OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

PERFORMANCE ASSESSMENT LABORATORY
DEPARTMENT OF PSYCHOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

Progress Report No. PR-76-7

DEVELOPMENT OF RIDE COMFORT CRITERIA FOR MASS TRANSIT SYSTEMS

(NASA-CR-147962) DEVELOPMENT OF RIDE COMFORT CRITERIA FOR MASS TRANSIT SYSTEMS Final Report (Old Dominion Univ. Research Foundation) 32 p HC $4.00 CSCL 05H
N76-24903
Unclas
G3/54 28261

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Final Report

Prepared for the
National Aeronautics and Space Administration
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Under
Research Grant NSG 1042

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Submitted by the
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Norfolk, Virginia 23508

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DEVELOPMENT OF RIDE COMFORT CRITERIA FOR MASS TRANSIT SYSTEMS

This research program under grant NSG 1042 involved a series of interdependent research studies that were the product of a number of planning sessions with the personnel of the Noise Effects Branch, Langley Research Center. This program consists of designs which (a) were primarily conducted by the principal investigators of this project, (b) those that were a joint effort of the grant investigators and members of the Noise Effects Branch, and finally (c) those which were supported by the Old Dominion University subject pool, but would not involve the principal grant investigators in a major capacity.

Below is a brief summary of the research conducted under this grant. The first two projects listed intimately involved personnel from the Performance Assessment Laboratory of Old Dominion University and the latter five were suggested through the provision of approximately 750 subjects.

A. Combined Axes of Vibration Input. These experiments were studies of the independence and/or the interaction of vibration axes on passenger discomfort. Input was varied in amplitude and frequency of vibration as well as axis. Further, the investigations were conducted in a parametric fashion so that the possibility of masking effects occurring with combined axes of input could be assessed. The first investigation on this topic was conducted, and the results were reported at the Ride Quality Conference at Langley Research Center in December 1974. The second study, investigating the role of simultaneous amplitude variations within these two axes, was completed and the results reported in the 1975 Ride Quality Symposium and Workshop at Williamsburg, Virginia in August. A copy of a paper based on each study is included in this report.

B. Effect of Combined Sinusoidal Vibration and Simulated Jet Noises on Ride Comfort Evaluation. This experiment examined the effect of accompanying vibration with simulated jet noise on ratings of discomfort. Sound level, amplitude of vertical vibration, and frequency of vertical vibration were varied factorialy in a single study and the effect on ratings of discomfort were assessed. The results were reported in a paper presented before the annual meeting of the Southeastern Psychological Association in New Orleans in March. Also, a paper containing the results of this study and those of the second study on combined axes was presented to the annual meeting of the American Industrial Hygiene Association in Atlanta in May.

C. An Evaluative Investigation of Subjective Rating Scales. This experiment, conducted on the NASA-Langley Research Center PRQA simulator, was designed to provide evaluation of subject rating scales of ride quality toward the ultimate goal of establishing the optimum rating scale to be used in future studies of ride quality.

D. Effects of Bandwidth on Subjective Rating of Vibration in Vertical Axis. The purpose of this experiment, conducted on the NASA-Langley Research Center PRQA simulator, was to determine if subjective ratings of discomfort to vibratory motion in the vertical axis were affected by the bandwidth of the stimulation. Specifically, an experiment was designed to compare subjective ratings of single frequency vertical vibration with ratings of vibrations of specific bandwidths having center frequencies equal to the single frequencies. This experiment was viewed as a preliminary exploration to determine if subjective ratings are attenuated or amplified by the increased bandwidth.

E. Equal Discomfort Curve Studies. These five studies determined the lower thresholds and equal discomfort curves for the discomfort of vibrations. The studies included methodological modifications of the psychophysical methods of constant stimuli, average error, and magnitude estimation. The data for these studies were used to form the basic scale of discomfort. Separate discomfort curves were determined from five different studies, using different types of vibration input: vertical, lateral, longitudinal, roll, and pitch.

F. Effects of Frequency on Sensitivity to Vibration Compared to the Effect on Discomfort. This area of research was not a part of the original grant proposal; however, it was suggested that other variables might arise during the grant period which would merit investigation. The grant proposal further indicated that in the event that additional investigations were called for, the research plan would be altered to incorporate the new variables. Such was the case with the study of sensitivity to frequency of vibration compared to discomfort produced by the various frequencies.

Effect of Vibration in Combined Axes on Subjective Evaluation of Ride Quality

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Two studies were conducted on the effects of simultaneous sinusoidal vibration in the vertical and lateral axes on ratings of discomfort in human subjects in a simulated passenger aircraft. In the first experiment each of 24 subjects experienced each of ten levels of vertical frequency in combination with each of ten levels of lateral frequency of vibration and rated the discomfort produced on a nine-point, unipolar scale. The results showed that both vertical frequency and lateral frequency, as well as the interaction between the two, significantly affected the subjective ratings. In the second experiment 72 subjects experienced one of four levels of vertical frequency at each of four levels of vertical amplitude combined with 16 (or 4 x 4) lateral frequency and amplitude conditions. Not only did the four major variables studied significantly affect ratings of discomfort, but the interactions between them had significant effects as well. The results of these two studies strongly suggest that there are effects on discomfort that occur when subjects are vibrated in several axes at once that cannot be assessed with research using vibration in only one axis. The relevance of the results to the standard recommended by the International Standards Organization covering human exposure to whole-body vibration in more than one axis simultaneously is discussed.

The first study of subjective evaluations of ride quality produced by simultaneous vibrations occurring in more than one axis was reported by Jacklin and Liddell (1933). The results of that study showed that introduction of various combinations of amplitudes and frequencies in the horizontal axis lowered the thresholds for ratings of "disturbing" and"uncomfortable" in the vertical axis, for frequencies below 7 Hz. The experimental design of the study, however, did not permit detection of interactions between the effects of vertical and horizontal vibrations on subjective ratings.

Holloway and Brumaghim (1972) have studied the effects of narrow-band, random frequency vibrations with center frequencies between 0.20 and 7 Hz applied simultaneously to the vertical and lateral axes. That study showed that increasing the amplitude of vibrations in the lateral axis led to lower levels of amplidude in the vertical axis being rated as "objectionable."

As with the Jacklin and Liddell study, it was beyond the scope of the research to study possible interactions between the effects of vibrations in the two axes.

The International Standards Organization (1972) has recommended in the Guide for the Evaluation of Human Exposure to Whole-Body Vibration limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz. Three sets of limits have been recommended: a "reduced comfort boundary," a "fatigue-decreased proficiency boundary," and an "exposure limit." Among its recommendations is one covering vibrations occurring in more than one axis simultaneously which says that the acceptable limits of exposure to vibration should apply separately to each component in the three axes. A primary purpose of the present research was to evaluate this recommendation, particularly with respect to the "reduced comfort boundary."

The studies herein reported investigated the effects of simultaneous sinusoidal vibration in the vertical and lateral axes on ratings of discomfort. The first experiment concentrated on the effects of variation of frequency in the two axes, and the second study concentrated on the effects of amplitude variation in the two axes.

Experiment I

Method

Subjects. The subjects for this research were 11 males and 13 females recruited from the undergraduate study body of Old Dominion University. The 24 subjects used were recruited from a larger list of volunteers who had been medically screened and approved by the NASA-Langley Research Center. The median age of the subjects was 19.5 years and the range of the ages was from 18 to 50 years.

Apparatus. The apparatus used in this experiment was the Passenger Ride Quality Apparatus (PRQA) located at NASA-Langley Research Center. This apparatus, designed as a simulated passenger aircraft, can present subjects with whole-body vibration of various frequencies, amplitudes, and waveforms in the vertical, lateral (side-to-side), or roll axes. For this experiment the PRQA was equipped with 6, tourist class seats. Additional details about the

PRQA can be obtained from Clevenson and Leatherwood (1972) and Stephens and Clevenson (1973).

Design. The experimental design used was treatments by treatments by sessions with subjects nested under sessions (Winer, 1971). The first treatment variable was the frequency of vibration input in the vertical axis; the ten levels of vertical frequency employed were 0, 1, 2, 3, 4, 5, 8, 10, 15, and 20 Hz. The second treatment variable was frequency of input in the lateral axis; the same ten levels of frequency were used in the lateral axis as were used in the vertical. Groups of 6 subjects were simultaneously tested on the PRQA, and there were four such groups, or sessions. For each group of subjects the apparatus was set at one level of vertical frequency. Then the next level of vertical frequency was presented. A different random order of lateral frequencies was used for each level of vertical frequency and a different random order of vertical frequencies was used for each of the four sessions. The amplitude of all stimuli was .15 g (peak).

Rating scale. The rating scale employed was a nine-point, unipolar scale. For each stimulus the subject was provided with a separate scale consisting of a line with nine divisions, numbered from "0" to "8". Above the "0" was the anchor "Comfortable or zero discomfort" and above the "8" was "Maximum discomfort." The subjects were instructed to use the scale as an equal-interval scale, rating stimuli between the numbered divisions as well as on them. The subjects were also instructed to rate the discomfort produced by the stimuli. Before beginning each new level of vertical frequency, the subjects were presented with two anchor stimuli. The first had no vertical input and a lateral input of 10 Hz and was described as "One that many people might give a low number rating." The second had a vertical input of 4 Hz and a lateral input of 5 Hz, and was described as "One that many people would probably assign a high number rating."

Procedure. The subjects were transported to the Langley Research Center from Old Dominion University, a distance of approximately 25 miles, in a late-model, nine-passenger station wagon. Upon arriving at the Langley Research Center the subjects were taken to a conference room adjacent to the room housing the PRQA. Here the subjects were given their instructions regarding the experiment and appropriate safety procedures. The subjects were then seated in the PRQA and asked to fasten their seat belts.

Throughout the testing, two-way audio communication was maintained with the subjects and the subjects were also continually observed through a one-way mirror as part of the safety procedures.

