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EXPERIMENTAL STUDIES FOR DETERMINING HUMAN DISCOMFORT RESPONSE TO VERTICAL SINUSOIDAL VIBRATION

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16. Abstract

A study was conducted to investigate several problems related to methodology and design of experiments to obtain human comfort response to vertical sinusoidal vibration. Specifically, the studies were directed to the determination of (1) the adequacy of frequency averaging of vibration data to obtain discomfort predictors, (2) the effect of practice on subject ratings, (3) the effect of the demographic factors of age, sex, and weight, and (4) the relative importance of seat and floor vibrations in the determination of measurement and criteria specification location. Results indicate that accurate prediction of discomfort requires knowledge of both the acceleration level and frequency content of the vibration stimuli. More importantly, the prediction of discomfort was shown to be equally good based upon either floor accelerations or seat accelerations. Furthermore, it was demonstrated that the discomfort levels in different seats resulting from similar vibratory inputs were equal. Therefore, it was recommended that criteria specifications and acceleration measurements be made at the floor location. The results also indicated that practice (or experience) did not systematically influence discomfort responses nor did the demographic factors of age, weight, and sex contribute to the discomfort response variation.

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SUMMARY

A study was conducted to investigate several problems related to methodology and design of experiments to obtain human comfort response to vibration. Specifically, the studies were directed to the determination of (1) the adequacy of frequency averaging of vibration data to obtain discomfort predictors, (2) the effect of practice or experience with vibrations on subjective ratings, (3) the effect of the demographic factors of age, sex, and weight, and (4) the relative importance of seat and floor vibration in the determination of measurement and criteria specification location. The study utilized a total of 152 subjects who experienced selected sinusoidal vibrations as applied by the Langley passenger ride quality apparatus. Vibration frequencies ranged from 1 to 30 Hz and input floor acceleration peak amplitudes varied from 0.05g to 0.25g. The major portion of the study used a nine-point unipolar rating scale to obtain subjective ratings, although some data were obtained with the use of a simple binary rating scale.

Results indicated that accurate prediction of discomfort requires knowledge of both acceleration level and frequency rather than an overall measure obtained by frequency averaging. More importantly, the prediction of discomfort was shown to be equally good when based upon either floor accelerations or seat accelerations. It was further demonstrated that the discomfort in different seats resulting from similar vibratory inputs was equal. Therefore, it was recommended that criteria specifications and acceleration measurements be made at the floor location. The results also indicated that practice (or experience with vibration) did not systematically influence discomfort responses nor did the demographic factors of age, weight, and sex contribute to the explanation of discomfort response variation.

INTRODUCTION

The design of new transportation systems or the modification of existing systems to produce acceptable levels of ride quality necessitates a comprehensive understanding

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of the many factors (both vibratory and nonvibratory) that affect passenger comfort. Numerous investigations (refs. 1 to 7) of the effects of vibration on passenger comfort have been conducted but there still remains a lack of information on the empirical relationship between vibration (as well as other interactive factors such as noise, ventilation, etc.) and human comfort response. This lack of information specifically results from a shortage of comprehensive and systematically derived experimental data describing the relationships between vibration stimuli and human comfort response, as well as a lack of complex laws governing comfort response to multiaxis and multifrequency vibrations. Recently, a comfort model has been proposed at Langley Research Center (ref. 8) which provides a framework to account for the effect of both multifrequency and multiaxis vibratory stimuli, as well as nonvibratory factors, on human comfort response. The research contained within this paper represents initial investigations of this model for the vertical axis of vibration.

Prior to conducting the specific and detailed experiments required for development and application of the model described in reference 8, there are certain problems and questions concerning methodology and measurement location which must be considered. An initial problem is related to the level of sophistication required in the measurement and analysis of ride spectra data to obtain accurate predictions of passenger discomfort. Specifically, the problem is, can the prediction of passenger discomfort be based on an overall measure obtained by frequency averaging (see refs. 9 to 13) or is information on the frequency content of the spectrum (refs. 14 to 23) also required. Frequency averaging uses a measure such as rms acceleration which gives overall intensity of a spectrum but does not convey information regarding the frequency content of the spectrum. The first objective of this study is, therefore, to determine whether the discomfort associated with separate and distinct frequencies of vibration is sufficiently similar to justify frequency averaging, or whether the vibratory energy at each separate frequency must be considered.

Two additional problems of a methodological nature are the affects of "practice" or "experience" and demographic factors on the discomfort ratings of the subjects. Prior to an accurate assessment of the influence of various factors (e.g., exposure duration, noise, etc.) on discomfort, there must be a decision whether to use "practiced" or "naive" (i.e., untrained) subjects. Reference 24 indicated a slight change in discomfort ratings for selected levels of acceleration for successive exposures to the vibratory stimuli. However, the type of sample, sample size, number of exposures, and so forth would restrict generalization of these results. The present study examined in detail the influence of practice or experience with vibrations on the discomfort ratings of the subjects. The demographic factors addressed were age, weight, and sex. The objective within this problem area was to obtain information to assess the effects of these factors on discomfort response variation.

A fourth and very basic methodological problem concerns the relative contributions of vibratory accelerations measured at the floor and at the seat to human comfort response. It is well known that the two principal points of entry of vibratory motion to seated subjects are at the body trunk (seat-buttocks interface) and at the floor (feet). A recent investigation (ref. 25) has demonstrated in a systematic manner and for a large number of subjects that the vibratory acceleration at the seat and floor of typical transport-system seats (tourist-class aircraft seats, first-class aircraft seats, and urban transit bus seats) differs appreciably due to the respective seat transfer functions. This brings up the logical question as to whether comfort criteria should be based upon floor stimuli, seat stimuli, or some weighted combination of both. This is a particularly important practical problem since the ease of applying comfort criteria to real world design problems will depend upon the location at which the criteria are specified.

Most previous investigations (e.g., refs. 12, 14, 15, and 26) have developed comfort criteria based upon floor measurements, or they have used rigid seats where the stimuli at the trunk and feet of a seated subject are assumed to be identical. (Seat compliance has not been accounted for in criteria development.) Thus, the present investigation examined the relative contribution to human discomfort of vibration at these two locations in order to establish the location for measurement and specification of criteria.

