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PSYCHOPHYSICAL RELATIONSHIPS CHARACTERIZING HUMAN RESPONSE TO WHOLE-BODY SINUSOIDAL VERTICAL VIBRATION

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16. Abstract

An experimental investigation determined that the psychophysical relationships between subjective discomfort evaluations to vibratory stimuli and subjective evaluations of the intensity of vibratory stimuli can be expressed in a linear fashion. Furthermore, significant differences were found to exist between discomfort and intensity subjective responses for several but not all the discrete frequencies investigated. The implication of these results is that ride quality criteria based upon subjective evaluation of vibration intensity should be applied cautiously in the development of criteria for human comfort.

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SUMMARY

An experimental study utilizing the Langley passenger ride quality apparatus (PRQA) was conducted in a systematic manner to determine (1) the psychophysical relationships governing human assessment of (a) the intensity (magnitude) and (b) the discomfort due to whole-body vertical sinusoidal vibration and (2) whether intensity and discomfort responses differ from one another.

Results indicated that both intensity and discomfort responses of human subjects can be described by a simple linear relationship. This result was demonstrated by the fact that for each of the candidate psychophysical relationships investigated (power, exponential, logarithmic, and linear), and for each sensation (discomfort or intensity), there existed a high degree of correlation between subjective responses and acceleration. However, there were no statistical differences between the correlations associated with the four psychophysical relationships for a particular sensation.

Results also indicated that three of the ten sinusoidal frequencies investigated gave statistically significant differences between subjective assessment of intensity and discomfort. Thus, assessments of vibration intensity are not generally interchangeable with assessments of vibration discomfort. Therefore, caution should be used when applying results based upon evaluations of vibration intensity to the development of ride comfort criteria. Finally, from the point of view of data reduction, it was shown that computation of the geometric mean of magnitude estimates offered no advantage over the use of the simpler arithmetic mean.

INTRODUCTION

Human response to whole-body vibration has been the subject of numerous investigations (for example, refs. 1 to 7) which have utilized a wide variety of experimental designs and techniques. An excellent review and summary of the literature are presented in reference 8, which points out the many differences and contradictions prevalent in the results obtained from the various investigations. For example, many "criteria" or "constant comfort" curves have been proposed (for example, refs. 9 to 30), and it is not unusual for the vibration levels associated with these sets of curves to differ by as much as an order of magnitude. Several reasons have been offered as explanation for this diversity of results. These reasons include such factors as poor experimental design, unrealistic laboratory environments, use of inadequate rating scales or adjectives, small subjective samples, and a lack of information (see ref. 31) regarding the nature of the relationship (for example, linear, power, logarithmic, exponential, etc.) between subjective ratings and the vibration stimuli. Notable exceptions are the work of Schoenburger and Harris (ref. 32) and Jones and Saunders (ref. 33). These investigations presented data to support the hypothesis that magnitude estimates of subjective intensity obey a power law (as has been discovered for many psychophysical relationships, for example, see ref. 34) with respect to the physical magnitude of the input vibration. The power law exponents obtained by these researchers ranged from 0.86 to 1.04 as a function of frequency. The question arises as to whether the data could have been represented equally well or better by other relationships such as linear, logarithmic, or exponential. The fluctuation of the exponents about a value of unity (corresponding to a linear law) suggests a strong hint of linearity which may have been hidden because of the data averaging process (for example, refs. 35 and 36) or one or more of the limiting factors already mentioned. Demonstration that human subjective response to whole-body vertical vibration could be represented by a linear relationship would greatly facilitate the development and application of ride quality criteria.

In addition to the question concerning the form of the psychophysical relationship between vibration and subjective estimates of discomfort or intensity, there is an equally important consideration which must be mentioned. This consideration involves the basic question as to whether subjective assessments of vibration intensity (magnitude) are equal to or synonymous with subjective assessments of discomfort. For example, Miwa (refs. 24 to 30) developed vertical equal sensation (intensity) curves using a paired comparison technique with a 20-Hz reference frequency. Direct applicability of Miwa's results to the development of discomfort criteria depends upon a determination as to whether the sensations of vibration intensity and discomfort can be used interchangeably.

The purpose of this paper is to explore in a systematic manner the questions posed in the preceding paragraphs. The specific objectives are to determine (1) the psychophysical laws governing both human intensity (magnitude) and human discomfort responses to vertical sinusoidal vibration; implicit in this objective is the assessment of the effect of frequency on the psychophysical relationships, and (2) whether subjective responses to vibration differ depending upon whether the subjects are asked to evaluate the intensity as opposed to the discomfort of a vibration. It should be noted that the terms "intensity" and "magnitude" are used interchangeably in this paper. A minor point of interest in this paper is a consideration of the relative merits of using a geometric mean of the subjective ratings as opposed to the use of the simpler arithmetic mean. This point is included since many researchers have used geometric mean reduction of data, the justification for doing so not being clear to the authors. Finally, this paper is restricted to human response to whole-body vertical sinusoidal vibration since it is the dominant axis of motion in most air transportation systems.

METHODS

Subjects

A total of 48 subjects participated in the study. The volunteer subjects were undergraduates from Old Dominion University and were paid for their participation in the study. The ages and weights of the subjects are listed in the following table. It should be noted that reference 37 indicated that subjective responses for a similar population sample were not significantly correlated with either sex or weight.

Subject		Age		Mass			
				Mean		Standard deviation	
Sex	Number	Median	Range	kg	lb	kg	lb
Males	13	21	18 to 45	72.0	158.7	10.4	23.0
Females	35	18	18 to 55	55.8	123.1	9.1	20.1
Total	48	18	18 to 55	60.2	132.7	11.8	26.1

Apparatus and Instrumentation

The apparatus used was the Langley passenger ride quality apparatus (PRQA). The PRQA is described briefly in this section and a detailed description can be obtained from references 38 and 39. Photographs of PRQA and associated programing and control instrumentation are displayed in figure 1. Figure 1(a) shows the waiting room where subjects are instructed as to their participation in the experiment, complete questionnaires, and so forth. Shown in figure 1(b) is a model of PRQA indicating the supports, actuators, and restraints of the three-axis drive system. A photograph of the exterior of the PRQA is shown in figure 1(c) and it should be noted that the actual mechanisms which drive the three-axis simulator are located beneath the pictured floor.

An interior view of PRQA with the subjects seated in first-class type aircraft seats (tourist-type aircraft seats were used in the present study) is presented in figure 1(d). The control console is shown in figure 1(e) and is located at the same level as the simulator to allow the console control operator to constantly monitor subjects within the simulator. Figure 1(f) is a photograph of tourist-type aircraft seats used in the present study. To mask the influence of extraneous noises produced by the equipment, music was played into the PRQA through the cabin speaker system and each subject was requested to use ear plugs. (See ref. 40.)

Subjective Evaluation Instrument

A particular subject was asked to provide evaluations of either the discomfort of a vibration or of the intensity of a vibration, but never both. The subjective evaluation of discomfort and intensity were obtained by the use of a magnitude estimation procedure. This procedure involves applying a standard stimulus to the subjects with a numerical value assigned to the standard. Comparison stimuli are then applied and the subjects are required to evaluate these comparison stimuli relative to the standard by assigning an appropriate numerical value. For this study the standard vibration ride was assigned the number 100. The subjects then gave numbers to succeeding rides to reflect how much greater or less the intensity or discomfort of the ride was as compared with the standard ride. For example, if the discomfort of a ride was felt to be twice the discomfort of the standard ride, the subjects would give the ride a value of 200. The subjects were instructed not to use zero or negative numbers in making their subjective evaluation. The instructions given to the subjects to read as the chief experimenter read them aloud to explain the magnitude estimation procedure for both the sensations of discomfort and intensity are given in appendixes A and B, respectively.