Instructions regarding the anchor stimuli and the test stimuli were recorded on audiotape. At the beginning of each test stimulus the subjects were told "Begin" and at the end of the stimulus presentation the subjects were told "Rate." Each trial consisted of 5 seconds for the stimulus to reach the appropriate level, 15 seconds of stimulus, 5 seconds for the offset of the stimulus and ten seconds between trials. The subjects were given one minute rest between each series of ten stimuli and a 15-minute intermission halfway through the testing, i.e., after fifty stimuli.

Results

Table 1 shows the results of analysis of variance with repeated measures on two variables. Clearly the most significant variable affecting the ratings of the subjects was the frequency of lateral vibrations. The effect of frequency in the vertical axis was also significant, as was the interaction between these two variables.

Figure 1 shows the mean ratings of the subjects as a function of the frequency of vertical input with frequency of lateral input as a parameter. Figure 2 shows the same data but with the ratings as a function of lateral frequency with vertical frequency as a parameter. The lateral axis appears to have a dominant effect at lower frequencies, whereas at higher frequencies the relative significance of the vertical frequencies is much greater than it is at lower frequencies. The significant interaction appears to be due to each axis masking the effects of the other axis at frequencies rated at maximum discomfort in the former axis, with the lateral axis masking the effects of the vertical axis more than in the reverse direction.

A multiple-regression analysis was subsequently computed using the physical measures of vertical and lateral frequency and various tranformations of these measures to predict the subjective responses of discomfort. This analysis employed the two physical measures (i.e., lateral and vertical frequency) and eleven other transformations of these measures for a total of 13 predictor variables (Variables V_1 through V_{13} of Table 2) to predict the criterion variable, subjective rating (SR). The analysis consisted of a stepwise regression analysis. The resulting predictive equation was used to generate the response surface presented in Figure 3; it should be noted that the multiple correlation coefficient associated with the criterion variable and the predictor variables employed was 0.685, accounting for 46.92% of the variability in the individual subjective responses.

Experiment II

Whereas the first experiment was primarily concerned with the effects of variation in frequency of vibrations simultaneously presented in the two axes, this experiment was concerned with the effects of variation of amplitude in the two axes on ratings of discomfort, and with interactions between the effects of amplitude and the effects of frequencies.

Method

Subjects. The subjects for this research were 42 male and 30 female undergraduate students recruited from the student body of Old Dominion University in manner similar to that used in recruiting subjects for Experiment I. The median age of the subjects was 20 years and the range of the ages was from 18 to 45 years.

Apparatus. As in Experiment I the apparatus used was the PRQA located at NASA-Langley Research Center.

Design. The experimental design was a 4 x 4 x 4 x 4 factorial design with 12 subjects nested under each of the vertical frequencies and with repeated measures over the vertical amplitudes, the lateral frequencies and the lateral amplitudes. Thus, each subject was exposed to only one of the four vertical frequencies but experienced that frequency at each of its four amplitudes combined with 16 (or 4 x 4) lateral frequency and amplitude conditions. The four levels of vertical frequency were 2, 5, 9, and 15 Hz. The four levels of vertical amplitude were 0.05 g, 0.10 g, 0.15 g, and 0.25 g (peak). The four levels of lateral frequency were 2, 4, 8, and 16 Hz, and the four levels of lateral amplitude were, like the vertical amplitudes, 0.05 g, 0.10 g, 0.15 g, and 0.25 g (peak). In addition, as a control condition, 12 other subjects experienced each of the vertical frequencies at each of the four amplitudes in the absence of lateral input. As a final control, another group of

12 subjects experienced each of the lateral frequencies at each of the four amplitudes in the absence of vertical input.

Groups of six subjects were tested on the PRQA simultaneously; twelve such groups were tested with the two groups experiencing each of the two control conditions. For each of the ten experimental groups plus two control groups that experienced lateral vibration, the apparatus was set at a level of lateral frequency and all combinations of vertical amplitude and lateral amplitude were presented with that level of lateral frequency before going on to another level of lateral frequency. For the control group that received only vertical input, the apparatus was set at a level of vertical frequency and all levels of vertical amplitude were presented with that before going on to another level of vertical frequency. To the extent possible, the order of presentation of levels of amplitude was counterbalanced.

Procedure. The rating scale and procedure used were the same as in Experiment I, except that the anchor stimuli and one-minute rest were given after each eight trials rather than after each ten trials.

Results and Discussion

The results of the analysis of variance of the ratings of discomfort, excluding the control conditions, are shown in Table 3. All four main effects (vertical frequency, vertical amplitude, lateral frequency, and lateral amplitude) were significant, as were all six of the simple interactions between these four parameters of vibration. Two of the triple interactions were significant, as was the four-way interaction.

Figures 4 to 7 show the mean ratings of the subjects as a function of each of the parameters of vibration plotted with data from the appropriate conditions exposed to vibration in only one axis. These figures were obtained by averaging across all the remaining experimental conditions not shown in each figure. Figure 4 shows that, among the ratings of the four levels of vertical frequency studied, 5 Hz was rated as highest in discomfort while there was little difference among the other three levels. Also, it is apparent that simultaneous exposure to vibration in two axes was rated higher in discomfort at all frequencies than vibration in the vertical axis alone. Figure 5 shows a different relationship exists between lateral frequency and ratings of discomfort. Here the highest ratings were given the lowest frequency, 2 Hz, with ratings of the other frequencies decreasing as the frequency of lateral vibration was increased. Again, ratings for the control condition exposed to vibration only in the lateral axis were less than those for combined axis vibration at all frequency levels. The results shown in Figures 4 and 5 replicate the main effects found in Experiment I as well as the findings of a number of previous studies. Figures 6 and 7 show that the effect of increasing amplitude in either axis is to increase ratings of discomfort, another expected finding. However, it is apparent that difference in ratings between the combined axis and control conditions are limited to low amplitude levels with differences between the two conditions diminished as amplitude was increased to 0.25 g (peak). This effect was not expected.

Figures 8 to 13 show the form of the simple interactions between the six pairs of vibration parameters. In each of the figures, the discomfort ratings were averaged across both of the vibration parameters not shown in each figure, thus revealing the form of the interaction between the two variables that are shown. The interaction shown in Figure 8, between vertical frequency and lateral frequency, is a replication of the interaction found in Experiment I, and shown in Figure 1. The results of both experiments show there is less variation in ratings of the various levels of lateral frequency when they are combined with a vertical frequency of 5 Hz than when they are combined with other frequencies of lateral vibration. Also, there is less variation in ratings of the various levels of vertical frequency when they are combined with 2 Hz lateral vibrations than when they are combined with the other levels of lateral vibration.

Figure 9 shows the interaction between the effects of the vertical amplitude and the lateral amplitude. It appears that the form of this interaction is terminative, since high amplitudes in either axis tend to mask the effects of variation in amplitude in the other axis.

The interactions between frequency and amplitude within each axis are shown in Figure 10 for the vertical axis and Figure 8 for the lateral axis. In both figures the effect of variation in amplitude is greatest at those frequencies rated as being of most discomfort while amplitude variation had less effect at frequencies rated as being of less discomfort.

The interactions between frequency in one axis and amplitude in the other are shown in Figures 12 and 13. First, the interaction between vertical frequency and lateral amplitude is shown in Figure 12; the other interaction, between lateral frequency and vertical amplitude, is shown in Figure 13. In contrast to the form of the interaction shown in Figures 10 and 11, these interactions are in the opposite direction, with amplitude variation of the same axis having the greatest effect at frequencies rated as being of least discomfort. Perhaps a more appropriate conclusion, however, is that at frequencies rated as producing the most discomfort, there is some masking of amplitude effects from the other axes while the effects of amplitude from the same axis are enhanced.

Regarding the simple interactions, note should be taken that the three smallest interactions as reflected by the statistical values were found for interactions involving vertical frequency, suggesting that perhaps interaction with vertical frequency is the least important among those found. Regarding the other interactions, no pattern is apparent beyond that obvious from Table 3. Although two three-way and a four-way interaction were found to be significant, no explanations of these are readily apparent.

To summarize the results of Experiment II, it appears that the four major parameters of vibration not only affect ratings of discomfort, but they also interact with each other in their effects. Interaction between frequencies in the two axes and between amplitudes in the two axes was expected, as was, to some extent, the interaction between frequency and amplitude within one axis. However, the interaction between frequency in one axis and amplitude in the other was not expected. Also unexpected was the finding that the control conditions receiving vibration in but one axis were rated as high in discomfort as were the same amplitudes of vibration when accompanied by added vibration in the other axis. It appears that the combination of vibration inputs in separate axes has the greatest combined effect at relatively low levels of stimulation, whereas high levels of stimulation in one axis are relatively unaffected by additional input from another axis. If this is generally true for the various combinations of axes of vibration, the I. S. O. recommendation regarding the limits for exposure of humans to vibration in combined axes may be the most appropriate one.

Taken together, the results of these two experiments strongly suggest that there are effects on discomfort that occur when subjects are vibrated in several axes at once that cannot be assessed with research using vibration in only one axis. Although the interactions between the four parameters of vibration used in these experiments may be of less importance in accounting for discomfort than are the main effects of these four major parameters, an understanding of these interactions may very well affect the precision with which standards can be set to govern the acceptable limits for exposure of humans to vibration. In conclusion, these results also suggest the wisdom of further research on the effects of vibration in combined axes directed toward appropriate revision of the standard established by I. S. O. regarding vibrations occurring in more than one axis simultaneously.

References

Clevenson, S. A., and Leatherwood, J. D. On the Development of Passenger Ride Acceptance Criteria. Proceedings of the 43rd Shock and Vibration Symposium, December 1972, Pacific Grove, California.

Guide for the Evaluation of Human Exposure to Whole-Body Vibration. Draft Int. Stand. ISO/DIS 2631, Int. Organ. Stand., 1972.

Holloway, Richard B., and Brumaghim, Stanley H. Tests and Analyses Applicable to Passenger Ride Quality of Large Transport Aircraft. Symposium on Vehicle Ride Quality, NASA TM X-2670, 1972, pp. 91-113.