In summary, the objectives of this investigation were

(1) the determination of the adequacy of frequency averaging techniques in developing predictors of human discomfort response

(2) the assessment of the influence of practice on subsequent discomfort responses

(3) the determination of the amount of discomfort response variation that is attributable to certain demographic factors

(4) the determination of the importance of vibration at the floor and at the seat for the selection of measurement and specification location

SYMBOLS AND STATISTICAL NOTATION

f	frequency, Hz
g	acceleration due to gravity
df	degrees of freedom
F	F statistic

MS mean square

p probability

r correlation

SS sum of squares

χ^2 chi-square test statistic

APPARATUS AND INSTRUMENTATION

The apparatus used was the Langley passenger ride quality apparatus (PRQA). A short summary of PRQA equipment is provided, although a more complete description can be obtained from references 27 and 28. Photographs of the PRQA and appropriate programing and control instrumentation are displayed in figure 1. Figure 1(a) shows the waiting room where subjects receive instructions, complete questionnaires, and so forth. Shown in figure 1(b) is a model of the PRQA indicating the supports, actuators, and restraints of the three-axis drive system. Figure 1(c) is a view of the exterior of the PRQA simulator. The actual mechanisms that control the simulator are located beneath the pictured floor. Figure 1(d) displays the interior of the PRQA with the subjects seated in first-class (two abreast) aircraft seats. These seats, as well as tourist-class (three abreast) aircraft seats and urban transit bus seats, were used in this study, as will be discussed in the experimental method section. The dimensions of each seat type are presented in table 1. Figure 1(e) is a view of the control console which is located at the same level as the simulator to allow the control console operator to constantly monitor subjects within the simulator.

Floor and seat accelerations for each of the six subjects were recorded as they simultaneously evaluated a vibration. The floor structure contains four servoaccelerometers, three of which measure vertical acceleration directly above each of the three vertical hydraulic actuators that drive the system, whereas the fourth measures the lateral (side to side) acceleration at the location of the horizontal actuator. (The present investigation made use of only the vertical accelerometers.) Figure 1(f) is a photograph of tourist-class aircraft seats used in the present study, showing the general location of the seat accelerometer. The accelerometers used are not visible in the photographs since they were located within the seat itself. Figure 2(a) illustrates the subject-seat interface and locations for the measurement of vertical and lateral accelerations. Figure 2(b) shows details of the accelerometer for the vertical seat measurements. A disk and sleeve arrangement was inserted within the cushion material, with the flat surface of the disk resting immediately under the seat fabric. The accelerometers were then inserted into the metal sleeve and fixed in place by means of set screws. To reduce the influence of extraneous noises produced by the equipment, music was played in the PRQA. In addition, each subject was requested to use ear plugs. (See ref. 29.)

METHOD

This section describes the methods used to produce the data required for fulfilling the objectives listed in the preceding section. Two separate experiments were actually conducted, designated study A and study B. Study A encompassed all four problem areas, whereas study B dealt specifically with the last problem area (location of measurement and criteria specification for different seat types). The design for study A and that for study B are presented in detail in the following sections but a couple of comments regarding the differences between the two studies will be made here. The major difference between study A and study B is the fact that tourist-class aircraft seats were used in study A, whereas several seat types (first-class aircraft, tourist-class aircraft, and urban transit bus seats) were used in study B. Additional differences between the studies include the order of vibration stimulus presentation, exposure duration, etc., but these were not considered to be of major importance in relation to the objectives of this study.

Study A

Subjects.- A total of 60 subjects (23 males and 37 females) participated in the study. The volunteer subjects were undergraduate students from Old Dominion University and personnel from Langley Research Center. The undergraduates were paid for their participation, whereas the Langley personnel participated during regular duty hours. The ages of the subjects ranged from 18 to 39 years, with a median age of 19 years. The mean weight of the subjects was 65.6 kg (144.6 lb), with a standard deviation of 13.0 kg (28.7 lb).

Subjective evaluation scale.- A nine-point unipolar scale, with associated numerical integers, was used to evaluate the discomfort of a vibration. The scale was anchored at zero with the words "comfortable" or "zero discomfort." The anchor at the opposite end of the scale was "maximum discomfort." Thus, the scale continuum of increasing numbers was interpreted as representing increasing degrees of discomfort. The subjects were instructed to interpret the scale in an equal-interval fashion. The subjects were further instructed to base evaluations upon the discomfort of vibrations rather than the detection of sensitivity differences. Prior to the application of the stimuli for the first and fourth sessions, the subjects were exposed to anchor stimuli that typically produced low or high levels of discomfort. The anchor vibration for the lower end of the discomfort continuum was at 20 Hz and 0.05g, whereas the vibration at the high end was at 4Hz and 0.25g. The exact instructions for the task are reproduced in appendix A.

Procedure. - The task for each subject (six subjects concurrently) was an evaluation of successive "ride segments." A ride segment is defined as a vibration at a single vertical frequency (2 to 20 Hz) for 10 sec and at one of five levels of peak acceleration (0.05g, 0.10g, 0.15g, 0.20g, and 0.25g). Through the use of a two-way auditory communication system, the subjects were instructed when to begin the evaluation by the word "start" and when to end the evaluation by the word "stop." The subjects were instructed to ignore rise and decay vibrations that occurred prior to and subsequent to the words "start" and "stop," respectively.

Table 2(a) displays the design of study A. Subjects in groups of six were randomly assigned to one of the five constant acceleration levels. Therefore, a particular subject received vibrations only at one level of floor acceleration. For each acceleration level the corresponding subject group experienced a random order of the sinusoidal frequencies (2 to 20 Hz) where each frequency constituted a ride segment. This series of 19 ride segments was defined as a session and each subject group was exposed to a total of six sessions ($6 \times 19 = 114$ ride segments). Each session lasted approximately 8 min, with a 1-min rest period after each session. A 15-min rest interval was provided after the third session instead of the minute interval.

Study B

Subjects. - A total of 92 subjects (44 males and 48 females) participated in this study. The source of subjects was the same as for study A. The ages of the subjects ranged from 18 to 49 years, with a median age of 22 years. The mean weight of the subjects was 67.2 kg (148.2 lb), with a standard deviation of 16.3 kg (35.9 lb).

Subjective evaluation scale. - The task instructions were similar for subjects seated in bus, tourist-class aircraft, and first-class aircraft seats. The subjects were required to depress one of two pushbuttons to indicate satisfactory or unsatisfactory for the evaluation of a specific ride segment. The exact instructions for the task are reproduced in appendix B.