Procedure

A total of 24 subjects performed evaluations by using the discomfort instructions and 24 different subjects performed evaluations by using the intensity instructions. The task for each subject (six subjects concurrently) was to make subjective estimates of either the discomfort or the intensity of sinusoidal "target" ride segments. A "target" ride segment was defined as a vibration at a single vertical frequency (2, 5, 8, 11, 14, 17, 20, 23, 26, or 29 Hz) at one of nine floor peak acceleration levels, whereas the "standard" ride segment was of the corresponding frequency, but at a specified floor peak acceleration level. The actual acceleration levels used for each of the ten frequencies are presented in table I. This list does not represent the order in which the stimuli were applied. A pilot investigation was used to determine the peak floor acceleration levels for the standard and comparison rides of different frequencies. These acceleration levels were selected so that (1) the standard rides produced noticeable discomfort (comparison rides varied above and below this discomfort value), (2) the standard rides produced roughly similar amounts of discomfort (published literature on this topic does not allow selection of what would be considered stable estimates of the acceleration level required of various frequencies to produce constant discomfort), and (3) both the standard and comparison rides covered an acceleration level typically experienced in various transportation systems. However, it should be mentioned that comparison of subjective evaluations (for example, discomfort compared with intensity) was restricted to within rather than between frequencies of vibration due to the procedures required for selection of the standard and comparison rides. Each group of subjects received a "standard" ride segment prior to each of the three "target" ride segments for a total of 12 ride segments per session (9 target and 3 standard rides). Each group was exposed to a total of ten sessions, each session representing a randomization of the ten frequencies investigated. There were four different stimulus presentation orders, composed of four different frequency randomizations (also acceleration randomizations within a frequency or session) administered to a group of subjects receiving one set of evaluation instructions. The subjects receiving the other type of instructions received the same set of four presentation orders.

Each session lasted approximately 5 minutes, with a 1-minute rest period subsequent to each session. A 15-minute interval was provided after the fifth session marking the midpoint of the test.

The experimental design for session 1 is illustrated by the table that follows:

Ride	Session 1
1	Standard
2	Target
3	Target
4	Target
5	Standard
6	Target
7	Target
8	Target
9	Standard
10	Target
11	Target
12	Target

The pattern remained the same for all sessions but the standard and target vibration levels varied from session to session for a total of ten sessions. The time allocated for each ride consisted of 5 seconds onset, 10 seconds duration, and 5 seconds offset. Interstimulus interval was 5 seconds.

RESULTS AND DISCUSSION

The results and discussion section is divided into two sections corresponding to the two questions posed in the introduction. Specifically, the first section addresses the question of the form of the psychophysical relationship between discomfort and vibration, and intensity and vibration. The second section addresses the differences between these two psychophysical relationships.

Psychophysical Relationship

There are four major potential psychophysical formulations that have been selected to describe the relationship of discomfort to vibration or intensity to vibration. These psychophysical relationships include

(1) Power $\quad$ Rating = ax^b

(2) Logarithmic $\quad$ Rating = $a + b \log x$

(3) Exponential $\quad$ Rating = $a\ 10^{bx}$

(4) Linear $\quad$ Rating = $a + bx$

where x is the peak acceleration level and a and b are coefficients determined from the appropriate least-square fitting techniques. These four relationships are discussed in turn for discomfort and intensity response to vibration.

Comparisons of the four selected psychophysical relationships (for both discomfort and intensity) were obtained by comparison of the four correlation coefficients that resulted from each relationship. However, in order to optimize information about these relationships, the comparison of correlation coefficients was made subsequent to several levels of data reduction. The correlation coefficients were computed for (1) individual subjects, (2) after both arithmetic and geometric averaging of the subjective evaluation data for four groups of six subjects, and (3) subsequent to arithmetic averaging of the total responses of all subjects. A determination of the significant difference between correlation coefficients was made through z-score tests. Appendix C contains a brief description of the meaning and computational procedure for both correlation coefficients and z-score values. Tables II to V contain the correlation coefficients for the various averaging procedures and table VI is a summary table of z-scores obtained from the first four tables. These will be discussed in more detail in the following section.

Discomfort Response

The four psychophysical relationships and corresponding correlation coefficients described above between discomfort and acceleration level were determined first for each subject and at each frequency. The purpose of examining data for individual subjects was to determine the range of fluctuation of the coefficients a and b. These correlations for discomfort are summarized in table II which displays the arithmetic averages of the correlations of 24 subjects at each frequency and for each psychophysical law. The bottom row of table II is the average correlation over frequency for each psychophysical law, for example, the average of each column in table II. Inspection of these latter averages indicates a high degree of correlation for all relationships, the power law giving a slightly higher degree of association. The significance of the differences between the correlations for each psychophysical law was determined by computing z-score values based upon the correlations in the bottom row and these z-scores are tabulated in row 1 of table VI. These z-score values did not achieve statistical significance and indicated that no significant differences exist between the frequency-averaged correlations. This result implies that no difference exists between the capability of the four candidate psychophysical laws to describe the relationship between discomfort and acceleration level when based upon individual subject data.

The fact that the correlations between discomfort ratings and acceleration for the power relationship were slightly higher than those for the other relationships (although not significant) might imply that the power law be selected for description of the psychophysical relationship. However, several factors must be considered in the selection process. The power relationship (for example, ref. 34) is typified by the power law exponent b as defined by equation (1). Large values of b imply large increases of discomfort with acceleration level as well as large deviations from a linear relationship ($b = 1$ implies linearity). Figure 2 displays the mean b values and the corresponding standard deviation of b as a function of frequency based upon individual data obtained from 24 subjects. Figure 2 shows that the power law exponent b varies across frequency and, more importantly, exhibits large fluctuations between subjects within a particular frequency. This result illustrates that the use of a single b obtained through data averaging for the power relationship would be a misleading description of the psychophysical relationship.

Table III shows an additional set of correlations between discomfort rating and acceleration level for the four psychophysical relationships based upon a different averaging process. The four sets of correlations entered in table III were obtained by the following procedures. The arithmetic mean of the subjective ratings corresponding to each acceleration level was computed for each group of six subjects (four groups were used) and correlated with successive acceleration levels at each frequency investigated. The resultant correlations were then averaged over the four groups and entered in table III.

As in table II, the bottom row of table III is the frequency averaged correlation coefficients which were used to compute z-score comparisons between the psychophysical relationships. These z-scores are entered in row 2 of table IV and also indicate no significant differences between any of the psychophysical laws when arithmetic averaging is used.

Table IV presents data analogous to that of table III except that the correlations were based upon geometric means of the rating data instead of upon arithmetic means. The z-score comparisons of the resultant correlations are given in row 3 of table VI and again were not significant. Table V displays the correlations between discomfort ratings and acceleration level for the four psychophysical relationships where the subjective rating data corresponding to each acceleration level were reduced through arithmetic averaging prior to computation of correlation coefficients. The z-score comparisons between the correlations in the bottom row of table V (averaged over frequency) are presented in row 4 of table VI. Row 4 of table VI is based on arithmetic averages of total subjective responses at each acceleration level. For this case the exponential correlation was significantly lower than either the power or linear relationship, but no other differences were apparent. Thus, tables II to V indicate no differences between the correlations produced by the four psychophysical relationships (except the significantly lower exponential correlation of table V) regardless of whether the correlations were based upon individual rating data, arithmetic means of group ratings, geometric means of group ratings, or arithmetic averaging of total ratings. A final point of interest is table VII, which contains z-scores used to compare correlation coefficients obtained from arithmetic and geometric mean reduction of the rating data. Table VII shows no significant difference between correlations produced from geometric or arithmetic reduction of the data for a particular psychophysical relationship.

In summary, based upon results shown in tables II to V, a linear relationship between discomfort ratings and acceleration level can be selected. The reasons for this conclusion include several major points. First, there was no difference between the correlations for the various relationships except for the exponential which was lower than the power or linear correlation. Secondly, the slightly higher correlations (although not statistically significant) for the power relationship as compared with alternative relationships, are offset through slope fluctuations as illustrated in figure 2. Finally, the difference (variation) of correlation values between various frequencies within a psychophysical relationship are equal to or higher than differences (variation) of average correlations between different psychophysical relationships. In other words, the variability inherent within the data does not justify selection of the more complex power law relationship over the simpler linear relationship. The practical advantages of a simple linear law in the development of ride quality criteria are readily obvious.

Intensity Response

The intensity data were analyzed in exactly the same fashion as the discomfort data. Tables VIII to XI display summaries of correlations between intensity ratings and acceleration level (analogous to tables II to V which displayed correlations between discomfort ratings and acceleration level). Presented in rows 5 to 8 of table VI are the z-score comparison between the four psychophysical relationships for each level of correlation data analysis (individual, arithmetic, or geometric mean reduction of the data and total response averaging). Figure 3 (analogous to fig. 2) displays the average power law exponent b and the standard deviation of the value for 24 subjects. The same conclusions can be made regarding intensity ratings as were made about discomfort ratings. Specifically, intensity ratings can be more simply and as accurately described as a linear function of floor acceleration stimuli without the necessity of resorting to one of the more complex relationships.