Jacklin, H. M., and Liddell, G. J. Ride Comfort Analysis. Research Bulletin No. 44, Engineering Experiment Station, Purdue University, 1933.

Stephens, D.G., and Clevenson, S.A. The Measurement and Simulation of Vibration for Passenger Ride Quality Studies. Proceedings of National Noise and Vibration Control Conference and Exhibition, September 1973, Chicago, Illinois.

Winer, B. J. Statistical Principles in Experimental Design. McGraw-Hill Book Company, Inc., New York: 1971.

Table 1

Three-Way Analysis of Variance with
Repeated Measures on Two Variables.

Source of Variation	Sum of Squares	df	Mean Square	F	P
Sessions(Se)	321.69	3	107.23	2.50	N.S.
Vertical Hz(V)	1751.37	9	194.60	50.71	.01
Lateral Hz(L)	5680.88	9	631.21	327.56	.01
Se x subj. w. gr.	858.31	20	42.92		
Se x V	200.27	27	7.42	1.93	.01
Se x L	146.89	27	5.44	2.82	
V x L	722.35	81	8.92	8.33	.01
V x subj. w. gr.	690.80	180	3.84		
L x subj. w. gr.	346.86	180	1.93		
Se x V x L	551.64	243	2.27	2.12	.01
V x L x subj. w. gr.	1734.26	1620	1.07		

Table 2

Summary of Variables Involved in the Multiple Regression Analysis of Combined Axis Experiment I.

Variable Symbol	Description of Variable
SR	Subjective Rating
V_1	Lateral Frequency
V_2	Vertical Frequency
V_3	$\text{Log}_{10} V_1$
V_4	$\text{Log}_{10} V_2$
V_5	$\sqrt{V_1}$
V_6	$\sqrt{V_2}$
V_7	$V_1{}^2$
V_8	$V_2{}^2$
V_9	$\sqrt{V_7 + V_8}$
V_{10}	$V_1 \times V_2$
V_{11}	$\sqrt{V_{10}}$
V_{12}	$1/V_1$
V_{13}	$1/V_2$

Table 3

Four-Way Analysis of Variance with Repeated Measures on Three Variables.

Source of Variation	Sum of Squares	df	Mean Square	F	P
Vertical Hz (VF)	951.56	3	317.19	13.39	.01
Lateral Hz (LF)	1178.82	3	392.94	105.73	.01
Vertical Amplitude (VA)	1851.90	3	617.30	273.32	.01
Lateral Amplitude (LA)	2160.80	3	720.21	260.80	.01
Subject w. VF (S w VF)	1042.38	44	23.69		
VF x LA	103.33	9	11.48	3.09	.01
VF x VA	173.37	9	19.26	8.53	.01
LF x VA	222.99	9	24.78	18.73	.01
VF x LA	103.65	9	11.52	4.17	.01
LF x LA	469.01	9	52.11	58.59	.01
VA x LA	249.03	9	27.67	39.92	.01
LF x S w VF	490.58	132	3.72		
VA x S w VF	298.13	132	2.26		
LA x S w VF	364.52	132	2.76		
VF x LF x VA	39.26	27	1.45	1.10	N.S.
VF x LF x LA	42.75	27	1.58	1.78	.05
VF x VA x LA	15.67	27	.58	0.84	N.S.
LF x VA x LA	65.04	27	2.41	4.30	.01
LF x VA x S w VF	523.86	396	1.32		
LF x LA x S w VF	352.22	396	.89		
VA x LA x S w VF	274.48	396	.69		
VF x LF x VA x LA	80.21	81	.99	1.77	.01
LF x VA x LA x S w VF	665.45	1188	.56		

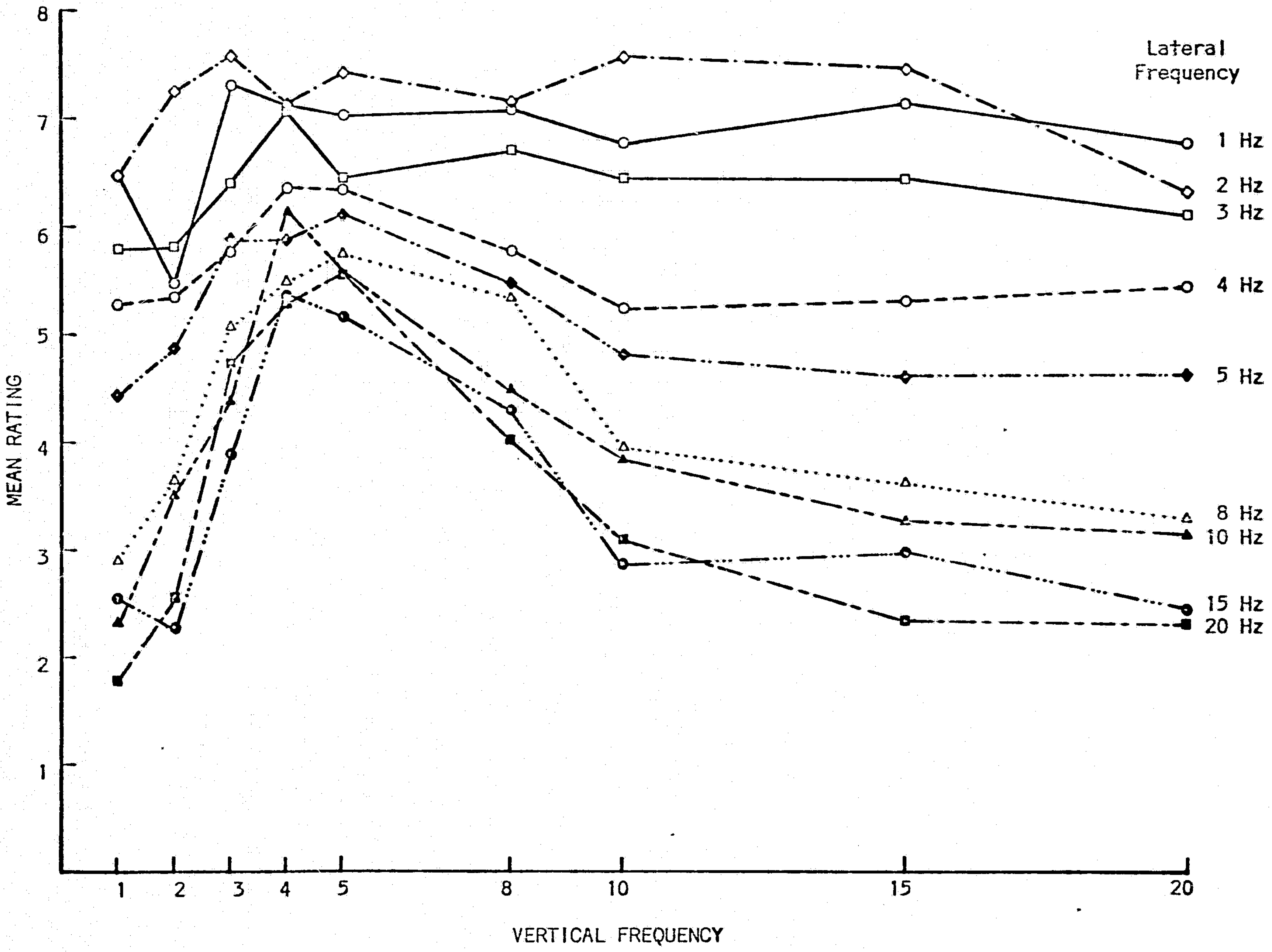

Figure 1. Mean rating as a function of vertical frequency with lateral frequency as a parameter.

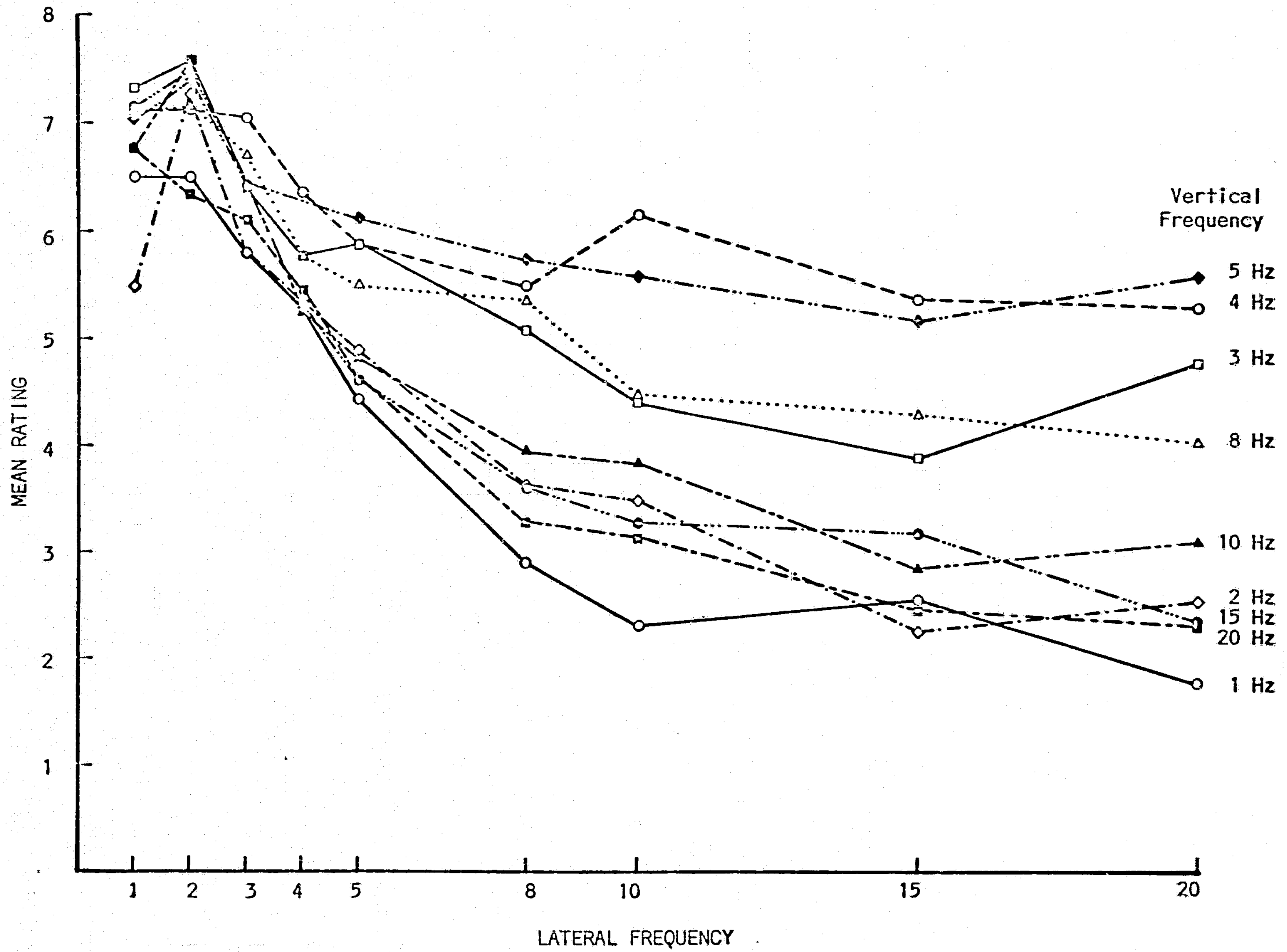

Figure 2. Mean rating as a function of lateral frequency with vertical frequency as a parameter.