Procedure. - The design of study B is displayed in table 2(b). The task for each subject (four subjects concurrently in bus seats, six subjects concurrently in tourist-class aircraft seats, and four subjects concurrently in first-class aircraft seats) was to evaluate successive ride segments as being satisfactory or unsatisfactory. A ride segment was composed of a sinusoidal vibration at a discrete frequency within the range of 1 to 30 Hz (vertical or lateral axis) and at a peak acceleration amplitude at the floor of either 0.05g, 0.10g, or 0.15g. Through the use of a two-way auditory communication system, subjects were instructed when to begin evaluation of a ride segment by the word "start" and when to end the evaluation by the word "stop." Each ride segment (i.e., each frequency and acceleration) was applied for approximately 10 sec with 3 stimuli applied in succession (total of 30 sec). A 10-sec rest period was provided subsequent to each block of 3 stimuli. The remaining frequency and acceleration combinations were then completed in blocks of three. After exposure of subjects to this first sequence of all frequency and acceleration combinations and prior to the second sequence, subjects were rotated between seats (a similar rotation of subjects occurred after the second sequence for subjects seated in tourist-class aircraft seats). After this second sequence (or third sequence for subjects seated in tourist-class aircraft seats), subjects were provided with a 15-min rest interval. After the rest interval, a procedure similar to that before the 15-min rest interval was followed. As a result, each test subject experienced each sequence of frequency and peak floor accelerations a total number of times equal to the total number of seats. Thus, the effect of seat location was counterbalanced by rotation of the subjects from seat to seat prior to the application of each set or sequence of stimuli.

RESULTS AND DISCUSSION

The results of the two investigations are divided according to the four problem areas, which are addressed in turn. Study A was directed at all four problem areas, whereas study B was concerned with the last problem area (location for measurement and criteria specification) for different seat types.

To provide an overall summary of the discomfort responses of study A, an analysis of variance was computed. Specifically, a three-dimensional analysis of variance ($5 \times 6 \times 19$, with repeated measures on the same subject across levels of the last two dimensions, see ref. 30) was used to determine the effect of peak floor acceleration, intermittent exposure or practice over successive sessions, and frequency upon discomfort responses. There were 5 levels of peak acceleration within the first dimension, 6 sessions within the second, and 19 levels of frequency within the third dimension.

Table 3 presents a summary of the analysis of variance. The results indicate that each of the main effects of acceleration, session, and frequency, as well as their interactions, was significant. The graphs corresponding to these effects are displayed in figures 3 to 7 and each will be discussed in detail in the following sections as they relate to the four problem areas mentioned earlier.

Frequency Averaging

The problem of concern in this section is to determine whether the prediction of passenger discomfort can be based upon a frequency averaging process or whether information on the frequency content of the spectrum is also necessary. The main effects obtained from the analysis of variance of acceleration level and frequency, as well as their interaction, are relevant to this problem area and are discussed in turn.

Acceleration.- Figure 3 displays the mean discomfort ratings that occurred as a function of floor acceleration level. The mean discomfort ratings of figure 3 have been averaged over all frequencies and all sessions. It is seen that the general trend is for increasing discomfort for increasing floor acceleration level. The t-test comparisons of the mean discomfort ratings between successive acceleration levels of figure 3, given in the following table, were all significant ($p < 0.05$; t-test values $\geqq 1.645$ needed to achieve statistical significance for $df = 2734$).

Acceleration levels compared	t-test value
0.05g and 0.10g	1.833
0.10g and 0.15g	2.613
0.15g and 0.20g	5.150
0.20g and 0.25g	7.921

The comparison of mean ratings for the 0.05g and 0.10g acceleration levels indicated a reversal which was statistically significant. For undetermined reasons, the discomfort responses were greater for the 0.05g level of acceleration than for the 0.10g level of acceleration. There are two possible explanations for these results. First, the reversal could be due to the fact that both acceleration levels (for the majority of frequencies) may be below a "discomfort threshold" causing the difference in evaluation to be an artifact. Secondly, the experimental design restricted a particular subject's evaluation of a single level of floor acceleration. Therefore, direct evaluation by the subjects of their discomfort to these two low levels of acceleration were not made and differences, if they existed, were not directly obtainable. At acceleration levels equal to and greater than 0.10g, human discomfort to vibration increases with acceleration ($r = 0.883$; $r \geqq 0.805$ needed to achieve statistical significance ($p < 0.05$) for $df = 3$) implying that despite averaging of discomfort across frequencies and sessions, the resultant peak acceleration will show a significant trend with discomfort responses.

Frequency.- Figure 4 shows the mean discomfort ratings (averaged over floor acceleration levels and sessions) as a function of frequency. The general trend of this plot shows that mean discomfort ratings vary considerably with frequency and that maximum discomfort occurs over the frequency range of 3 to 9 Hz. Table 4 presents the t-test comparisons between successive frequencies for the data of figure 4. Results of the t-tests indicated that discomfort ratings for 4, 5, 6, and 7 Hz did not differ significantly from each other. There was a significant decrease of discomfort ratings for successive sinusoidal rides between 7 and 12 Hz. The discomfort ratings did not differ for successive ride segments between 12 and 20 Hz. However, there was a significant decrease (not displayed in table 4) of discomfort ratings from a ride of 12 Hz to a ride of 20 Hz (t-test value equals 6.865; t-test value $\geqq 1.960$ needed to achieve statistical significance ($p < 0.05$) for $df = 718$). It should be noted that the frequency trend displayed in figure 4 is similar to that of the recommended ISO weights. (See ref. 23.) More important, however, is the fact that discomfort is highly dependent upon frequency, with the result that frequency averaging will weaken the predictive capability of an overall measure such as rms acceleration. This latter point becomes more apparent from the analysis of the acceleration-frequency interaction that follows.

Acceleration-frequency interaction.- It should be recalled that the analysis of variance indicated a significant interaction between acceleration and frequency (table 3). This interaction is displayed in figure 5 which shows the mean discomfort ratings plotted as a function of frequency for each level of floor acceleration. The mean discomfort ratings in this case are averaged only over all the sessions (the curve of fig. 4 was averaged over both sessions and acceleration levels). Thus figure 5 is merely a breakdown of figure 4 into the five separate acceleration levels from which the ordinate of figure 4 was computed. Complementary to figure 5 are tables 5 and 6 which give the statistical significance of these results through the use of t-test comparisons for the two divisions of variance associated with the acceleration-frequency interaction.

The initial division of the acceleration-frequency interaction is between successive acceleration levels for each frequency. It is readily apparent from examination of figure 5 and the t-test values of table 5 that the effect of floor acceleration level (successive acceleration levels) on discomfort ratings is discernable and is continuous in nature over the frequency range of 3 to 8 Hz. Above a frequency of 10 Hz, however, the discomfort response as a function of acceleration begins to assume a dichotomous form indicating a possible threshold effect. For example, the t-tests of table 5 indicate that beyond 10 Hz the differences of ratings between acceleration levels of 0.05g, 0.10g, and 0.15g (at each frequency) are not statistically significant. At a floor acceleration level of 0.20g, some significant differences in discomfort response begin to become apparent, and at 0.25g almost all comparisons of discomfort responses are significant.