Comparison of Discomfort and Intensity

This section addresses the second major question posed in the introduction which is whether there is a difference between the sensations of discomfort and intensity. Intuitively, one would expect that for a given frequency it would be possible to detect differences of intensity without necessarily noting a corresponding change in discomfort. Thus, it is hypothesized that the slope of the least-square curve fitted to the subjective response ratings of vibration intensity should be significantly greater than the slope of the curve fitted to subjective discomfort evaluations, and that both slopes are significantly greater than zero. To test this hypothesis, t-test comparisons were made between (1) the slope of each sensation (discomfort and intensity) and zero and (2) the slopes of each sensation. The results of these t-test comparisons are presented in table XII. The second and fourth columns of table XII show that the slopes of both intensity and discomfort differ significantly from zero. The sixth column presents the t-statistic for testing whether the two slopes differ from one another. As indicated, significant differences (one-tailed test) between the two sensations occurred at frequencies of 17, 20, and 23 Hz. Figures 4 to 6 show the magnitude estimates of discomfort and intensity as a function of peak acceleration level for the three frequencies (17, 20, and 23 Hz) at which the two sensations differed. The solid curves represent subjective ratings of intensity and the dashed curves ratings of discomfort based upon a least-square fit to the data. All frequencies show monotonically increasing trends of magnitude estimates with increasing peak acceleration level for both discomfort and intensity. For these frequencies the intensity rating increased with acceleration level at a faster rate than did the discomfort ratings; thus, the hypothesis stated earlier is supported.

In summary, significant differences between intensity and discomfort occurred at three of the ten frequencies investigated. Differences between the two sensations were not displayed at all frequencies; however, it is likely that other frequencies may display differences if investigated. Thus, caution should be used in applying results from intensity studies to the problem of human discomfort. An important point to be made with regard to the work of Miwa (for example, refs. 24 to 30) is that his standard frequency for intensity matching was 20 Hz, one of the frequencies at which the intensity and the discomfort were shown to be significantly different.

CONCLUDING REMARKS

A systematic investigation using a total of 48 subjects was conducted to determine (1) the psychophysical laws governing intensity and discomfort responses of humans to whole-body vertical sinusoidal vibration and (2) whether human subjective response to vibration differs depending upon whether the subjects are asked to evaluate the intensity or discomfort of vibration. The important conclusions and implications are described in the following paragraphs.

A linear law was selected to describe the relationship between subjective ratings of intensity or discomfort and acceleration level. The three primary reasons for selection of a linear law are as follows: First, the correlations of subjective ratings of intensity or discomfort with acceleration level for each of the four psychophysical laws (power, exponential, logarithmic, and linear) did not differ significantly from one another when based upon individual or group data averaged over six subjects. However, for rating data averaged over all subjects, the exponential correlations were found to be significantly lower than the power or linear correlations. Secondly, for individual data, the power law exponent b had large fluctuations and indicated that averaging to obtain b is misleading. Finally, the differences (variation) between various frequencies were equal to or greater than the differences (variation) of the average correlations between the psychophysical relationships.

Comparisons of the magnitude estimates of intensity and discomfort indicated significant differences between the sensations for frequencies of 17, 20, and 23 Hz. Thus, differences between these sensations occurred for three out of ten frequencies investigated and it is likely that further differences may be discovered if other frequencies are investigated. Therefore, caution should be used in applying results from intensity studies to the problem of human discomfort response. For example, the work of Miwa described earlier in this paper used a reference frequency of 20 Hz to generate equal sensation contours. Since this frequency is one at which this study found intensity and discomfort response to be significantly different, it is not apparent that Miwa's results can be directly applied to the assessment of discomfort. Finally, it was determined that the use of geometric means of magnitude estimates offered no advantage over the use of the simpler arithmetic mean.

Langley Research Center
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March 15, 1976

APPENDIX A

PASSENGER INSTRUCTIONS FOR DISCOMFORT TESTS

Discomfort Instructions

You have volunteered to participate in a research program to investigate the quality of rides. Specifically, we wish to identify the types of vibration in transportation vehicles which most influence a person's sense of well-being. To assess the influence of these vibrations, we have built a simulator which can expose passengers to realistic ride motions. The simulator essentially provides no risk to passengers. The system has been designed to meet stringent safety requirements so that it cannot expose subjects to motions which are known to cause injury. It contains many built-in safety features which automatically shut the system down if it does not perform properly.

The vibrations that you will receive today are representative of the vibrations you may experience in an airplane. You will enter the simulator, take a seat, fasten the seatbelt, and assume a comfortable position with both feet on the floor. Selected vibrations will then be applied to the cabin. You are to make yourself as comfortable and relaxed as possible while the test is being conducted. However, you must keep your feet on the floor and keep your seatbelts fastened at all times. During the tests you will at all times be in two-way communication with the test conductor.

You have the option at any time and for any reason to terminate the tests in any one of three ways: (1) press overhead button labeled "STOP," (2) by voice communication with the test conductor, or (3) by unfastening your seatbelt. Because of individual differences in people, there is always the possibility that someone may find the motions objectionable and may not wish to continue. If this should happen to you, please do not hesitate to stop the tests by one of these methods.

Instructions for Ride Estimations

The task you will now be required to perform is to evaluate the vibration of a ride segment. The discomfort evaluation you make of a particular ride segment will always be in comparison to a standard ride segment. Each ride segment will be presented for 20 seconds. I will specify the start of a ride segment with the word "start," and I will specify the end of a ride segment with the word "stop." After you hear the word stop, you are to evaluate the ride segment in comparison with the standard ride segment.

Task.- I will present a ride segment, termed the standard, at the beginning and intermittently throughout your evaluations. The standards will be the same within each session but differ from session to session. The discomfort of the standard ride segment is to be assigned the number 100. I will present ride segments that provide both less or more discomfort than the standard 100. Your task will be to assign numbers to each of these ride segments above and below the standard 100. Try to assign the appropriate number to each ride segment regardless of what you may have called the previous ride segment. If, for example, the ride segment seems to provide twice the discomfort as the standard, say 200. If the ride segment provides one-tenth the discomfort, say 10. If the ride segment provides one-fourth the discomfort of the standard, say 25. As you know, there are infinite numbers above as well as below the standard of 100. You may use decimals, fractions, or whole numbers. Do not use zero or negative numbers.

Evaluation marks.- You should record your evaluation (number) of the ride segment on the blank space next to the ride segment number. For example, the data sheet for you to record your evaluation of a ride segment will look like the following:

Ride segment	
1	23
2	200
3	25
4	___

Evaluations.- There are two requirements you should use in your evaluations. First, your evaluations should be based upon vibration. Certainly, you could evaluate a ride based on other factors such as temperature, pressure, etc. However, restrict your evaluations of a ride segment to the comfort associated with various vibrations, and not upon variations of vibration. In other words, rate a ride segment in terms of comfort of a vibration, not on whether you notice differences of vibration. This requirement is important because we are interested in differences of comfort, not merely in your ability to detect differences of vibrations.

Consistency.- It is typical for participants in the study to "try and be consistent." Instead of trying to be consistent with previous ride segments, try to evaluate each segment without looking at evaluations of previous ride segments. Please do not be concerned about whether your ratings agree with the others in the simulator with you. Remember we want to know how different people feel about the ride. You may talk between the segments you are to rate, but please do not talk during them. It is also typical for participants to feel that they are not doing well at this task. It is usually true, however, that participants are doing better than they think they are, so don't be discouraged if you find the task difficult or monotonous at times.

APPENDIX A

Remember.-

(1) Listen for the words "Start" and "Stop."

(2) Evaluate only the discomfort of vibrations.

(3) Place your evaluation number on the appropriate blank.

Are there any questions?

Simulator Instructions

(Upon entering the simulator, the subject should be told:)

Please be seated and fasten your seatbelt. (Wait until all the subjects are ready.) Now, the mirror you see in front of you is a two-way mirror to allow the operator to monitor any discomfort you may have during a ride. In addition, as I told you before, the test conductor will be able to hear everything you say. Also, if you wish to end the test, you can undo your seatbelt, press one of these little buttons (point to both), or you can ask the test conductor to stop the test and let you out. This first test will take about one-half hour.