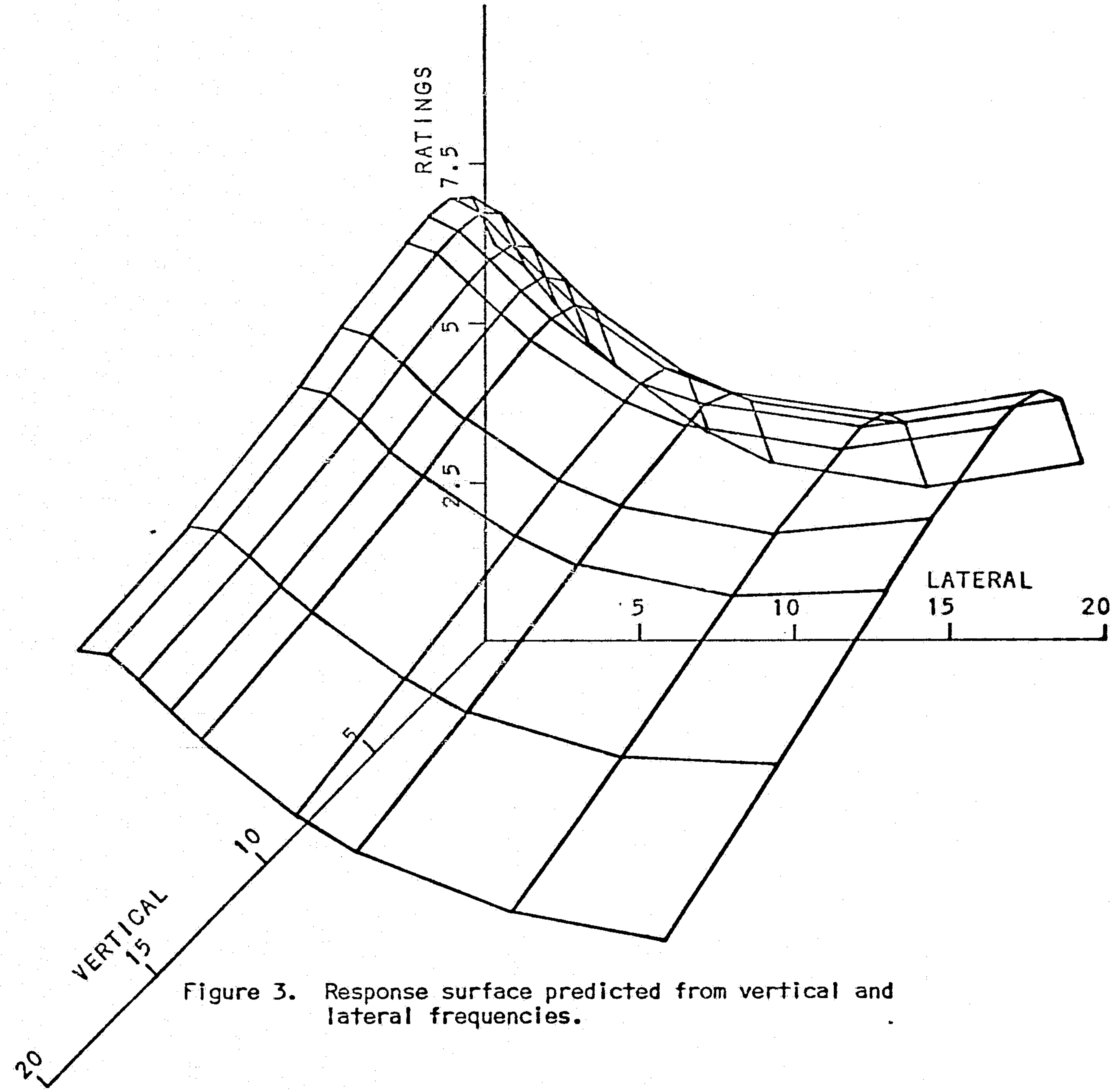

Figure 3. Response surface predicted from vertical and lateral frequencies.

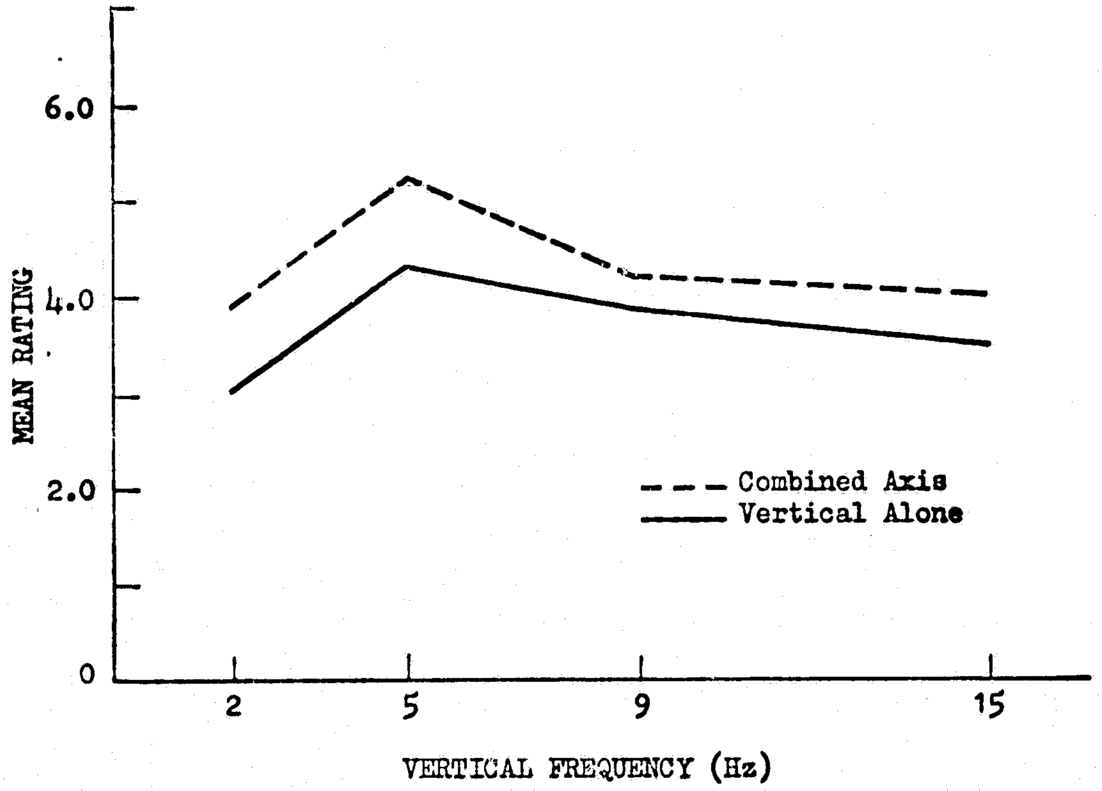

Figure 4. Subjective rating as a function of vertical frequency of combined axis vibration compared to the vertical alone control condition

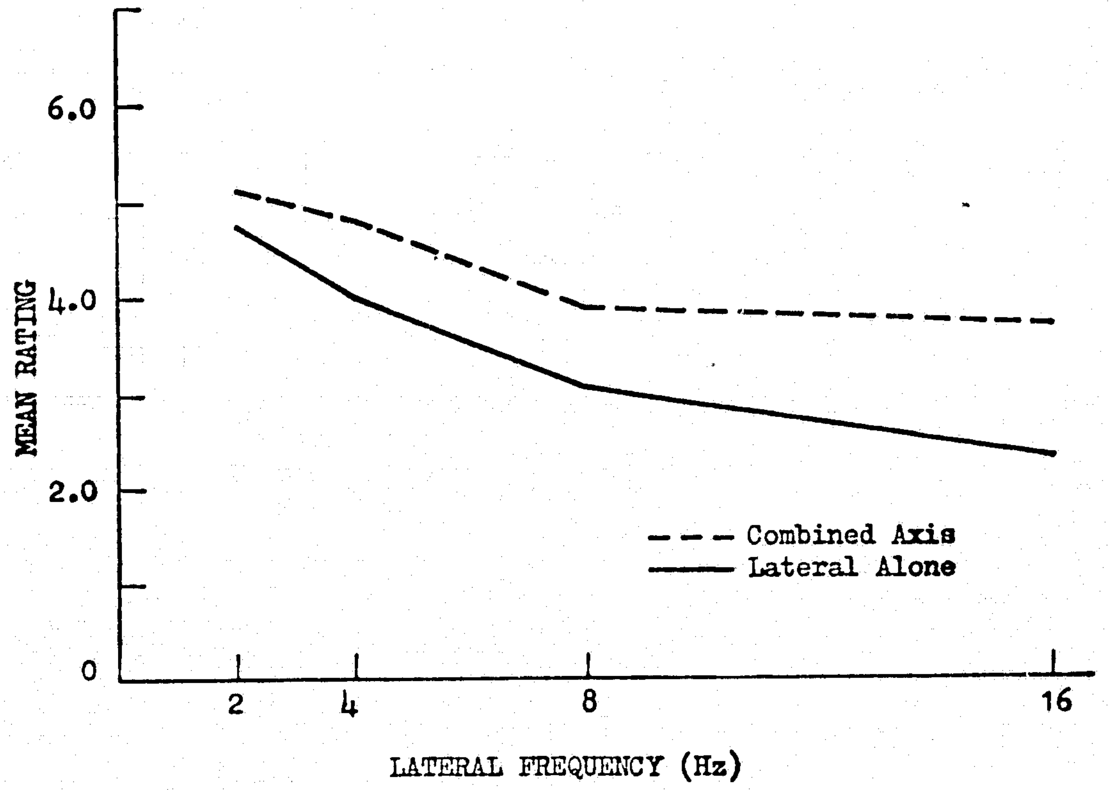

Figure 5. Subjective rating as a function of lateral frequency of combined axis vibration compared to the lateral alone control condition