The second division of the acceleration-frequency interaction is between the discomfort ratings for successive frequencies for each floor acceleration level. The statistical significance of these comparisons are given in table 6. These results indicate, for each acceleration level, a discomfort trend across frequency similar to the trend for combined acceleration levels (fig. 4). Thus discomfort is a function of both acceleration and frequency, and consequently, frequency averaging may not generally be appropriate for the prediction of discomfort.

Transmissibility effects.- The discomfort trend across frequencies is similar to the transmissibility (seat acceleration divided by floor acceleration; see ref. 10 for a complete discussion of the measure) across frequency as displayed in figure 6 for each level of floor acceleration. However, the discomfort trend can not be attributed to the transmissibility trend. Figure 7, which accounts for transmissibility differences, displays the discomfort responses that occurred for constant seat acceleration levels (0.05g, 0.10g, 0.15g, 0.20g, and 0.25g) as a function of frequency. Figure 7 was generated through several computations. The first was a calculation of a least-square fit (for each frequency) between the discomfort responses and actual seat acceleration experienced by the subjects for the five levels of floor acceleration. The second calculation, upon which the actual figure was based, was a prediction of the discomfort, for select levels of seat acceleration. The implication is that the differences between frequencies still exist, subsequent to a control of transmissibility.

ISO comparison.- As mentioned in an earlier section, the trend illustrated by figure 4 (and also fig. 5) appears to be similar to the ISO standards for reduced comfort. To facilitate comparison with ISO, each curve of figure 5 was normalized by dividing each data point by the value of mean discomfort for frequencies of 4 to 8 Hz. The result is a set of frequency weighting factor curves corresponding to each value of floor acceleration. These normalized curves are compared to the ISO (see ref. 23) frequency weighting factor curve in figure 8. The results show generally good agreement between the data of this study and the ISO weighting factor curve with respect to frequency dependence (shape of the curves). However, examination of the vertical spread of the curves at each frequency indicates that the weighting factors vary somewhat with acceleration level. For example, at a frequency of 2 Hz, the weighting factors range from a value of approximately 0.61 to a value of 0.78 and at a frequency of 20 Hz, from about 0.32 to 0.64 (a difference of a factor of two).

Summary of frequency averaging.- The implications of the results of this section as they apply to the question of frequency averaging are summarized as follows: First, human discomfort responses when averaged over all frequencies displayed significant increases as a function of peak acceleration level at and beyond 0.10g. This indicates that a crude prediction of discomfort is possible from mere knowledge of an overall measure of vibration intensity (such as rms acceleration). Second, it was demonstrated that discomfort has a significant dependence upon both frequency and acceleration. Hence, both should be used for a comprehensive prediction of discomfort. This implies that frequency averaging is generally not an appropriate procedure to be used in the prediction of human discomfort response. Finally, the discomfort responses to vertical sinusoidal vibrations were generally a continuous function of acceleration rather than dichotomous and followed a trend across frequency similar to that reported by ISO. (See ref. 23.) This means that over the most critical frequency region (3 to 8 Hz) the subjects are capable of making fine discriminations of discomfort to single-axis vibrations.

Practice

This section addresses the question of whether practice or repeated exposure to vibration influences subsequent discomfort responses. The main effect of sessions from the analysis of variance as well as its interactions with acceleration and frequency are relevant to this problem and are discussed in turn.

Sessions.- Figure 9 shows the mean discomfort ratings that occurred as a function of session (increasing session number implies increasing exposure time). The curve shows a slight decrease in discomfort from sessions 1 to 4 and then a trend of increasing discomfort for sessions 5 and 6. The significance of this trend was established by computing paired-observation t-tests between the mean discomfort ratings of successive sessions, which are as follows: (All values, except 0.989, were statistically significant ($p < 0.05$); t-test values $\geqq 1.671$ needed to achieve statistical significance for $df = 59$.)

Sessions compared	t-test value
1 and 2	2.841
2 and 3	.989
3 and 4	2.664
4 and 5	2.034
5 and 6	1.916

The t-test values indicate that the changes in discomfort ratings between successive sessions are statistically significant. This trend, however, is not indicative of a practice or learning effect since it is not truly systematic. That is, a learning related task would give either a systematic increase or decrease of response as a function of sessions, not a reversal of trend as exhibited in figure 9. The next section of this paper will explain this reversal by examining the session effect for each acceleration level (i.e., session-acceleration interaction).

Session-acceleration interaction.- Figure 10 displays the mean discomfort ratings that occurred for each acceleration level as a function of session and tables 7 and 8 display the t-test comparisons for the division of variance associated with this interaction. Inspection of figure 10 and the statistical data of table 7 (t-test comparisons between the discomfort ratings of successive sessions for each acceleration level) indicates that the ratings associated with the 0.05g acceleration level did not vary across successive sessions. The discomfort ratings for the 0.10g acceleration level remained constant, except for a statistically significant decrease between sessions 2 and 3.

Table 7 further indicates there was no difference between successive sessions for the 0.15 or 0.25g levels, except between the initial sessions and sessions 4 and 5, respectively. The largest change in discomfort ratings across sessions was for the 0.20g acceleration level. There were statistically significant decreases in discomfort ratings between sessions 1 and 2 and 3 and 4, and a significant increase between sessions 5 and 6. The latter result together with the 0.10g data may explain the trend reversal of figure 7. In other words, this means that the nonsystematic trend of discomfort ratings across sessions seems to be largely attributable to discomfort ratings associated with the 0.20g acceleration level and to a lesser extent the ratings at the 0.10g acceleration level. The implication of these results is that, in a practical sense, either naive or practiced subjects can be used for the investigation of ride quality factors (e.g., exposure duration, noise, etc.).

In order to provide a more complete division of the variance associated with the session-acceleration interaction, t-test comparisons were computed between the discomfort ratings for successive acceleration levels for each session. Table 8 which lists these t-test comparisons was included for completeness. However, these results were expected from previous analyses and are not discussed.

Session-frequency interaction.- Corresponding to the significant session-frequency interaction, figure 11 displays the mean discomfort ratings that occurred for each frequency as a function of session. Tables 9 and 10 display the t-test comparisons for the division of variance associated with this interaction.