APPENDIX B

INTENSITY TESTS

Intensity Instructions

You have volunteered to participate in a research program to investigate the quality of rides. Specifically, we wish to identify the types of vibration in transportation vehicles which most influence a person's sense of well-being. To assess the influence of these vibrations, we have built a simulator which can expose passengers to realistic ride motions. The simulator essentially provides no risk to passengers. The system has been designed to meet stringent safety requirements so that it cannot expose subjects to motions which are known to cause injury. It contains many built-in safety features which automatically shut the system down if it does not perform properly.

The vibrations that you will receive today are representative of the vibrations you may experience in an airplane. You will enter the simulator, take a seat, fasten the seatbelt, and assume a comfortable position with both feet on the floor. Selected vibrations will then be applied to the cabin. You are to make yourself as comfortable and relaxed as possible while the test is being conducted. However, you must keep your feet on the floor and keep your seatbelts fastened at all times. During the tests you will at all times be in two-way communication with the test conductor.

You have the option at any time and for any reason to terminate the tests in any one of three ways: (1) press overhead button labeled "STOP," (2) by voice communication with the test conductor, or (3) by unfastening your seatbelt. Because of individual differences in people, there is always the possibility that someone may find the motions objectionable and may not wish to continue. If this should happen to you, please do not hesitate to stop the tests by one of these methods.

Instructions for Ride Estimations

The task you will now be required to perform is to evaluate the vibration of a ride segment. The magnitude evaluation you make of a particular ride segment will always be in comparison with a standard ride segment. Each ride segment will be presented for 20 seconds. I will specify the start of a ride segment with the word "start," and I will specify the end of a ride segment with the word "stop." After you hear the word stop, you are to evaluate the ride segment in comparison with the standard ride segment.

Task.- I will present a ride segment, termed the standard, at the beginning and intermittently throughout your evaluations. The standards will be the same within each session but differ from session to session. The magnitude of the standard ride segment is to be assigned the number 100. I will present ride segments that provide both greater or less magnitude than the standard 100. Your task will be to assign numbers to each of these ride segments above and below the standard 100. Try to assign the appropriate number to each ride segment regardless of what you may have called the previous ride segment. If, for example, the ride segment seems to provide twice the magnitude as the standard, say 200, etc. If the ride segment provides one-tenth the magnitude, say 10. If the ride segment provides one-fourth the magnitude of the standard, say 25. As you know, there are infinite numbers above as well as below the standard of 100. You may use decimals, fractions, or whole numbers. Do not use zero or negative numbers.

Evaluation marks.- You should record your evaluation (number) of the ride segment on the blank space next to the ride segment number. For example, the data sheet for you to record your evaluation of a ride segment will look like the following:

Ride segment	
1	23
2	200
3	25
4	___

Evaluations.- There are two requirements you should use in your evaluations. First, your evaluations should be based upon vibration. Certainly, you could evaluate a ride based on other factors as temperature, pressure, etc. However, restrict your evaluations of a ride segment to variations of vibration.

Second, base your evaluation of a ride upon magnitude of the vibration, not upon variations of comfort. In other words, rate a ride segment in terms of magnitude of a vibration, not on whether you notice differences of comfort. This requirement is important because we are interested in differences of magnitude, not merely your ability to detect differences of comfort.

Consistency.- It is typical for participants in the study to "try and be consistent." Instead of trying to be consistent with previous ride segments, try to evaluate each segment without looking at evaluations of previous ride segments. Please do not be concerned about whether your ratings agree with the others in the simulator with you. Remember we want to know how different people feel about the ride. You may talk between the segments you are to rate, but please do not talk during them. It is also typical for participants to feel that they are not doing well at this task. It is usually true, however, that participants are doing better than they think they are, so don't be discouraged if you find the task difficult or monotonous at times.

Remember.-

(1) Listen for the words "Start" and "Stop."

(2) Evaluate only the magnitude of vibrations.

(3) Place your evaluation number on the appropriate blank.

Are there any questions?

Simulator Instructions

(Upon entering the simulator, the subject should be told:)

Please be seated and fasten your seatbelt. (Wait until all the subjects are ready.) Now, the mirror you see in front of you is a two-way mirror to allow the operator to monitor any discomfort you may have during a ride. In addition, as I told you before, the test conductor will be able to hear everything you say. Also, if you wish to end the test, you can undo your seatbelt, press one of these little buttons (point to both), or you can ask the test conductor to stop the test and let you out. This first test will take about one-half hour.

APPENDIX C

REVIEW OF STATISTICAL CONCEPTS

This appendix provides a brief review of the correlation coefficient, z-score, and t-test statistics used within the present paper. A more complete and detailed description of these statistics as well as their derivation can be obtained from almost any elementary statistics text. (See ref. 41.)

Correlation Coefficient

The Pearson product moment correlation coefficient was the type of correlation used in the present paper. The statistic is most often used to measure the type of relationship between two variables (for example, positive or inverse) as well as the degree of relationship between the variables. Mathematically, the statistic can be expressed as

$$r = \frac{N \sum XY - \left(\sum X\right)\left(\sum Y\right)}{\sqrt{\left[N \sum X^2 - \left(\sum X\right)^2\right]\left[N \sum Y^2 - \left(\sum Y\right)^2\right]}}$$

where

r	correlation coefficient
X	data value on abscissa
Y	data value on ordinate
N	number of data pairs

For the linear correlation coefficients computed in the present investigation, the X and Y values were acceleration levels and subjective ratings, respectively. The power, exponential, and logarithmic relationships were obtained through a logarithmic transformation of data for the X or Y variable (for example, see "Results and Discussion") and a subsequent computation of the correlation coefficient by using this equation.

z-Score

The z-score statistic was used in the present paper to determine (through the use of the table of the standard normal curve) whether the two correlation coefficients were statistically different. Mathematically, the z-score can be expressed as

$$z = \frac{z_1' - z_2'}{\sqrt{\frac{1}{N_1 - 3} + \frac{1}{N_2 - 3}}}$$

where

z' a transformation of r (correlation coefficient), $\frac{1}{2}\left[\log_e (1 + r) - \log_e (1 - r)\right]$

N_1 number of paired scores for sample 1

N_2 number of paired scores for sample 2

Many statistics texts provide a table for the z' transformation of any size correlation. The z-score value that results is merely interpreted with the use of the table for the standard normal curve to determine the probability of two correlations differing by as much as discovered.

t-Test Statistic

The t-test statistic was used in the present paper to determine whether the slope of a sample differed from zero, and also whether there was a statistical difference between the slopes of two different samples. Mathematically, the t-test for a single sample can be expressed as

$$t = \frac{b - B}{S_b}$$

where

b sample slope

B population slope of zero

S_b standard error of slope, $\frac{S_E}{\sqrt{\sum x^2}}$

S_E standard error of estimate, $\sqrt{\frac{\sum y^2 - \frac{\left(\sum xy\right)^2}{\sum x^2}}{n - 2}}$

x deviation of score from mean of X variable, $X - \overline{X}$

APPENDIX C

y deviation of score from mean of Y variable, $Y - \overline{Y}$

n number of scores

Mathematically, the t-test to determine whether the difference between two slopes is statistically significant can be expressed as

$$t = \frac{b_1 - b_2}{S_{b_1 - b_2}}$$

where

b_1 slope for sample 1

b_2 slope for sample 2

$S_{b_1-b_2}$ standard error of difference between b_1 and b_2, $\sqrt{S_R^2\left(\frac{1}{\sum x_1^2} + \frac{1}{\sum x_2^2}\right)}$

S_R^2 residual variance, $\dfrac{\left[\sum y_1^2 - \dfrac{\left(\sum x_1 y_1\right)^2}{\sum x_1^2}\right] + \left[\sum y_2^2 - \dfrac{\left(\sum x_2 y_2\right)^2}{\sum x_2^2}\right]}{N_1 + N_2 - 4}$

N_1 number of score pairs for sample 1

N_2 number of score pairs for sample 2

A t-test table is entered for a certain level of significance (0.05 in this case) and the associated degrees of freedom in order to determine the t-value that is needed to achieve significance.

