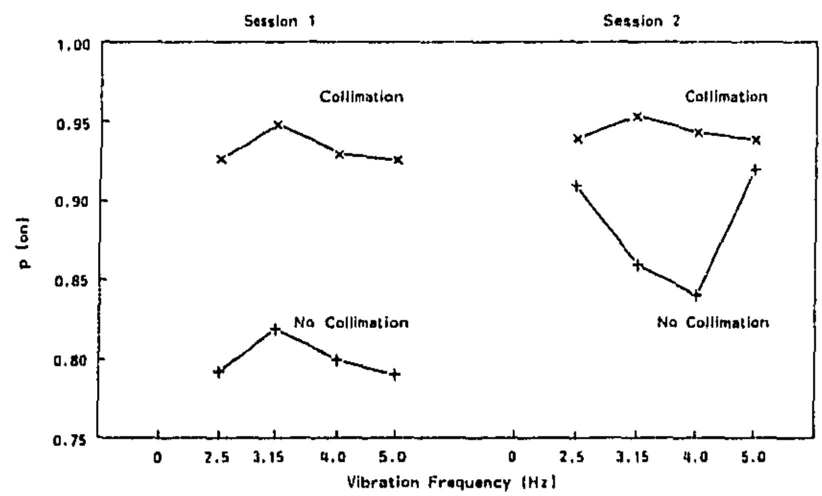
Results and Conclusions

The figure shows that in all conditions in which vibration disrupted performance, collimating the display removed the effect of vibration. Disruption in this frequency range was therefore attributed to visual blurring arising from translational motion of the subjects eyes relative to the display. It was suspected that there may have been subtle transfer of training effects between performance with and without display collimation.

Published Reference

McLeod R W (1984)

The effect of display collimation on performance of a complex manual control system during vertical whole-body vibration between 2.5 and 5.0 Hz. Paper presented to UK Informal Group meeting on Human Response to Vibration, Edinburgh.



The effect of display collimation in the probability of being on target with a complex manual control task.

2.2.11 Display collimation and vibration waveform at frequencies from 0.5 to 10 Hz

Aim

This study extended the findings from 2.2.10 by investigating the range of frequencies over which display collimation would reduce the disruption caused by vibration. It was expected that collimation would not improve performance below about 2 Hz or above about 8 Hz. The study also compared performance during sinusoidal and one-third octave band random vibration.

Experimental Details

Independent variables:	vibration frequency, vibration waveform, display collimation.
Subjects:	two independent groups of eight subjects each, (collimation and no collimation groups).
Task:	two-axis pursuit tracking with simplified version of aircraft dynamics plus button pressing to indicate when on target. Isometric side-arm control with no arm-rest.
Vibration:	sinusoidal and one-third octave band random vibration at each preferred one-third octave centre frequency between 0.5 and 10 Hz at an acceleration magnitude of 2.1 ms^{-2} rms. Subject, control and display vibrated.
Dependent variables:	simple probability measures (see 2.2.9), rms tracking error and components, human-operator closed-loop transfer functions.

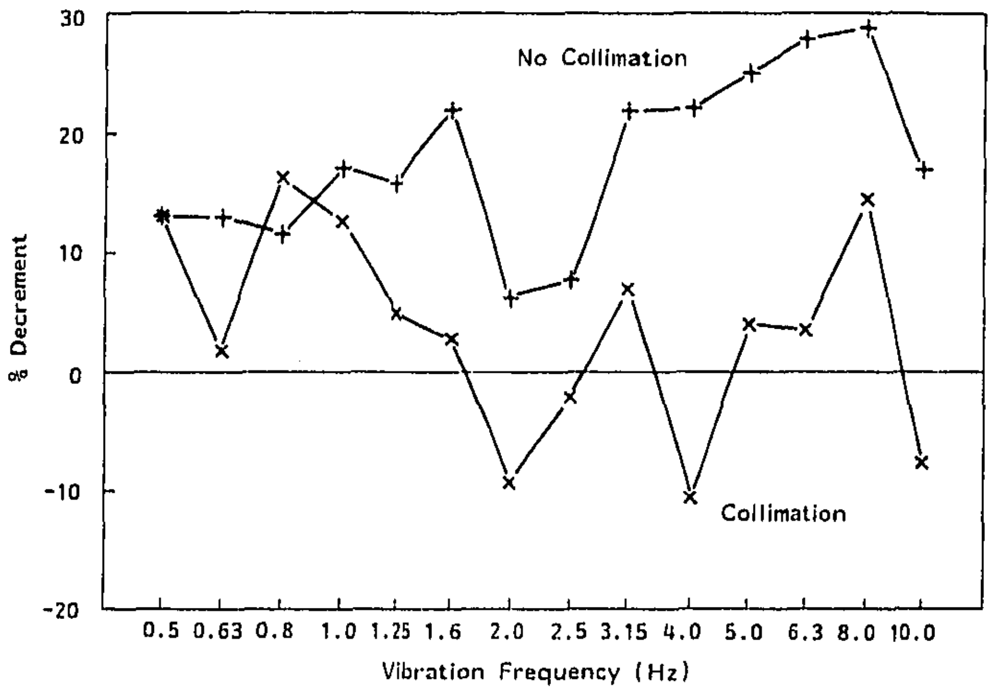
Results and Conclusions

Without display collimation both types of vibration significantly disrupted performance at all frequencies. Collimating the display removed the disruption at frequencies above about 2 Hz. Decrements in this range were therefore attributed to translational motion between the observers eyes and the display. With random vibration collimation also reduced the effect of vibration at frequencies below 2 Hz. With sinusoidal vibration, however, collimation did not remove the effect at low frequencies. The figure shows the effect of display collimation with sinusoidal vibration.