Table 9 represents a summary of the discomfort ratings between successive sessions for each frequency. Generally, table 9 and figure 11 indicate only sporadic fluctuations of discomfort responses for individual frequencies, with no apparent systematic increase or decrease in discomfort. A trend similar to that discovered from analysis of the session main effect was apparent; that is, there was a slight decrease in discomfort ratings for all frequencies through session 3 and a subsequent increase through session 6 (except at 16 Hz where a decrease in discomfort ratings in the final session was evident). However, as mentioned earlier, the discomfort trend across sessions displays this trend which can in large part be attributed to ratings at the acceleration level of 0.20g.

In order to provide a more complete division of the variance associated with the session-frequency interaction, t-test comparisons were computed between successive frequencies for each session and are presented in table 10. Figure 11 shows in graphical form the data upon which the t-test comparisons of table 10 were based. This figure illustrates the mean discomfort ratings (averaged across subjects and acceleration levels) obtained for each session. Table 10 and figure 11 indicate that the same pattern of discomfort across frequency obtained from analysis of the frequency and frequency-acceleration interaction occurred within each session, as evidenced by comparison of table 10 with table 4 or 6.

In summary, there is one major conclusion that results from the analysis of practice effects. There was no effect of practice upon subsequent discomfort responses; the initial decrease and subsequent increase of discomfort ratings across sessions (for all frequencies) can, in large part, be attributed to the ratings at the 0.20g level of acceleration. The implication of these results is that either naive or practiced subjects can be used for the investigation of various factors (e.g., exposure duration, noise, etc.). Finally, the earlier reported discomfort effect across frequency occurred within each session.

Demographic Factors

This section examines the amount of discomfort response variation due to the demographic factors of age, weight, and sex for the subject sample used in these studies. Table 11 gives the correlations between discomfort ratings and age, weight, and sex for the sixth session (the reasons for selection of the sixth session are discussed in the next section) for each frequency. None of these correlations achieved statistical significance, implying that the factors of age, weight, and sex do not contribute to discomfort response variation. However, it should be pointed out that the ages (and weights) of the subjects of this investigation were truncated, possibly accounting for the lack of a relationship of these factors with discomfort.

Floor-Seat Contributions

This section discusses the relative contribution of vibrations at the seat and at the floor (when the vibrations are simultaneously experienced) to the total discomfort of a passenger. Results obtained for tourist-class aircraft seats (study A) are first discussed and then results obtained for other seat types (first-class aircraft and bus seats – study B) are considered.

Tourist-class aircraft seats.- In order to optimize the chances of obtaining stable estimates of the relative contributions of vibrations at the seat and floor locations, the session with the most reliable discomfort ratings was used for these analyses. Discomfort response reliability was estimated through test-retest correlation coefficients which were computed at each frequency between successive sessions (i.e., 1 and 2, 2 and 3, 3 and 4, 4 and 5, and 5 and 6). The final estimate of discomfort response reliability was an average of these 19 reliability coefficients (one for each frequency). The average reliabilities of 0.60, 0.60, 0.63, 0.67, and 0.64 were all significant ($r \geqq 0.243$ needed to achieve statistical significance ($p < 0.05$) for $df = 46$). Since these reliability coefficients were approximately equal, it is logical to select session 6 data for the extraction of information about the importance of vibration at the two locations since session 6 should give the most stable estimates of performance. The analyses which determine these contributions (floor-seat) are single and multiple correlations computations. Since these analyses are based upon assumptions of linearity, the discomfort ratings for the acceleration level of 0.05g were excluded from these analyses. The fact that floor and seat accelerations appreciably differ is well documented in reference 25. For the tourist-class seats of study A these differences are illustrated in figure 12. This figure shows mean amplitude transmissibility as a function of frequency for tourist-class aircraft seats. The mean amplitude transmissibility is the ratio of seat acceleration to floor acceleration at each frequency averaged over all accelerations and a large number of subjects. From figure 12 it is seen that the seat accelerations are greater than floor accelerations (by a factor of 1.2 to 1.3) at frequencies below about 9 Hz and less than floor accelerations (by a factor of 0.6 to 0.7) above 9 Hz.

Multiple correlations.- In conjunction with the preceding information table 11 displays multiple correlations between the discomfort ratings and the five factors previously considered separately (floor acceleration, seat acceleration, weight, age, and sex). These multiple correlations were all significant except for those of 2 Hz and 13 Hz. The relative importance of floor and seat acceleration contributions to the discomfort ratings is obtainable from the multiple regression coefficients (by transforming into z-score (standard normal score) slopes to obtain beta weights) provided that each predictor is an independent predictor of the discomfort response criterion. (See ref. 31.) The data of figure 12 implies that there is some correlation between seat and floor accelerations and as a result their individual capacity for prediction of discomfort is weakened. The average correlation coefficient between seat acceleration and floor acceleration yielded a value of 0.87, indicating a high degree of correlation. This implies that (1) despite absolute differences between seat and floor accelerations, these measures are highly intercorrelated and therefore are not independent measures and (2) because they are not independent measures, they cannot be used to compute weighting factors for the relative contributions of floor and seat accelerations to discomfort response.

To further determine the degree of relationship between these predictors, t-tests for comparisons of related correlation coefficients (ref. 32) were computed. These comparisons were between correlations (the correlation of the discomfort rating with floor acceleration and the correlation of the discomfort rating with seat acceleration). Thus, the comparisons were between the correlations listed in the first two columns of table 11. Figure 13 displays the mean discomfort ratings of session six (for selected frequencies) as a function of both floor and seat accelerations which formed the bases of these separate correlations. The equal predictive capability of the two measurement locations is obvious from the parallel trends associated with each set of curves. The results of the t-test comparisons for these data are presented in table 11, which shows statistical differences between these correlations only for frequencies of 8, 15, and 18 Hz. This means that, except for these three frequencies, there is no difference in the contribution of vibration at the floor or at the seat to the total discomfort of a passenger. These results were obtained from tests using tourist-class aircraft seats. The logical question as to whether these results apply to other seat types is discussed in the following section.

Other seat types. - Study B, as described earlier, provided data on passenger acceptability of three types of seats (tourist-class aircraft seats, first-class aircraft seats, and bus seats). Typical data indicating passenger acceptance of each seat type is presented in figure 14. Figure 14 shows the percent acceptance of vertical and lateral vibrations for three types of seats as a function of both floor and seat accelerations at a frequency of 4 Hz. Percent acceptance is defined as the percentage of ride segments at each condition (acceleration level and frequency for each axis of motion) that were perceived as comfortable. Similar graphs and trends were obtained for each frequency in the range of 1 to 10 Hz and for each axis of motion. These results show that for each seat type the acceptance trends for floor and seat accelerations are roughly parallel, thus implying that either location of measurement can be used to predict comfort for any particular seat type. The problem still remains as to whether passenger acceptance differs significantly between the different seat types. The answer to this problem will determine whether a predictive equation of discomfort will be needed for each seat type or whether a single predictive equation will be adequate.