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TABLE I.- SUMMARY OF PEAK FLOOR ACCELERATION LEVELS OF EACH FREQUENCY USED IN THIS INVESTIGATION

[Numbers in parentheses indicate the standard acceleration level which was assigned the value of 100]

Peak floor acceleration level, g units, for frequency, Hz, of –									
2	5	8	11	14	17	20	23	26	29
0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
.075	.075	.075	.100	.100	.100	.100	.100	.100	.100
.100	.100	.100	.125	.150	.150	.150	.150	.150	.150
.125	.125	.125	.150	.200	.200	.200	.200	.200	.200
.150	.150	.150	.175	.250	.250	.250	.250	.250	.250
.200	.200	.200	.200	.275	.275	.300	.300	.300	.300
.220	.220	.220	.250	.300	.300	.350	.350	.350	.350
.240	.240	.240	.275	.325	.325	.375	.400	.400	.400
.260	.260	.260	.300	.350	.350	.400	.450	.450	.450
(.15)	(.15)	(.15)	(.175)	(.25)	(.25)	(.25)	(.25)	(.25)	(.25)

TABLE II.- SUMMARY OF ARITHMETIC MEAN OF INDIVIDUAL SUBJECT CORRELATIONS BETWEEN DISCOMFORT RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.8608	0.8531	0.8170	0.8462
5	.9441	.9228	.9100	.9387
8	.9158	.9019	.8866	.9216
11	.9366	.9110	.8890	.9337
14	.9437	.8964	.9038	.9160
17	.9190	.8888	.8595	.8867
20	.9172	.8996	.8455	.8975
23	.9401	.8991	.8709	.9069
26	.9332	.8825	.8921	.9045
29	.8895	.8251	.8437	.8454
Mean	.9200	.8880	.8718	.8997

TABLE III.- SUMMARY OF MEAN CORRELATIONS BETWEEN DISCOMFORT RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES WHERE CORRELATIONS WERE BASED ON ARITHMETIC MEAN OF SUBJECTIVE RATINGS OF SIX SUBJECTS WITHIN EACH OF FOUR GROUPS

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.9565	0.9644	0.9105	0.9591
5	.9800	.9597	.9452	.9772
8	.9848	.9574	.9550	.9803
11	.9792	.9566	.9294	.9780
14	.9861	.9482	.9472	.9745
17	.9759	.9677	.9185	.9713
20	.9613	.9595	.8921	.9683
23	.9795	.9578	.9115	.9716
26	.9828	.9525	.9387	.9761
29	.9731	.9214	.9324	.9486
Mean	.9759	.9545	.9281	.9705

TABLE IV.- SUMMARY OF MEAN CORRELATIONS BETWEEN DISCOMFORT RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS WHERE CORRELATIONS WERE BASED ON GEOMETRIC MEANS OF SUBJECTIVE RATINGS OF SIX SUBJECTS WITHIN EACH OF FOUR GROUPS

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.9439	0.9533	0.8897	0.9456
5	.9779	.9615	.9386	.9775
8	.9765	.9598	.9393	.9801
11	.9762	.9586	.9192	.9770
14	.9847	.9502	.9403	.9761
17	.9695	.9746	.9016	.9728
20	.9570	.9607	.8831	.9682
23	.9733	.9615	.8954	.9710
26	.9828	.9553	.9315	.9770
29	.9740	.9290	.9223	.9518
Mean	.9716	.9567	.9161	.9697

TABLE V.- SUMMARY OF CORRELATIONS BETWEEN DISCOMFORT RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS WHERE CORRELATIONS WERE BASED ON ARITHMETIC AVERAGES OF TOTAL SUBJECTIVE RESPONSES CORRESPONDING TO EACH ACCELERATION LEVEL

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.9823	0.9806	0.9530	0.9744
5	.9909	.9806	.9712	.9835
8	.9919	.9741	.9531	.9863
11	.9814	.9776	.9354	.9896
14	.9943	.9714	.9547	.9885
17	.9808	.9661	.9111	.9823
20	.9745	.9614	.8993	.9858
23	.9921	.9600	.9292	.9963
26	.9972	.9646	.9551	.9938
29	.9886	.9721	.9529	.9697
Mean	.9874	.9708	.9415	.9850

TABLE VI.- SUMMARY OF z-SCORES FOR COMPARISON OF CORRELATION COEFFICIENTS FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS FOR SENSATIONS OF DISCOMFORT AND INTENSITY, FOR CORRELATIONS OBTAINED FROM INDIVIDUAL SUBJECT DATA, ARITHMETIC OR GEOMETRIC MEAN REDUCTION OF RATING DATA IN GROUPS OF SIX SUBJECTS, AND TOTAL RESPONSE AVERAGING

	Comparison of psychophysical relationships[a] for –					
	Power with logarithmic	Power with exponential	Power with linear	Logarithmic with exponential	Logarithmic with linear	Exponential with linear
			Discomfort			
Individual	0.5411	0.8295	0.3791	0.2884	-0.1620	-0.4504
Arithmetic	.9869	1.8211	.3014	.8522	-.6675	-1.5197
Geometric	.6675	1.7336	.0000	1.0661	-.6675	-1.7336
Total responses	1.1374	2.2845*	.0000	1.1471	-1.1374	-2.2845*
			Sensitivity			
Individual	1.1114	0.6416	0.4537	-0.4699	-0.6578	-0.1879
Arithmetic	1.9313	1.1439	.5541	-.7874	-1.3772	-.5897
Geometric	1.8211	1.3026	.5541	-.5158	-1.2680	-.7485
Total responses	2.0512*	2.2710*	.6610	.2203	-1.3901	-1.6105

[a] In order to maximize the chances of obtaining differences between correlation values (that were based on mean correlations), z-score computations were based upon: $N_1 = 24$ and $N_2 = 24$. The z-scores with asterisks were statistically significant ($P < 0.05$); $-1.9600 \geqq$ z-scores $\geqq 1.9600$ needed to achieve statistical significance.

TABLE VII.- SUMMARY OF z-SCORES FOR COMPARISON BETWEEN CORRELATION COEFFICIENTS OBTAINED FROM ARITHMETIC AND GEOMETRIC MEAN REDUCTION OF RATING DATA FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS

	Comparisons[a] for –			
	Power	Logarithmic	Exponential	Linear
Discomfort (arithmetic compared with geometric	0.3014	0.000	0.2139	0.000
Sensitivity (arithmetic compared with geometric)	0.0000	-1.1102	0.1588	-0.2527

[a] In order to maximize the chances of obtaining differences between correlation values (based on mean correlations), z-score computations were based upon $N_1 = 24$ and $N_2 = 24$; $-1.9600 \geqq$ z-scores $\geqq 1.9600$ needed to achieve statistical significance ($P < 0.05$). Note that no comparisons were significant.

TABLE VIII.- SUMMARY OF MEAN OF INDIVIDUAL SUBJECT CORRELATIONS BETWEEN INTENSITY RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.8862	0.8717	0.8289	0.8766
5	.9346	.8908	.9337	.9270
8	.9550	.9278	.9052	.9380
11	.9201	.8781	.8926	.9089
14	.9429	.8415	.9233	.8958
17	.9516	.8603	.9184	.9039
20	.9456	.8908	.9028	.9257
23	.9553	.8714	.9152	.9262
26	.9467	.8670	.9268	.9233
29	.9396	.8666	.9298	.9304
Mean	.9377	.8766	.9076	.9155

TABLE IX.- SUMMARY OF MEAN CORRELATIONS BETWEEN INTENSITY RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS WHERE CORRELATIONS WERE BASED ON ARITHMETIC MEANS OF SUBJECTIVE RATINGS OF SIX SUBJECTS WITHIN EACH OF FOUR GROUPS

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.9364	0.9364	0.8805	0.9429
5	.9785	.9309	.9714	.9691
8	.9892	.9699	.9410	.9849
11	.9819	.9279	.9557	.9706
14	.9754	.9011	.9574	.9538
17	.9854	.9157	.9545	.9662
20	.9792	.9303	.9405	.9753
23	.9852	.8935	.9538	.9636
26	.9787	.9023	.9669	.9702
29	.9759	.8896	.9684	.9641
Mean	.9765	.9197	.9490	.9660

TABLE X.- SUMMARY OF MEAN CORRELATIONS BETWEEN INTENSITY RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS WHERE CORRELATIONS WERE BASED ON GEOMETRIC MEANS OF SUBJECTIVE RATINGS OF SIX SUBJECTS WITHIN EACH OF FOUR GROUPS