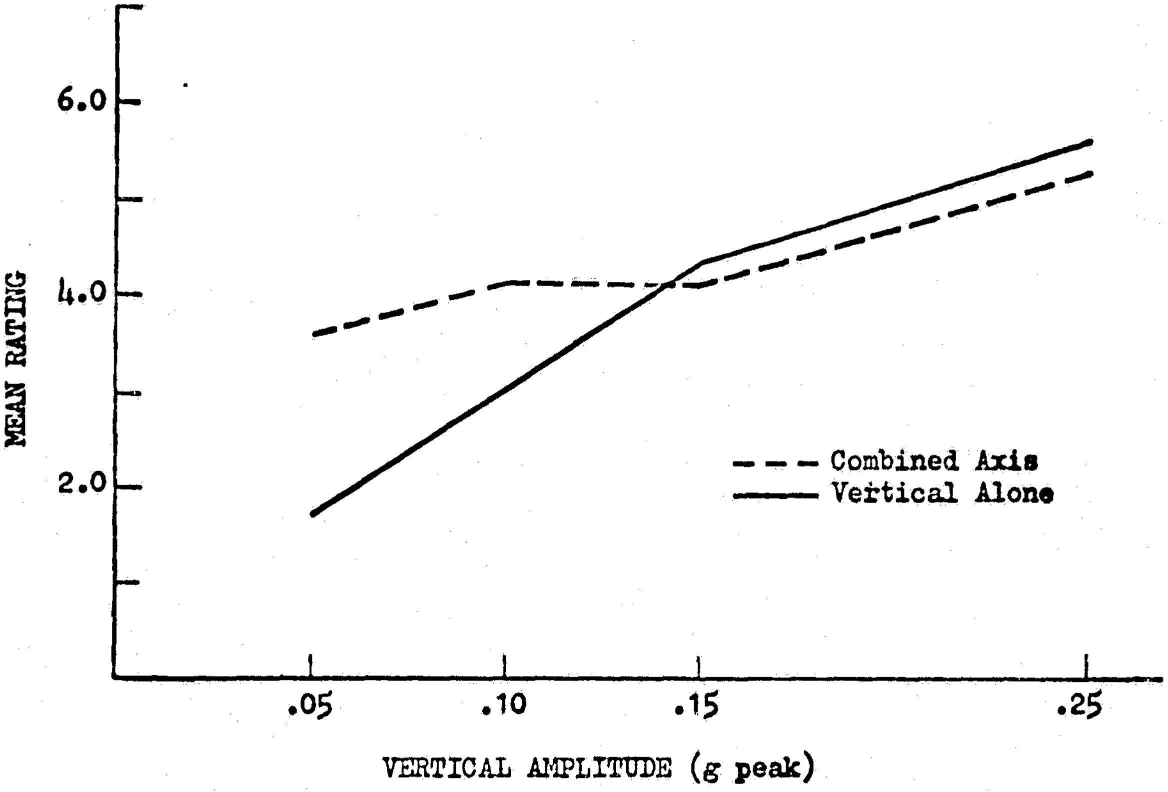

Figure 6. Subjective rating as a function of vertical amplitude of combined axis vibration compared to the vertical alone control condition

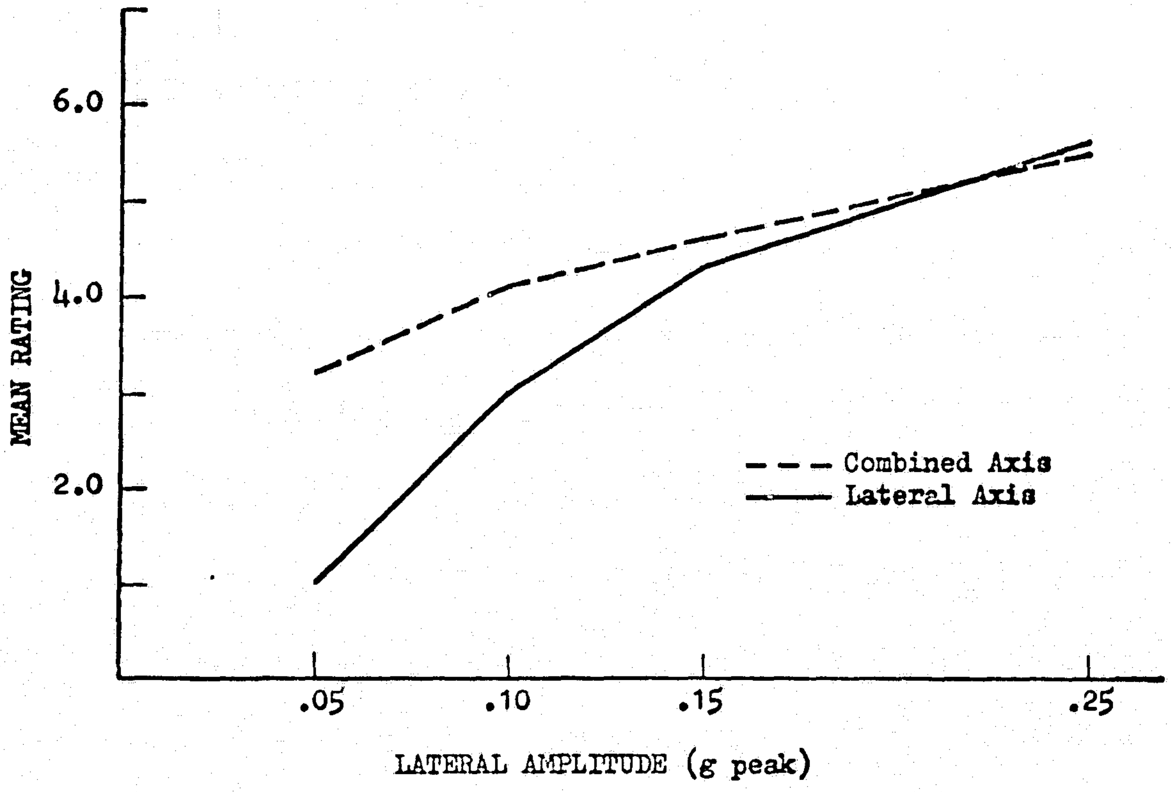

Figure 7. Subjective rating as a function of lateral amplitude of combined axis vibration compared to the lateral alone control condition

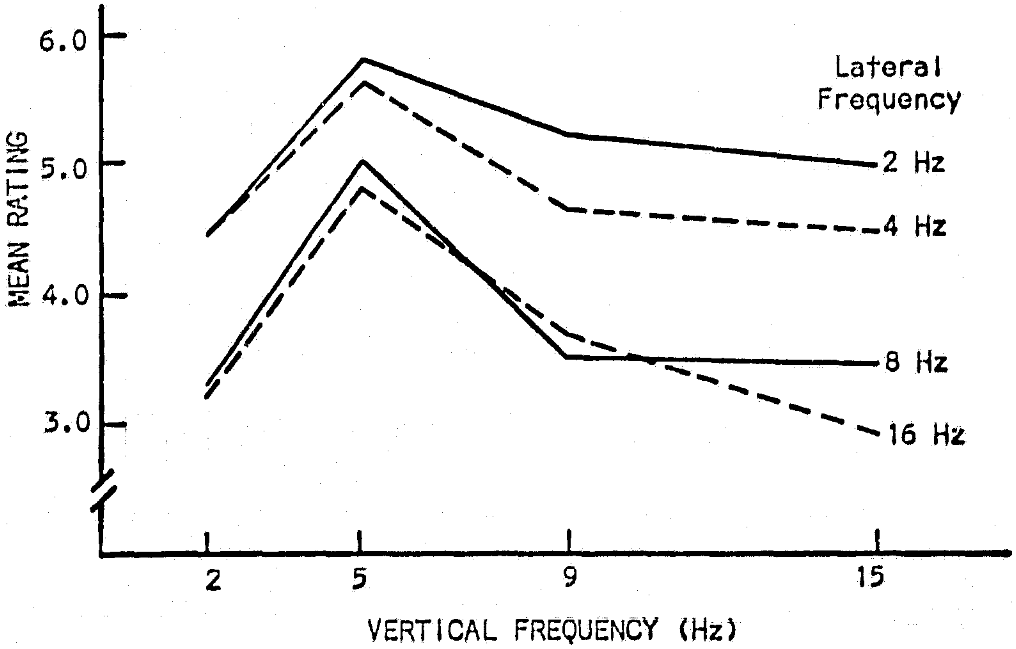

Figure 8. Subjective rating as a function of the interaction between vertical frequency and lateral frequency