In order to answer the question mentioned in the preceding paragraph, chi-square values χ^2 corrected for discontinuity because of small samples (see ref. 33) were computed between the number of comfort responses of passengers within the different types of seats. These chi-square values were computed between these responses at three floor acceleration levels (0.05g, 0.10g, and 0.15g) and three similar seat acceleration levels (approximately 0.05g, 0.10g, and 0.15g measured at the seat location) for both the vertical and lateral directions of motion. Tables 12 and 13 contain the actual seat acceleration levels (which varied for each frequency) at which the chi-square values were computed based upon least-squares estimates of percent acceptance by seat acceleration. Tables 14 and 15 give the chi-square values for vertical motion computed between different seats for selected floor and seat acceleration levels, respectively. These results indicate that the differences between the comfort responses for the different seat types are not statistically significant. Concerning the lateral axis of motion, tables 16 and 17 indicate similar chi-square values, with minor exceptions. Table 16 shows that 4 of 90 chi-square values indicated a difference between seats for similar floor acceleration level inputs. These four cases of a difference can be ignored for two reasons. First, the possibility exists that the differences are artifacts. Second, table 17 indicates these seat differences were removed for chi-square values computed between seats of equal seat acceleration level. The latter result implies that floor measurements for the three seats could be corrected at these selected frequencies if a lateral criteria specification were based upon the floor location.

In summary, the problem was to determine the importance of vibration at the floor, and at the seat, for determination of measurement and specification of criteria locations. The present recommendation, based upon these data, is to measure acceleration and specify criteria at the floor location. The reasons for the recommendation are twofold. First, the predictability of discomfort is equal, based on either floor or seat acceleration measurements. Secondly, the discomfort of different seats (tourist-class aircraft, first-class aircraft, and bus seats) for similar inputs are equal. The advantages of this recommendation include the (1) practicality of measurements, (2) avoidance of transmissibility testing for similar seat types, and (3) floor criteria can be corrected for distinctly different seats or at selected frequencies.

CONCLUSIONS

An experimental investigation was conducted to determine (1) the adequacy of frequency averaging of vibration data to obtain discomfort predictors, (2) the effect of practice, (3) the effect of demographic factors (age, weight, and sex), and (4) a location for ride quality criteria specifications. Statistical analyses of the discomfort responses of a total of 152 subjects to systematically applied vibratory inputs resulted in the following conclusions related to methodology and measurement location:

1. A prediction of discomfort is possible from knowledge of only the overall acceleration level of a ride. However, a more comprehensive and accurate prediction of discomfort results from knowledge of both the acceleration level and frequency content of a ride. The latter was illustrated by the overall frequency trend and the fact that the discomfort responses were a continuous rather than a dichotomous function of acceleration. The trend of discomfort as a function of frequency was similar to that reported by ISO, with similar trends displayed within each session and for each level of acceleration.

2. The study indicated that either practiced or naive subjects can be used equally well for the investigation of human response to vibration. Intermittent exposure of passengers to vibration generally causes only a slight decrease in discomfort responses; the initial decrease and subsequent increase of discomfort ratings across sessions can, in large part, be attributed to ratings at the 0.20g level of acceleration.

3. The demographic factors of age, weight, and sex did not contribute substantially to the explanation of discomfort response to vibration.

4. The prediction of discomfort was shown to be equally good whether based upon floor accelerations or seat accelerations. Furthermore, it was demonstrated that the discomfort in different seats to similar vibratory inputs was equal. It is therefore rec-

ommended that criteria specifications and acceleration measurements be made at the floor location. The advantages of using the floor location for measurement and specification of criteria include (1) the practicality of measurements, (2) the avoidance of transmissibility testing for similar seat types, and (3) the correction of floor criteria for distinctly different seats or selected frequencies.

Langley Research Center
National Aeronautics and Space Administration
Hampton, Va. 23665
September 17, 1975

APPENDIX A

SUBJECT INSTRUCTIONS – STUDY A

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 such 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 the methods above.

The task you will be required to perform is to evaluate the discomfort associated with various ride segments. Each ride segment, to be evaluated by yourself, will be presented to you for a total of 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." Evaluate the discomfort of a <u>vibration</u> contained in a ride segment in terms of the following discomfort scale:

ZERO DISCOMFORT								MAXIMUM DISCOMFORT
0	1	2	3	4	5	6	7	8

There will be several seconds between successive ride segments to allow you to mark your evaluation of discomfort.

APPENDIX A

Evaluation marks.- You should record your evaluation of the discomfort (associated with the vibration of each ride segment) by placing a checkmark (e.g., √) upon the scale continuum. Try to be careful in recording your evaluations because the point of the checkmark (√) will be used for interpretation of distance along the scale.

Scale interpretation.-

ZERO DISCOMFORT								MAXIMUM DISCOMFORT
0	1	2	3	4	5	6	7	8

The discomfort scale should be interpreted as if equal numerical distances represented equal discomfort. For example, the magnitude of discomfort between 1 and 2 is equal to the magnitude of discomfort between 5 and 6. The total continuum should be conceived as representing increasing discomfort values (smallest to greatest) you may associate with vibration. In addition, it should be emphasized that your evaluation of discomfort should be based only upon vibration. Certainly, you could evaluate the discomfort of a ride segment based upon other factors as temperature, pressure, etc. However, restrict your discomfort evaluations to variations of vibration.

The scale will be more meaningful when you are given several practice ride segment vibrations. The practice segments will contain representative vibrations that could be evaluated along the discomfort continuum. You will be given a total of two practice ride segments.

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 and 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 the vibration of each ride segment in terms of the discomfort you associate with such a ride.

3. Interpret the discomfort scale as if equal numerical distances represent equal discomfort magnitudes.

4. Carefully place your evaluation mark on the continuum.

Are there any questions?

(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 one-way mirror, and 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 a half hour.