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.9358	0.9397	0.8754	0.9450
5	.9803	.9342	.9679	.9699
8	.9878	.9733	.9362	.9855
11	.9820	.9321	.9490	.9718
14	.9780	.9090	.9574	.9570
17	.9869	.9260	.9514	.9735
20	.9782	.9322	.9339	.9751
23	.9862	.9105	.9464	.9674
26	.9815	.9105	.9611	.9738
29	.9760	.8899	.9634	.9643
Mean	.9772	.9248	.9442	.9683

TABLE XI.- SUMMARY OF CORRELATIONS BETWEEN INTENSITY RATINGS AND PEAK FLOOR ACCELERATION LEVEL FOR SELECT FREQUENCIES FOR EACH OF FOUR PSYCHOPHYSICAL RELATIONSHIPS WHERE CORRELATIONS WERE BASED ON ARITHMETIC AVERAGES OF TOTAL SUBJECTIVE RESPONSES CORRESPONDING TO EACH ACCELERATION LEVEL

Frequency, Hz	Correlation for –			
	Power	Logarithmic	Exponential	Linear
2	0.9524	0.9776	0.8891	0.9733
5	.9931	.9810	.9879	.9836
8	.9946	.9721	.9451	.9966
11	.9979	.9649	.9705	.9980
14	.9933	.9716	.9779	.9905
17	.9931	.9674	.9673	.9942
20	.9893	.9554	.9555	.9864
23	.9917	.9532	.9242	.9794
26	.9875	.9635	.9820	.9781
29	.9885	.9604	.9863	.9767
Mean	.9881	.9667	.9586	.9857

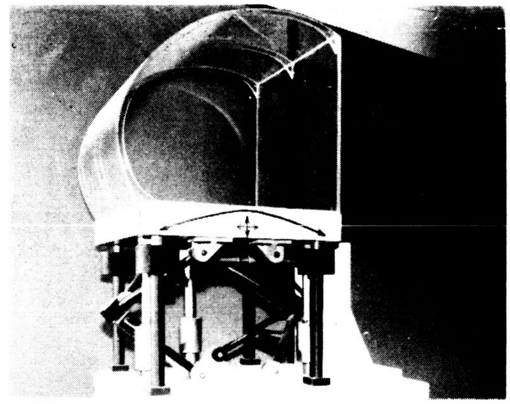
TABLE XII.- SUMMARY OF t-TEST COMPARISONS BETWEEN SLOPE OF DISCOMFORT-ACCELERATION CURVES AND ZERO, SLOPE OF INTENSITY-ACCELERATION CURVES AND ZERO, AND t-TEST COMPARISONS BETWEEN THESE TWO SLOPES FOR SELECT FREQUENCIES

[The t-values with asterisks were statistically significant (P < 0.05)]

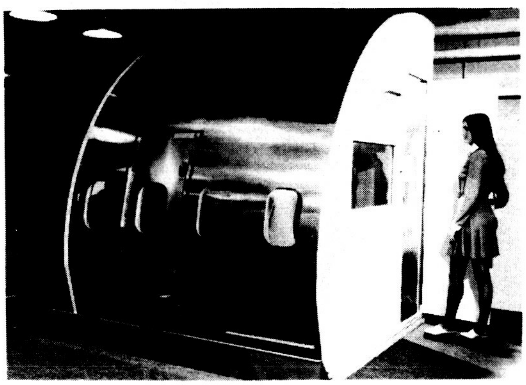
Frequency, Hz	Intensity	Degrees of freedom (a)	Discomfort	Degrees of freedom (a)	Intensity with discomfort	Degrees of freedom (a)
2	11.2617*	7	15.0277*	12	-1.8341	19
5	14.4457*	7	16.3161*	9	.8650	16
8	31.8173*	7	17.9494*	9	.7368	16
11	42.2029*	7	20.6478*	9	.9546	16
14	21.5784*	9	20.7014*	10	.6421	19
17	29.2913*	10	17.4137*	11	2.8889*	21
20	18.0237*	9	18.5425*	10	1.7775*	19
23	13.7072*	8	32.7190*	8	1.8182*	16
26	14.0929*	9	23.7032*	7	1.0097	16
29	12.0454*	7	11.2314*	8	1.6511	15

[a] The degrees of freedom for different comparisons varied in order to minimize the chances of obtaining significant differences. The subjective ratings of the four (or less) groups (of six subjects) were combined and treated as a single data point (reducing the degrees of freedom) when acceleration levels of a group fell within 0.005 peak floor acceleration of another group.

(a) Waiting room.

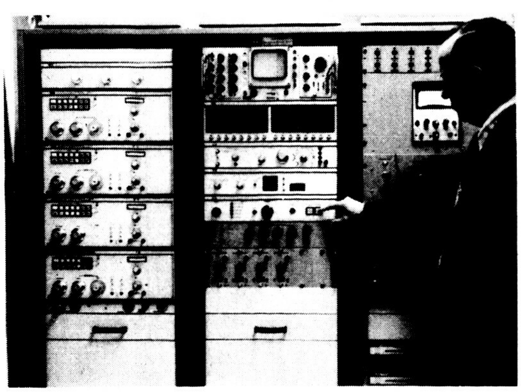


(b) Model of PRQA.



(c) Simulator exterior.

(d) Simulator interior.



(e) Control console.

L-75-218

(f) Tourist-class seats.

Figure 1.- Langley passenger ride quality apparatus (PRQA).

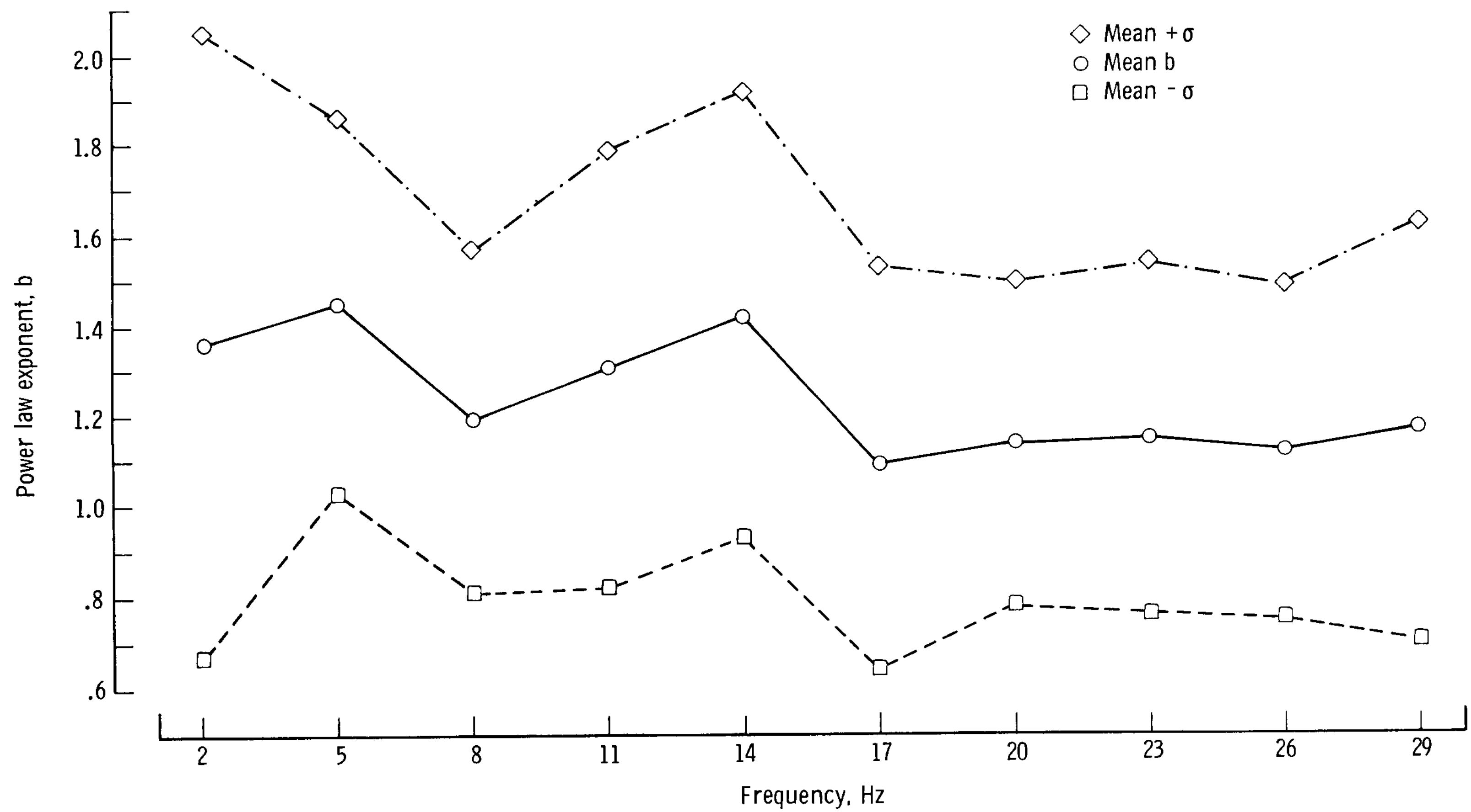


Figure 2.- Mean power law exponent for discomfort and standard deviation of this value as a function of frequency.