Effects of vibration without collimation were associated with changes in high frequency gains and phase lags of the human operator transfer functions. Display collimation removed these effects.

Published Reference

McLeod R W and Griffin M J (1986)
Performance of a complex manual control task during vertical whole-body vibration: effects of display collimation and vibration waveform. In preparation.



The effect of display collimation on the probability of being on target with a complex manual control task during exposure to z-axis sinusoidal whole-body vibration at frequencies from 0.5 Hz to 10.0 Hz. Median performance for 8 subjects.

2.2.12 Effect of exposure duration up to 202 minutes

Aim

This study investigated whether performance of the complex task used in earlier experiments (2.2.9, 2.2.10 and 2.2.11) was dependent upon the duration for which the task was performed and, if so, in what way. The study also investigated whether effects of vibration would interact with the effect of duration. It was hypothesised that subjects who were highly trained in short duration performance would show a learning effect if they performed for a long duration on two separate occasions.

Experimental Details

Independent variables:	duration, vibration, session.
Subjects:	two independent groups of seven subjects each. One group exposed to vibration on both sessions, the other group received no vibration exposure.
Task:	continuous pursuit tracking in two axes using simplified aircraft dynamics plus button pressing to indicate when on target. Continuous performance for 202 minutes on two separate occasions.
Vibration:	static or one-octave band random vertical vibration centred on 4 Hz at an acceleration magnitude of 1.4 ms^{-2} rms.
Dependent variables:	simple probabilities, rms tracking error and components, human-operator closed-loop transfer functions.

Results and Conclusions

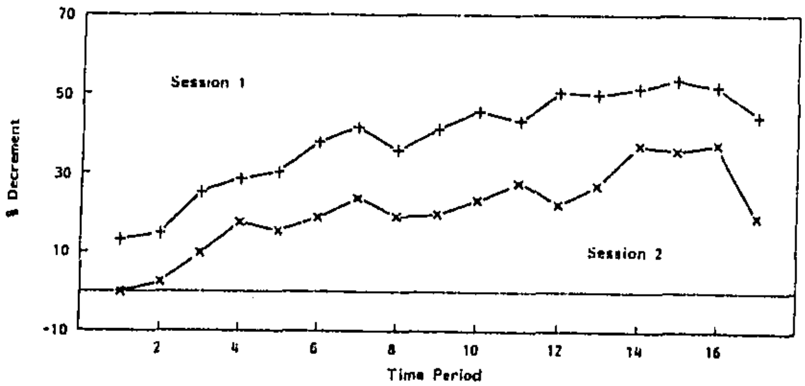
Performance significantly deteriorated with duration in all conditions and vibration did not alter the time dependence. Performance on Session 2 was significantly better than on Session 1. Subjects commented that they were well motivated, and that they felt better prepared on Session 2, they knew what to expect and that session two seemed easier.

There was therefore clearly some adaptation to the duration of performance even though subjects were highly trained at the tracking task for short durations. The effect of duration was attributed to muscular and mental fatigue.

The experiment demonstrated that a vibration exposure above the 'fatigue-decreased-proficiency' boundary defined in ISO 2631 (1985) did not affect performance relative to no vibration performance. The figure shows the mean effects of exposure duration and session on the probability of being on target.

<u>Published References</u>

McLeod R W and Griffin M J (1986)
The effect of exposure duration on performance of a complex manual control task during whole-body vibration exposure. In preparation.



The effect of repeated performance of a complex manual control task over two sessions of 202 minutes each. No vibration. Median data for 8 subjects. (Each time period is 11.25 minutes).

3.0 LITERATURE REVIEWS, DESIGN GUIDES AND THESES

Research performed under this programme has formed the basis of three theses submitted, or shortly to be submitted, to the University of Southampton for the degree of doctor of philosophy. This section identifies which of the experiments, described in Section 2, were included in each thesis. Literature reviews covering effects of vibration on visual acuity and continuous manual control were carried out and published. References to these reviews are given below. More recent reviews are in the theses by R W McLeod and M J Moseley. References are also provided to two design guides produced under this contract.

3.1 Literature Reviews

Griffin M J and Lewis C H (1978)
A review of the effects of vibration on visual acuity and continuous manual control, Part I: Visual Acuity. J. Sound. Vib. 56(3) 383-413.

Lewis C H and Griffin M J (1978)
A review of the effects of vibration on visual acuity and continuous manual control, Part II: Continuous Manual Control. J. Sound. Vib. 56(3) 415-457.

3.2 Ph D Theses

The following experiments, referred to in Section 2, are included in Ph D theses.

Author	Experiment
C H Lewis	2.2.2
	2.2.3
	2.2.4
	2.2.6
	2.2.7
M J Moseley	2.1.8
	2.1.9
	2.1.10
	2.1.11
	2.1.12

M J Moseley (cont) 2.1.13
2.1.14
2.1.15

R W McLeod 2.2.9
2.2.10
2.2.11
2.2.12

3.3 DESIGN GUIDES

Moseley M J and Griffin M J (1986)
A Design Guide for visual displays and manual tasks in vibration environments. Part I: Visual Displays. ISVR Technical Report No. 133 Southampton University.

McLeod R W and Griffin M J (1986)
A Design Guide for visual displays and manual tasks in vibration environments. Part II: Manual Tasks. ISVR Technical Report No. 134 Southampton University.

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