APPENDIX B

SUBJECT INSTRUCTIONS – STUDY B

You have volunteered to participate in a research program to investigate the quality of rides, or comfort, associated with various transportation systems such as aircraft, trains, and buses. Specifically, we wish to identify the types of motion or vibration in transportation vehicles which most influence a person's sense of well-being or comfort. To do this we have built an aircraft simulator which can expose passengers to realistic ride motions in one or more directions at a time. The system has been designed to meet stringent safety requirements such 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 test that you will participate in today is being conducted to determine how much vibration is transmitted from the floor of the aircraft through the seat cushion itself. The seat cushions have been instrumented to measure the transmitted vibrations. You will enter the aircraft, 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. You must, however, 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 anytime 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. It is important to keep in mind that unfastening the seatbelts will stop the motion. 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 the methods described above.

During the test there will be motions that we want you to rate as either "satisfactory" or "unsatisfactory." These motions will come in segments about 10 seconds long. At the beginning of each segment you are to rate, the test conductor will say "start," and at the end of the segment, he will say "stop." You will be provided a small black box with five push buttons with which to record your rating. If the quality of the ride segment is satisfactory to you, press the button numbered "one." If the quality is not satisfactory to you, press the button numbered "two." You are to press the appropriate button immediately after you hear the word "stop" signifying the end of the segment. Please do not be concerned about whether your ratings agree with the others in the aircraft with you. Remember we want to know how <u>different</u> people feel about the ride. You may talk between the segments you are to rate but please do not talk during them. Are there any questions about what you are to do?

(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 one-way mirror, and 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 a half hour.

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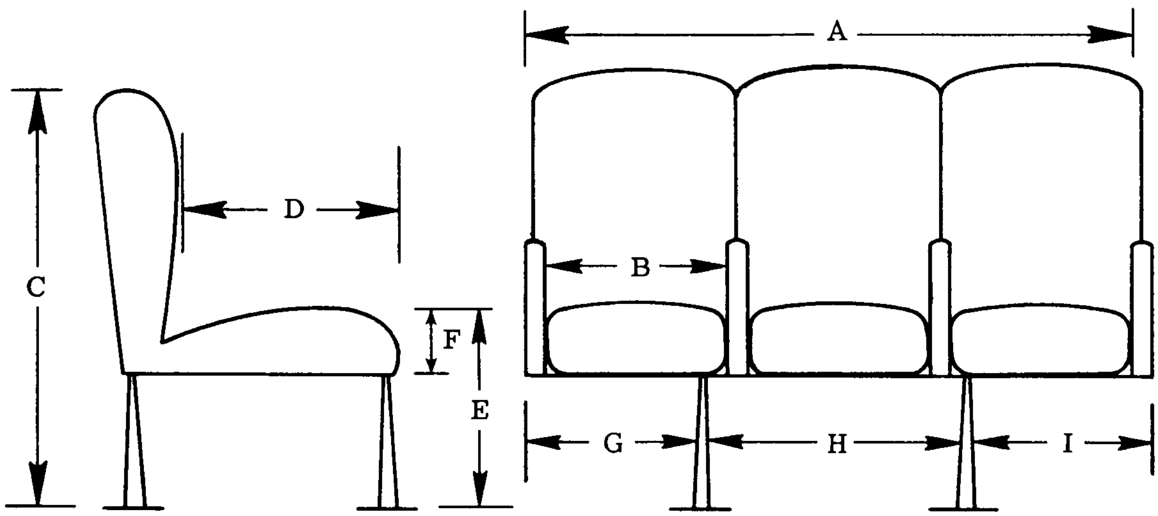
TABLE 1.- SEAT DIMENSIONS



Seat type	Dimensions, m (in.), for –								
	A	B	C	D	E	F	G	H	I
Tourist class	1.50 (59.2)	0.44 (17.5)	1.03 (40.5)	0.47 (18.5)	0.46 (18)	0.06 (2.5)	0.46 (18)	0.53 (21)	0.43 (17)
First class	1.50 (59.2)	0.52 (20.5)	1.09 (43.0)	0.48 (19.0)	0.46 (18)	0.10 (4.0)	0.53 (21)	0.53 (21)	0.36 (14)
Bus	0.88 (34.5)	(a) -----	0.90 (35.5)	0.43 (17.0)	0.46 (18)	0.10 (4.0)	0.18 (7)	0.53 (21)	0.18 (7)

[a]No armrests.

TABLE 2.- EXPERIMENTAL DESIGNS OF STUDY A AND STUDY B

(a) Study A

Sessions		1	2	3	4	5	6
f, Hz		2, 3, . . ., 20	2, 3, . . ., 20	2, 3, . . ., 20	2, 3, . . ., 20	2, 3, . . ., 20	2, 3, . . ., 20
Floor peak acceleration, g units	Subjects						
0.05	1 to 12						
.10	13 to 24						
.15	25 to 36						
.20	37 to 48						
.25	49 to 60						

(b) Study B

Floor peak acceleration	0.05g	0.10g	0.15g
f, Hz	1, 2, 3, 4, . . ., 30	1, 2, 3, 4, . . ., 30	1, 2, 3, 4, . . ., 30
Seat location			
1	Each subject experienced all combinations of frequency and floor acceleration in each seat location and seat type		
2			
3	Frequencies used were 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 20, 25, and 30 Hz		
4			
5			
6			

TABLE 3. - SUMMARY OF THE ANALYSIS OF VARIANCE OF THE DISCOMFORT EVALUATIONS

Source of variation	SS	df	MS	F (a)	
Between subjects	6 198.31	59			
Acceleration	2 554.00	4	638.50	9.64*	(2.54)
Subjects within groups (error: acceleration)	3 644.31	55	66.26		
Within subjects	22 506.53	6780			
Session	259.19	5	51.84	12.03*	(2.26)
Acceleration-session	396.80	20	19.84	4.60*	(1.62)
Session-subjects within groups (error: sessions)	1 184.89	275	4.31		
Frequency	12 875.08	18	715.28	282.88*	(1.67)
Acceleration-frequency	605.54	72	8.41	3.33*	(1.38)
Frequency-subjects within groups (error: frequency)	2 503.27	990	2.53		
Session-frequency	133.49	90	1.48	1.86*	(1.28)
Acceleration-session-frequency	605.04	360	1.68	2.11*	(1.17)
Session-frequency-subjects within groups (error: session-frequency)	3 943.22	4950	.80		
Total	28 704.84	6839			

[a]The values with asterisks were statistically significant ($p < 0.05$). The critical values of F needed to achieve statistical significance are indicated in parentheses. (These critical values were obtained where necessary from the next lower degree of freedom.)