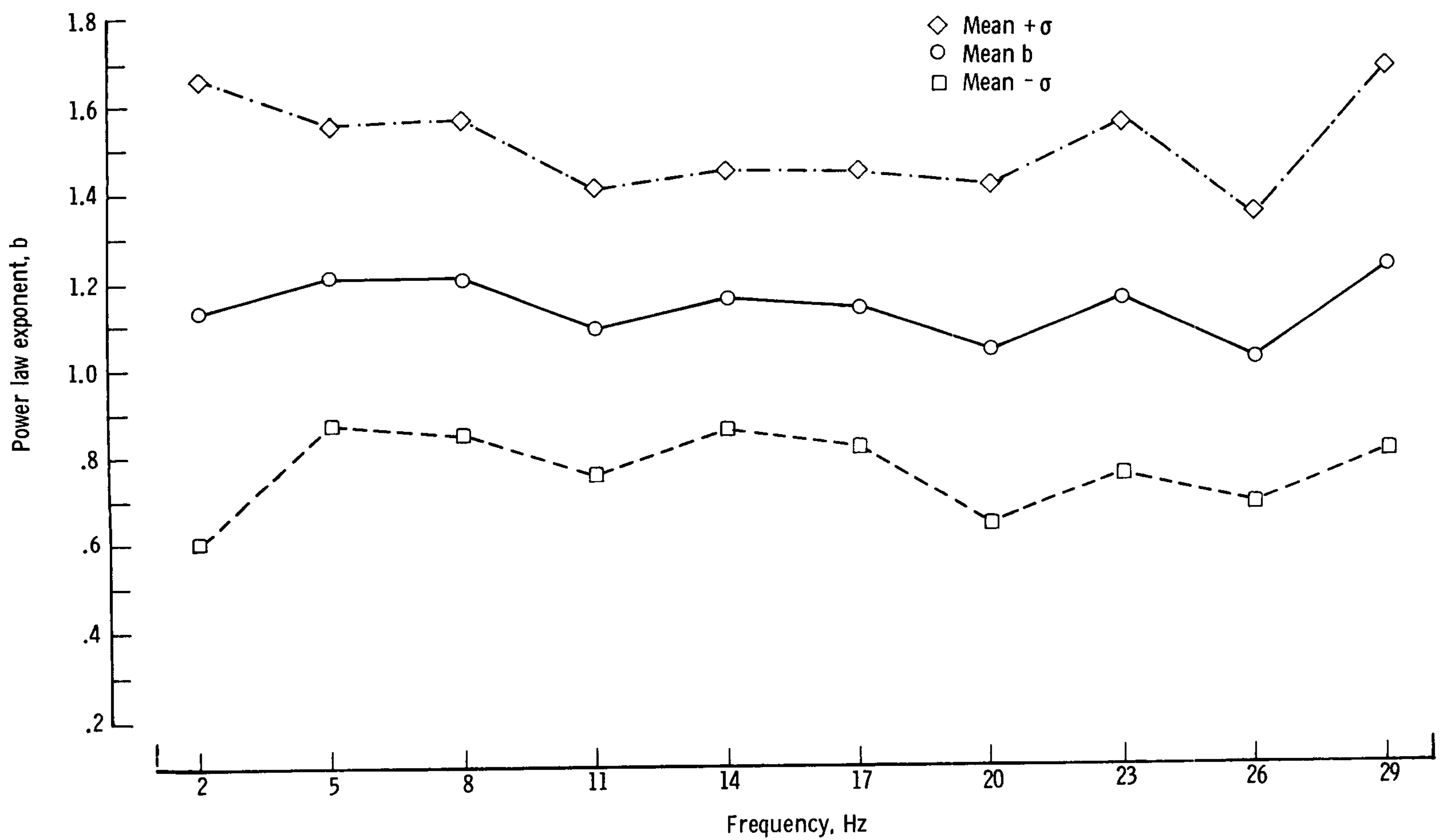


Figure 3.- Mean power law exponent for intensity and standard deviation of this value as a function of frequency.

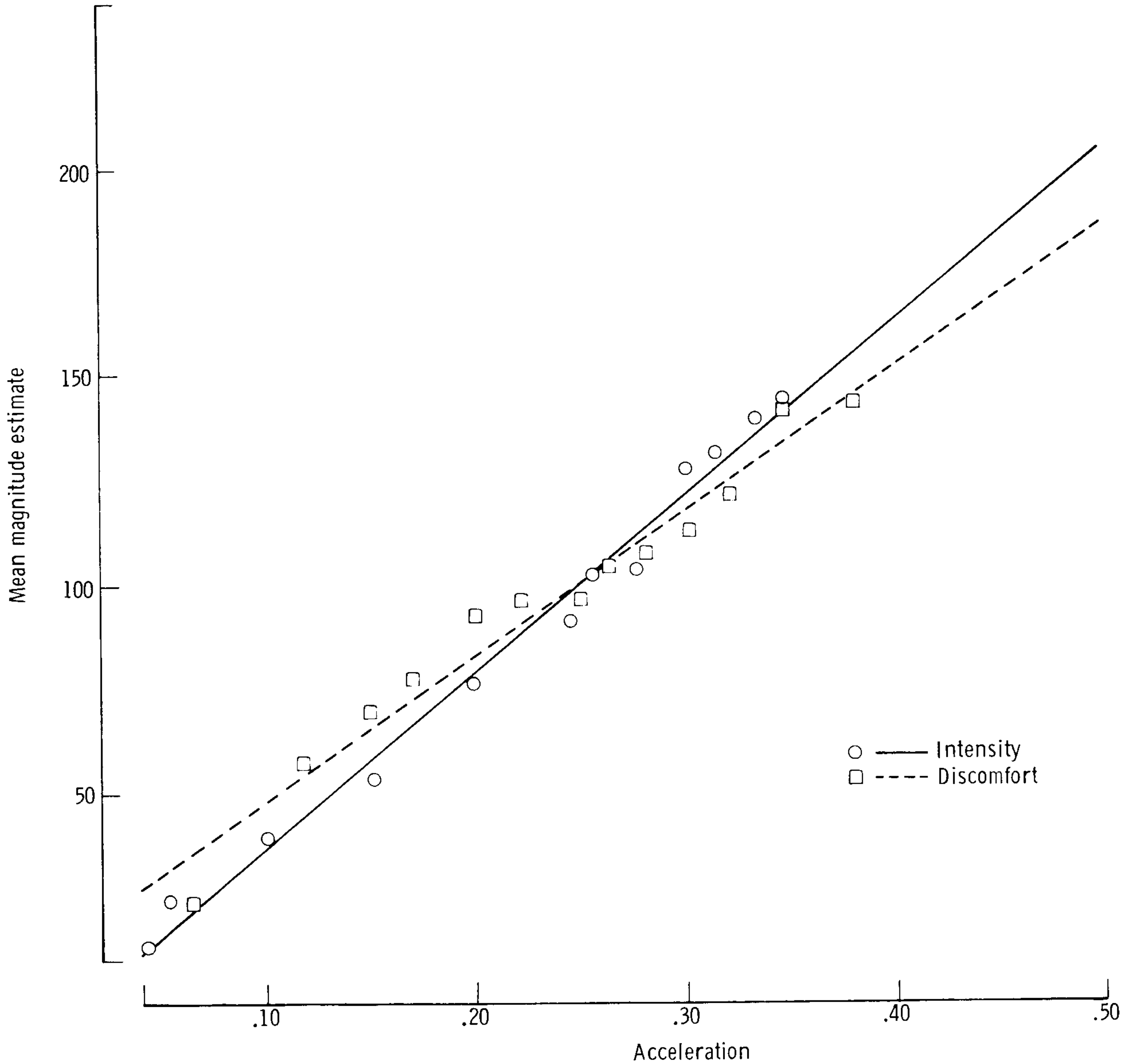


Figure 4. Mean magnitude estimates of intensity and discomfort for 17 Hz as a function of acceleration level.