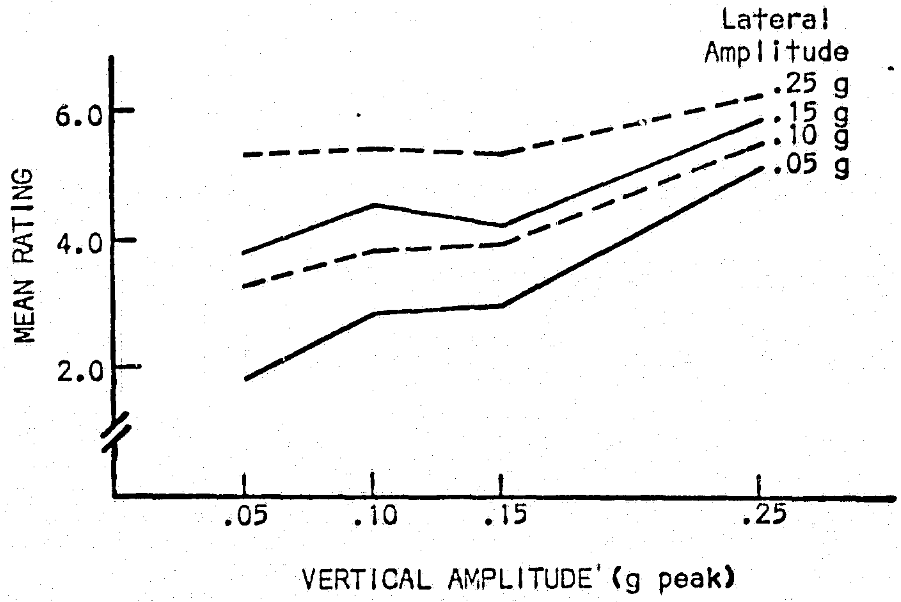

Figure 9. Subjective rating as a function of the interaction between vertical amplitude and lateral amplitude

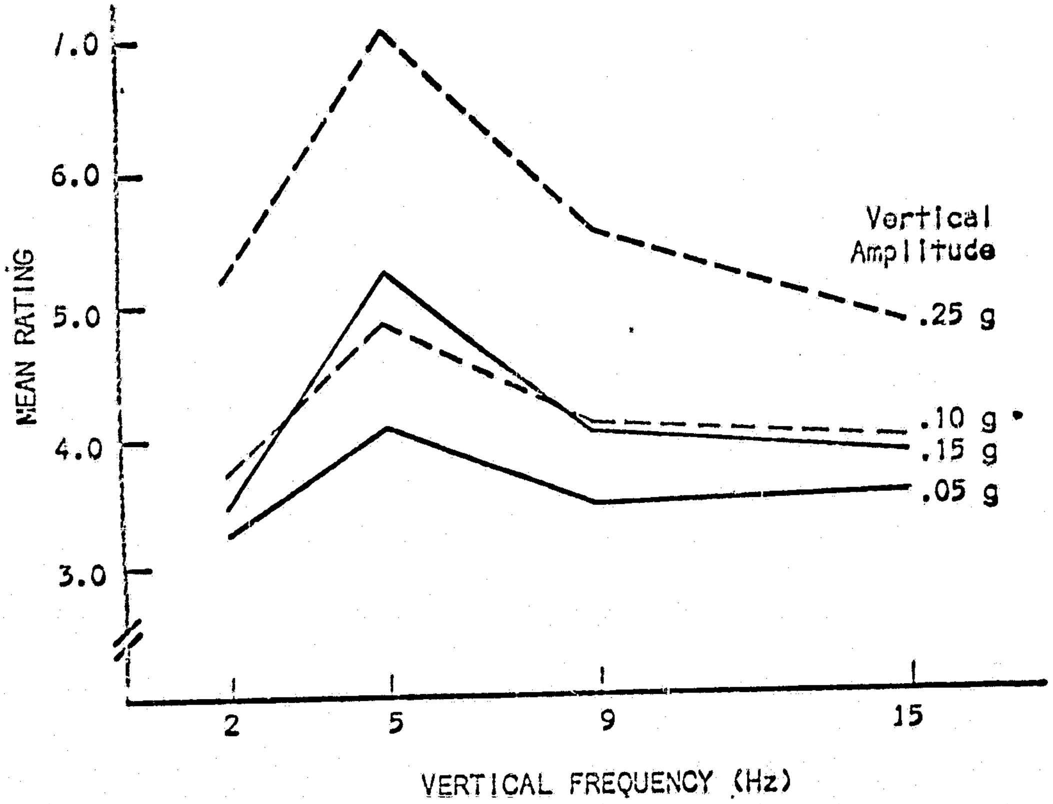

Figure 10. Subjective rating as a function of the interaction between vertical frequency and vertical amplitude

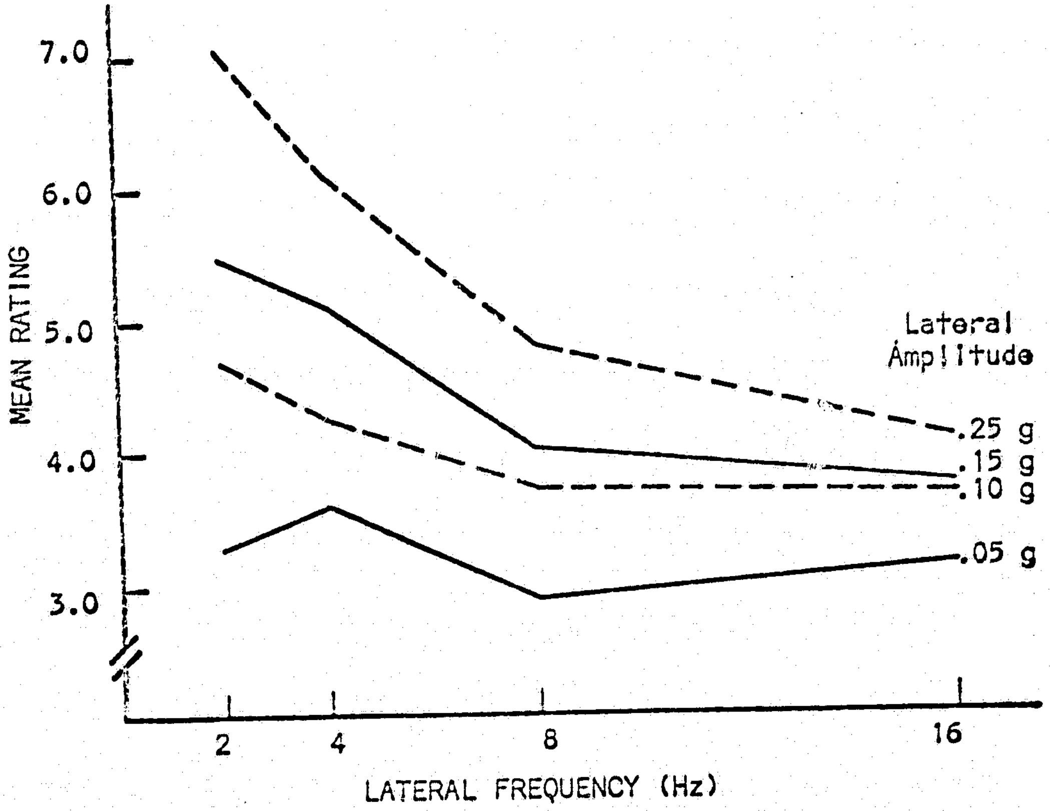

Figure 11. Subjective rating as a function of the interaction between lateral frequency and lateral amplitude

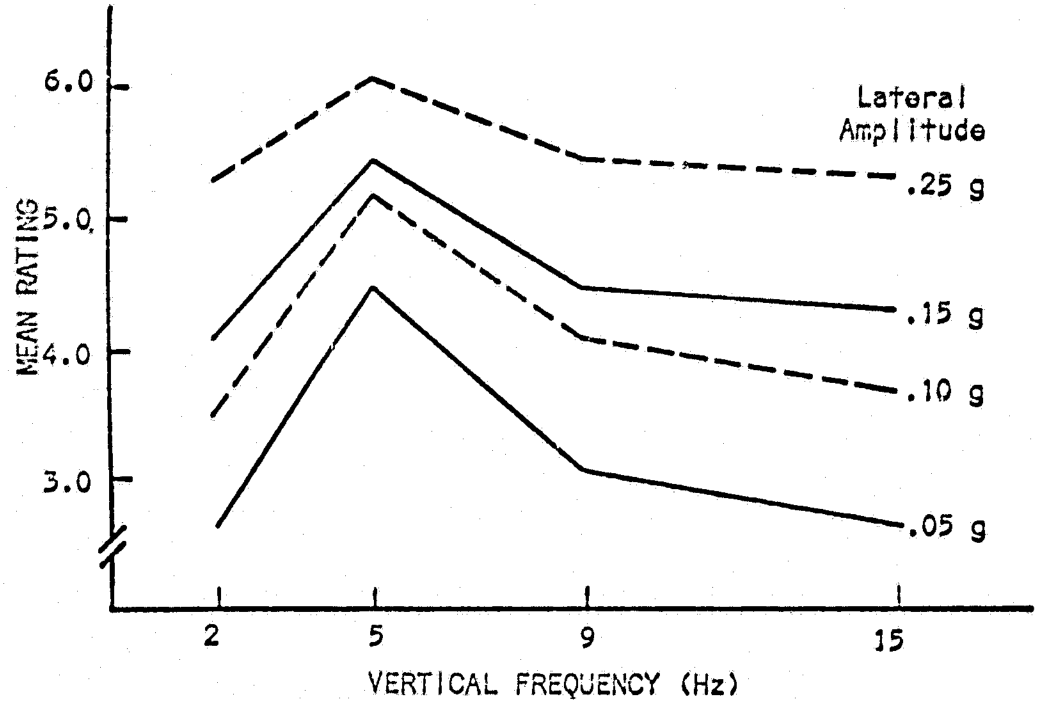

Figure 12. Subjective rating as a function of the interaction between vertical frequency and lateral amplitude