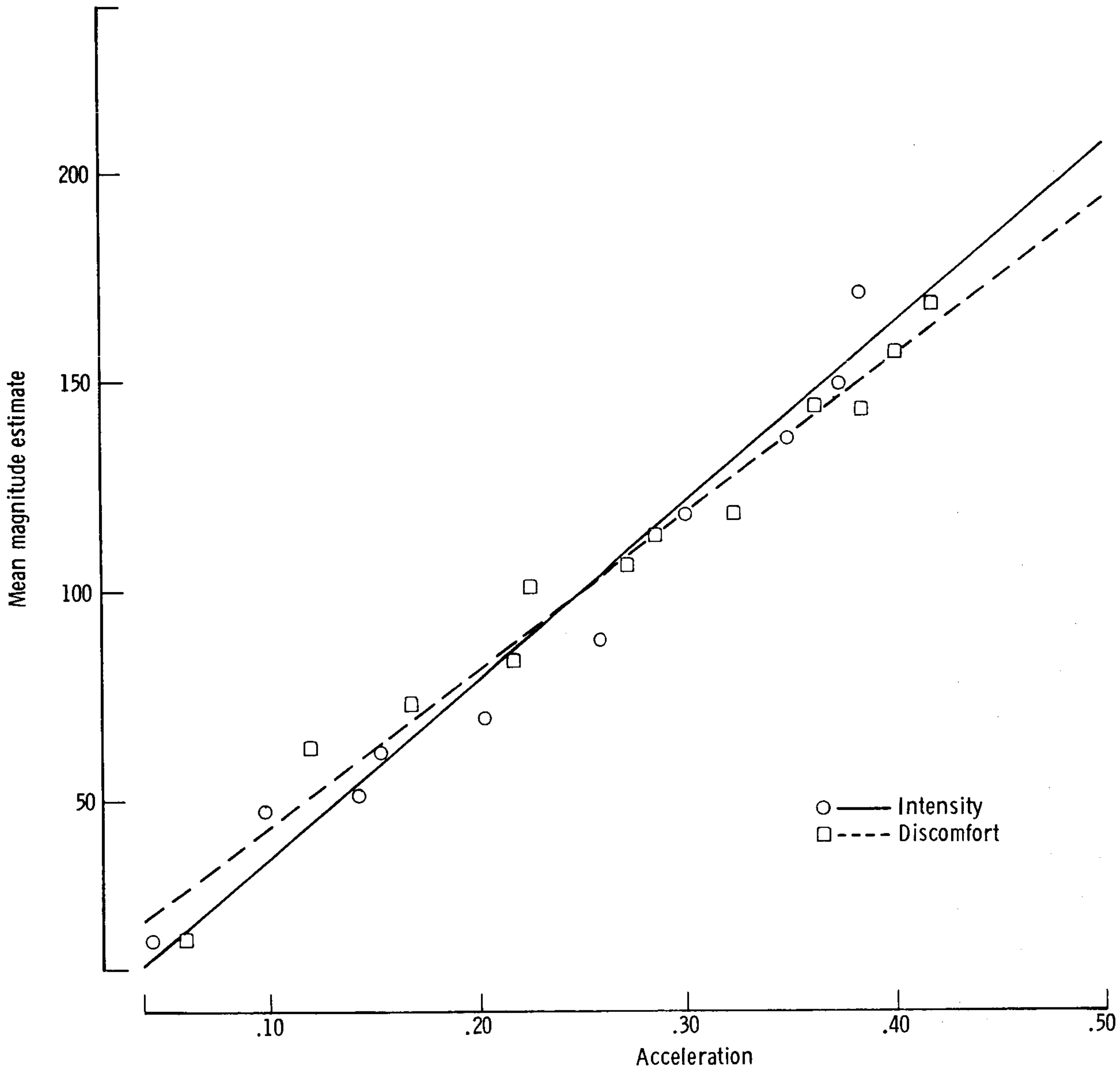


Figure 5.- Mean magnitude estimates of intensity and discomfort for 20 Hz as a function of acceleration level.

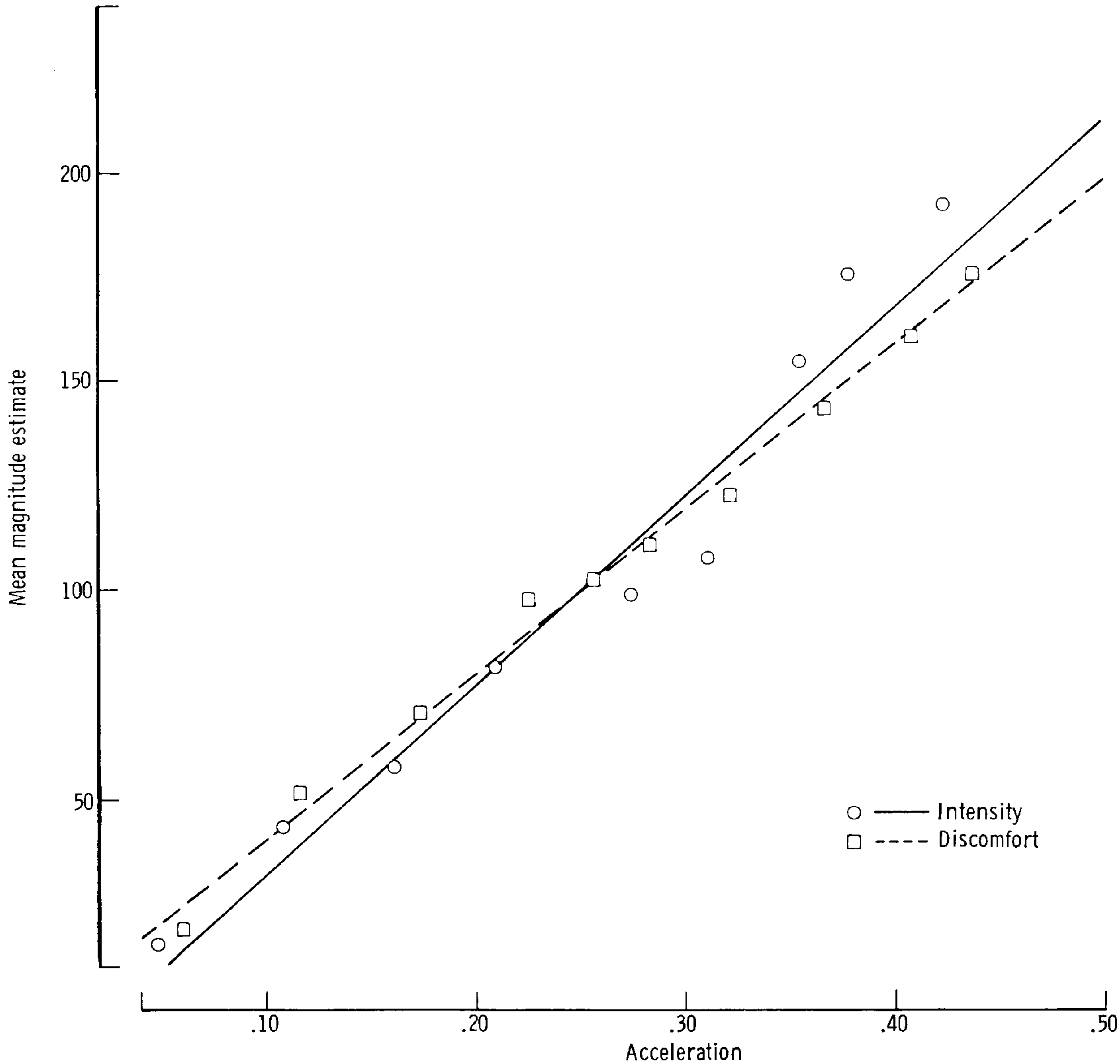


Figure 6.- Mean magnitude estimates of intensity and discomfort for 23 Hz as a function of acceleration level.

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