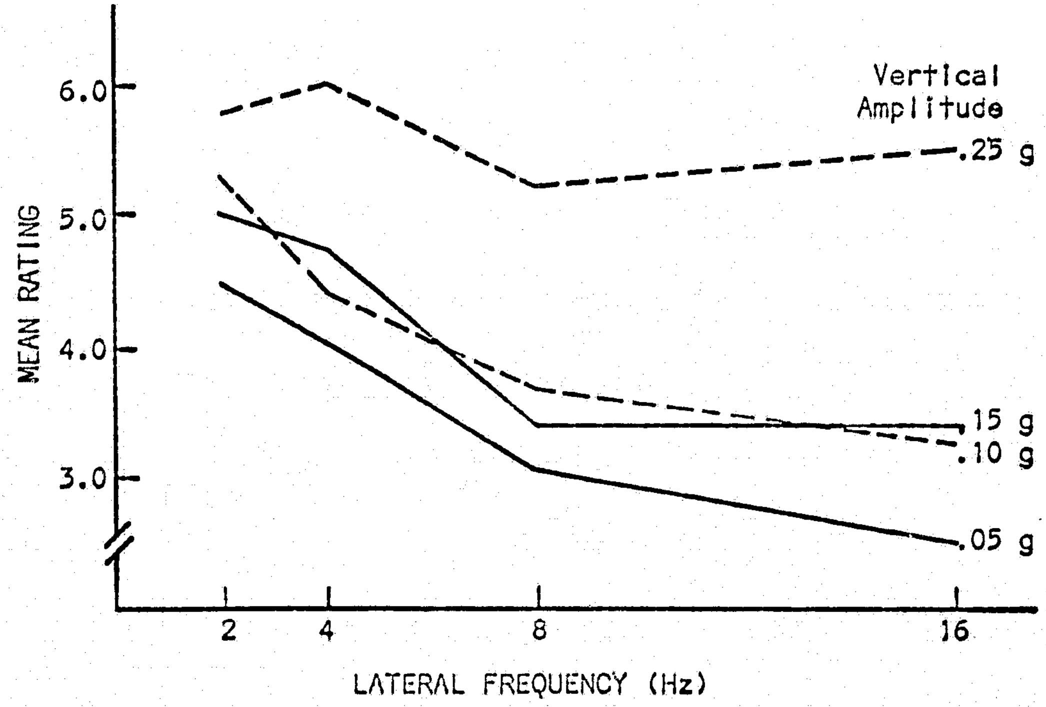

Figure 13. Subjective rating as a function of the interaction between lateral frequency and vertical amplitude

Effects of Simultaneous Exposure to Whole-Body, Vertical Vibration and Noise on Subjective Evaluation of Ride Quality

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Following the pioneering work of Jacklin and Liddell (1933), there has been an extensive amount of laboratory and field research on the effects of various types of vibration and various conditions of noise on ride quality (see reviews of Guignard and King, 1972 and Jacobson, 1972). While most of this research has been conducted with relatively simple stimuli (e.g., vibration in only one axis) there is a growing literature concerned with more complex stimulus situations (e.g., vibration in combined axes and combinations of vibration and noise; see Holloway and Brumaghim, 1972; Kirby, Coates, Mikulka, Dempsey, and Leatherwood, 1975). However, very few of the previous studies have investigated the combined effects of vibration and noise, and apparently none has been concerned with the interactive effect of these variables on the subjective evaluation of ride quality or discomfort. Arkad'yevskiy (1962) studied the physiological effects of separate and combined exposure to an 85 db noise and/or a 50 Hz vertical vibration and found some changes in ECG, reaction time and temporary auditory threshold shifts attributable to the combination of noise and vibration, both as main effects and in interaction. Other studies have shown that with performance tasks such as tracking and counting there is a performance decrement when noise is added to vibration (Ioseliana, 1967; Harris and Shoenberger, 1972). However, the extent to which noise and vibration stimuli interact in their effects on ride quality is not known.

In their study of the interaction of vibration simultaneous in the vertical and lateral axes, Kirby, et al. (1975) found that those levels of frequency and amplitude which were rated as least discomfortable in one axis, were most affected by vibration input from the other axis. To the extent that these results can be generalized to the study of simultaneous presentations of noise and vibration, frequencies and amplitudes of vibration rated as least discomfortable will be most affected by simultaneously presented noise stimuli.

The study herein reported was concerned with the effects of simultaneous exposure to sinusoidal vertical vibration and broad-band noise on ride quality as measured by subjective ratings of discomfort.

Method

Subjects. The subjects for this research were twelve female volunteers from the subject-pool of a private agency under contract to the NASA-Langley Research Center. They ranged in age from 23 to 51 years, with a median age of 31.4 years. They were medically screened prior to being approved for participation in the study. Audiograms were taken several days before the experiment to insure that all had relatively normal hearing at the beginning of the study; post-exposure audiograms were taken at the end of testing.

Apparatus. The apparatus used in this experiment was the Passenger Ride Quality Apparatus (PRQA) located at NASA-Langley Research Center. This apparatus, designed to represent the interior passenger section of a typical aircraft, can present subjects with whole-body vibration of various frequencies, amplitudes, and wave forms in either the vertical, lateral (side-to-side), or roll axes. For this experiment the PRQA was equipped with 6, tourist class seats. For additional details concerning PRQA see Clevenson and Leatherwood (1972) and Stephens and Clevenson (1973).

Design. The experimental design used was a 2 x 3 x 4 x 3 factorial design with repeated measures. Factorialy crossed were two levels of noise (85 dbA and 60 dbA), three levels of amplitude of vertical vibration (0.05 g, 0.15 g, and 0.25 g (peak)), four levels of frequency of vertical vibration (2, 5, 9, and 15 Hz) and three replications of each possible stimulus.

Rating scale. The rating scale employed was a nine-point, unipolar scale. For each stimulus the subject was provided with a separate scale consisting of a line with nine divisions, numbered from "0" to "8". Above the "0" was the anchor "Comfortable or zero discomfort" and above the "8" was "Maximum discomfort." The subjects were instructed to use the scale as an equal-interval scale and to rate the discomfort produced by the stimuli by responding between the numbered divisions as well as on them. An anchor stimulus consisting of a vertical vibration of 5 Hz at 0.15 g (peak) in combination with the 85 dbA noise was presented as having most discomfort and another anchor stimulus 15 Hz at 0.05 g (peak) with the 60 dbA noise was presented as a stimulus having the least discomfort.

Procedure. The subjects were exposed to the experimental conditions in groups of six. A standard set of task instructions were read aloud to each group of subjects. The subjects were informed generally about the composition of the ride stimulus (noise combined with vibration) and directed to use both modalities in determining discomfort ratings, but no attempt was made either to emphasize the noise or to tell the subjects that each vibration would be presented with and without noise. The subjects were then instructed how to use the rating scale. Specific directions were given to evaluate the discomfort of each ride segment in reference to two anchor segments presented prior to each group of eight ride segments, and not in comparison to the other test rides.

Subjects were then seated in the cabin with seatbelts fastened and both feet flat on the floor. A red light in the front of the cabin was turned on and off to signal the beginning and end of ride segments. Each ride segment stimulus was presented for a total of 20 seconds, with an onset of 5 seconds, 10 seconds (peak), and offset of 5 seconds. Interstimulus intervals were approximately 10 seconds to allow time for the subjects to record their ratings.

The testing of each group of six subjects was divided into sessions of eight stimulus presentations with a one-minute interval between sessions. At the beginning of each session the two anchor stimuli were presented.

The eight stimuli in each session were of the same vibration amplitude with order of presentation of the various amplitudes counterbalanced across sessions. Within each session each frequency of vertical vibration was presented twice, once with the 85 dbA noise and once with the 60 dbA noise. The order of presentation of the various frequencies of vibration and of noise levels was randomized. In all, there were nine sessions so that each of the twenty-four possible stimuli was presented three times to each subject, requiring approximately 55 minutes of testing. At the end of testing the subjects were debriefed and post audiograms were taken.

Results and Discussion

The results of the analysis of variance performed on the data are shown in Table 1. The main effects of vibration frequency, vibration amplitude, and noise level were all significant while the replications variable was not. Although there were several significant single interactions involving the replications variable, the only one involving the other three variables and not replications, was between vibration amplitude and noise level. Vibration frequency did not interact with either vibration amplitude or noise level. It should be noted that Kirby et al. found an interaction between frequency of vertical vibration and amplitude of vertical vibration.

The major results of the study are shown in Figure 1. In that figure vibration frequency is represented along the abscissa and mean subjective rating along the ordinate with the various combinations of vibration amplitude and noise-level represented by the different curves. The relationship found between vibration frequency and subjective rating replicates the results of many other researchers. Also, the increased ratings of discomfort with increasing vibration amplitude replicates previous results. It appears that noise level has its major effect when subjects are exposed to low levels of vibration amplitude. This can be better seen in Figure 2 in which ratings are averaged across the various levels of vibration frequency. Here it is apparent that the effect of noise level diminished as the amplitude of vibration was increased.

Although the replications variable significantly interacted with the main experimental variables, and with the interactions between these main variables, these results do not affect the main conclusions that can be drawn from the data, and therefore the effects due to the replications variable are not of major interest. These effects appear to be due to subjects habituating to the vibration somewhat and possibly also to incompleteness in counterbalancing due to the use of randomized order of stimulus presentation.

The main findings drawn from the data are consistent with those of Kirby et al. (1975) with respect to the influence of amplitude variable but not with respect to frequency of vibration. As in the present study, at amplitudes rated as most discomfortable, the addition of vibration in another axis has less effect on discomfort than at lower levels of amplitude.

There are two alternative explanations of the findings of the present study, and of Kirby et al., that appear obvious. First, the pattern of the results could be due to the type of rating scale used. It could be that the use of a scale with an upper limit on the ratings the subjects could give prevented the subjects from differentially rating intense vibration stimuli from only one source as opposed to those accompanied by stimulation from another source. Second, it could be that combined sources of stimulations to an extent have additive effects at low levels of stimulation but that this additivity decreases as the level of stimulation is increased. Such a result has important implications for research directed toward setting limits for the exposure of subjects to vibration or to the combination of noise and vibration.

Table 1

Four-Way Analysis of Variance with Repeated Measures.

Source of Variation	Sum of Squares	df	Mean Square	F	P
Frequency (F)	1285.45	3	428.48	89.01	.001
Amplitude (A)	2194.08	2	1097.04	151.63	.001
Noise (N)	11.35	1	11.35	8.97	.05
Replication (R)	5.96	2	2.98	0.73	
S x F	158.85	33	4.81		
S x A	159.17	22	7.23		
S x N	13.93	11	1.27		
S x R	89.57	22	4.07		
F x A	16.08	6	2.68	1.55	
F x N	4.87	3	1.62	2.12	N.S.
F x R	2.91	6	0.48	0.39	
A x N	16.14	2	8.07	8.08	.001
A x R	9.29	4	2.32	0.87	
N x R	10.58	2	5.29	5.76	.001
S x F x A	114.09	66	1.73		
S x F x N	25.23	33	0.76		
S x F x R	81.42	66	1.23		
S x A x N	21.98	22	1.00		
S x A x R	117.30	44	2.66		
S x N x R	20.19	22	0.92		
F x A x N	14.60	6	2.43	2.36	.05
F x A x R	92.80	12	7.73	7.36	.001
F x N x R	18.12	6	3.01	5.81	.001
A x N x R	9.43	4	2.36	3.57	.05
S x F x A x N	68.10	66	1.03		
S x F x A x R	138.66	132	1.05		
S x F x N x R	34.29	66	0.52		
S x A x N x R	29.08	44	0.66		
F x A x N x R	34.01	12	2.83	4.03	.001
S x F x A x N x R	92.74	132	0.70		

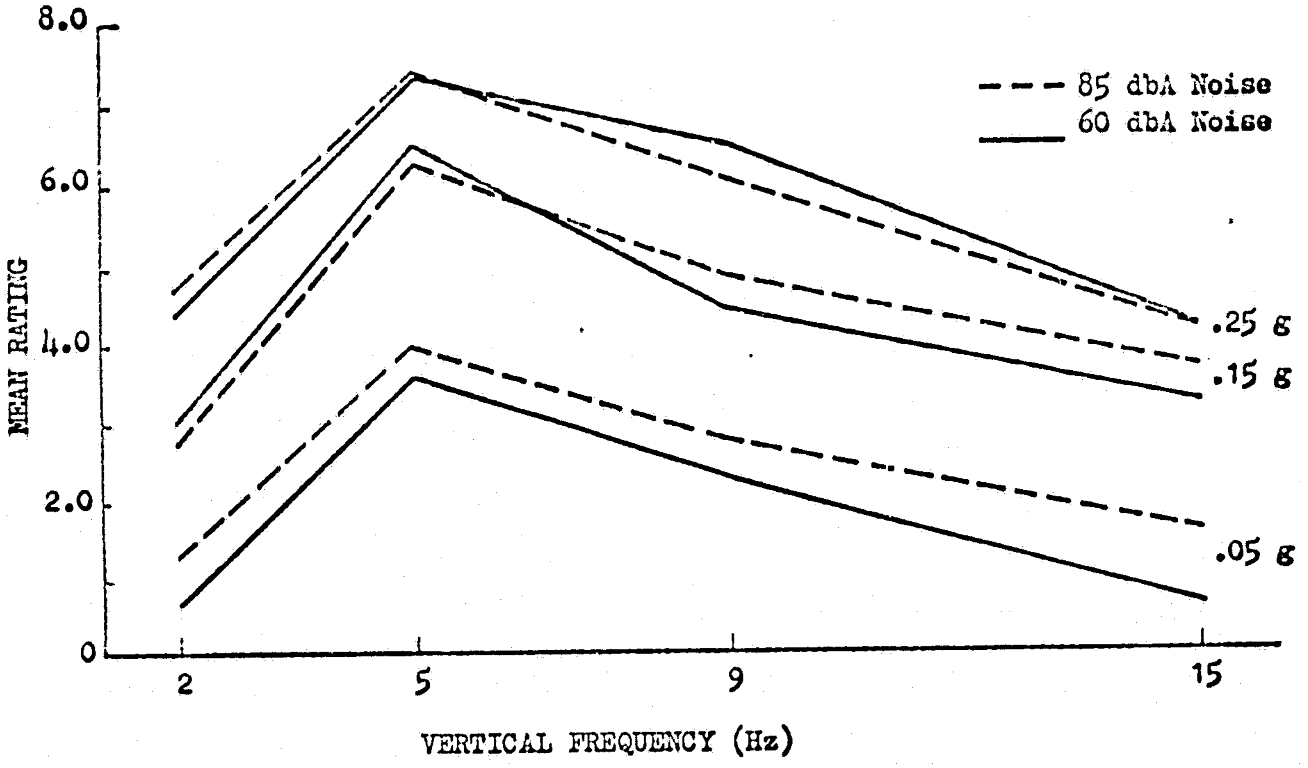

Figure 1. Subjective rating as a function of Vertical frequency, vertical amplitude and noise level

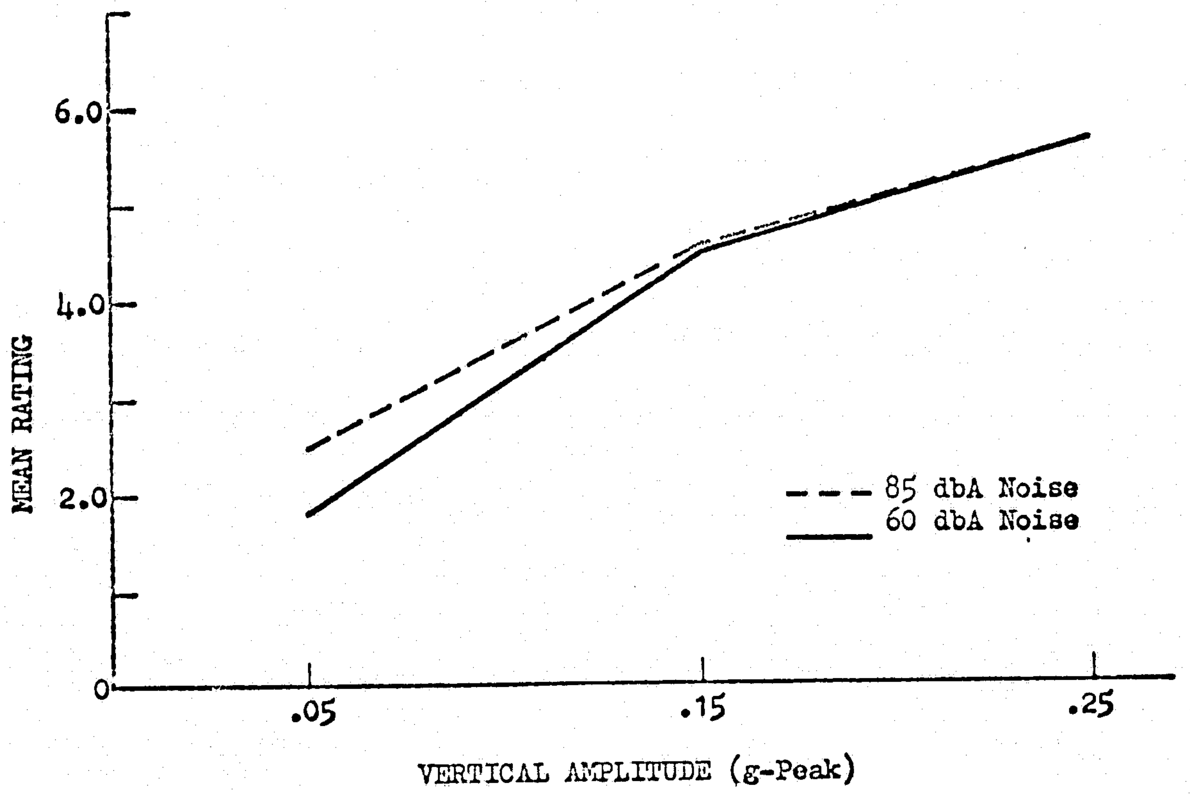

Figure 2. Subjective rating as a function of the interaction between vertical amplitude and noise level

References

Arkad'yevskiy, A. A.: Combined Effect of Vibration and Noise on the Human Organism. (63-292/1-2). Wright-Patterson Air Force Base, Ohio: Foreign Technology Division (trans), (1963). (NTIS No. AD-415 672).

Clevenson, S. A. and J. D. Leatherwood: On the Development of Passenger Ride Acceptance Criteria. Shock and Vibration Bulletin. 43:105, (1973).

Guignard, J. C. and P. F. King: Aeromedical Aspects of Vibration and Noise. AGARD-AG-151, (1972).

Harris, C. S. and R. W. Shoenberger: Combined Effects of Noise and Vibration on Psychomotor Performance. USAF Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio: Technical Report AMRL-TR-70-14, (1972).

Holloway, R. B. and S. H. Brumaghim: Tests and Analyses Applicable to Passenger Ride Quality of Large Transportation Aircraft. Symposium on Vehicle Ride Quality, NASA TM-X-2670, pp. 91-113, (1972).

Ioseliana, K. K.: Effect of Vibration and Noise and Ability to Do Mental Work Under Conditions of Time Shortage. Environmental Space Sciences. 1:144, (1967).

Jacklin, H. M. and G. J. Liddell: Ride Comfort Analysis. Research Bulletin Number 44, Engineering Experiment Station, (1933).

Jacobson, I. D.: Criteria for Ride Quality Motion. STOL Memorandum Report 40302, University of Virginia, CASEPA, Transportation Division, February, (1972).

Kirby, R. H., Coates, G. D., Mikulka, P. J., Dempsey, T. K., and Leatherwood, J. D. Effect of Vibration in Combined Axes on Subjective Evaluation of Ride Quality. 1975 Ride Quality Symposium, NASA TM X-3295, 1975, 355-371.

Stephens, D. G. and S. A. Clevenson: The Measurement and Simulation of Vibration for Passenger Ride Quality Studies. Proceedings of the Technical Program, NOISEXPO - National Noise and Vibration Control Conference, pp. 86-92, (1974).