TABLE 4.- SUMMARY OF t-TEST COMPARISONS OF DISCOMFORT RATINGS AVERAGED OVER ACCELERATION LEVELS AND SESSIONS FOR SUCCESSIVE FREQUENCIES[a]

Frequencies compared, Hz	t-test value	Frequencies compared, Hz	t-test value
2 and 3	10.533*	11 and 12	2.706*
3 and 4	8.570	12 and 13	.844
4 and 5	1.280	13 and 14	1.470
5 and 6	1.055	14 and 15	1.110
6 and 7	1.914	15 and 16	1.506
7 and 8	4.001*	16 and 17	.477
8 and 9	4.799*	17 and 18	.746
9 and 10	6.599*	18 and 19	.604
10 and 11	5.419*	19 and 20	.479

[a]The values with asterisks were statistically significant ($p < 0.05$); t-test values $\geqq 1.960$ needed to achieve statistical significance for $df = 718$.

TABLE 5.- SUMMARY OF t-TEST COMPARISONS OF DISCOMFORT RATINGS OF SUCCESSIVE ACCELERATION LEVELS FOR EACH FREQUENCY[a]

[Comparisons represent division of variance associated with acceleration-frequency interaction]

f, Hz	t-test comparison of discomfort ratings of acceleration levels –			
	0.05g and 0.10g	0.10g and 0.15g	0.15g and 0.20g	0.20g and 0.25g
2	0.618	1.814*	0.230	3.108*
3	2.250*	.066	5.782*	6.011*
4	1.359	3.691*	2.655*	4.820*
5	2.270*	.224	5.257*	3.899*
6	1.906*	.378	4.455*	3.046*
7	2.365*	.014	2.030*	2.363*
8	1.966*	1.037	1.494	.083
9	4.457*	1.080	1.824*	1.735*
10	2.819*	2.294*	.980	3.611*
11	.063	2.151*	.858	4.408*
12	1.450	1.608	1.804*	5.345*
13	.131	.297	3.346*	5.127*
14	.722	1.960*	1.781*	5.056*
15	.288	1.158	2.851*	4.978*
16	.553	1.200	1.792*	5.934*
17	.226	1.973*	1.336	7.350*
18	2.019*	.389	2.204*	5.762*
19	1.552	.488	1.035	6.737*
20	1.571	1.853*	2.315*	6.210*

[a]The values with asterisks were statistically significant ($p < 0.05$); t-test values $\geqq 1.645$ needed to achieve statistical significance for $df = 142$.

TABLE 6.- SUMMARY OF t-TEST COMPARISONS OF DISCOMFORT RATINGS OF SUCCESSIVE FREQUENCIES FOR EACH ACCELERATION LEVEL[a]

[Comparisons represent division of variance associated with session-frequency interaction]

Frequencies compared, Hz	t-test value at acceleration level of –				
	0.05g	0.10g	0.15g	0.20g	0.25g
2 and 3	0.912	2.416*	3.769*	9.970*	9.768*
3 and 4	4.689*	4.039*	6.969*	4.417*	3.596*
4 and 5	.073	.992	2.696*	.186	2.240*
5 and 6	.502	.675	.107	.975	1.277
6 and 7	.165	.221	.364	2.404*	3.432*
7 and 8	1.566	2.818*	1.828	2.069*	4.973*
8 and 9	.930	2.924*	3.021*	2.600*	1.219
9 and 10	4.396*	3.487*	2.300*	3.347*	1.677
10 and 11	4.452*	2.152*	2.108*	2.577*	1.335
11 and 12	.279	1.741	2.542*	1.715	.431
12 and 13	.720	.600	1.353	.018	.654
13 and 14	.824	1.651	.537	.987	.637
14 and 15	.772	.463	1.221	.062	.268
15 and 16	.203	.551	.535	1.801	.885
16 and 17	.974	.743	.025	.434	1.012
17 and 18	1.848	.000	1.516	.658	1.747
18 and 19	.606	.022	.064	1.072	.016
19 and 20	1.418	1.833	.103	1.089	1.046

[a]The values with asterisks were statistically significant ($p < 0.05$); t-test values $\geqq 1.960$ needed to achieve statistical significance for df = 142.

TABLE 7.- SUMMARY OF t-TEST COMPARISONS OF DISCOMFORT RATINGS OF SUCCESSIVE SESSIONS FOR EACH ACCELERATION LEVEL[a]

[Comparisons represent division of variance associated with acceleration-session interaction]

Acceleration level, g units	t-test comparison of discomfort ratings of sessions –				
	1 and 2	2 and 3	3 and 4	4 and 5	5 and 6
0.05	0.299	1.161	0.634	0.457	0.817
.10	.955	2.464*	1.761	.549	.879
.15	2.367*	2.095*	1.660	.601	.085
.20	2.927*	1.661	2.216*	1.852*	2.621*
.25	1.028	1.059	1.172	2.442*	1.463

[a]The values with asterisks were statistically significant ($p < 0.05$); t-test values $\geqq 1.796$ needed to achieve statistical significance for $df = 11$.

TABLE 8.- SUMMARY OF t-TEST COMPARISONS OF DISCOMFORT RATINGS OF SUCCESSIVE ACCELERATION LEVELS FOR EACH SESSION[a]

[Comparisons represent division of variance associated with acceleration-session interaction]

Session	t-test comparison of discomfort ratings of acceleration levels –			
	0.05g and 0.10g	0.10g and 0.15g	0.15g and 0.20g	0.20g and 0.25g
1	2.5228*	1.5837	5.4079*	0.0938
2	1.7083*	.7172	2.1195*	4.3036*
3	1.0411	1.6648*	1.3557	7.4378*
4	2.9742*	1.1365	.3147	9.0990*
5	2.0300*	1.1957	1.8448*	8.3131*
6	2.1149*	.6777	4.9264*	4.2118*

[a]The values with asterisks were statistically significant ($p < 0.05$); t-test values $\geqq 1.645$ needed to achieve statistical significance for df = 454.

TABLE 9.- SUMMARY OF t-TEST COMPARISONS OF DISCOMFORT RATINGS OF SUCCESSIVE SESSIONS FOR EACH FREQUENCY[a]

[Comparisons represent division of variance associated with session-frequency interaction]

f, Hz	t-test comparison of discomfort ratings of sessions –				
	1 and 2	2 and 3	3 and 4	4 and 5	5 and 6
2	2.86*	0.81	2.62*	1.70*	0.65
3	.71	2.26*	.54	.88	1.04
4	1.77*	1.54	.86	.36	.19
5	.03	1.51	.22	.54	.50
6	3.56*	1.81*	.44	.23	.24
7	1.73*	.16	.19	.00	.83
8	1.52	2.03*	.00	.51	.39
9	1.71*	.37	1.60	.57	2.74*
10	.06	1.38	.66	1.46	.20
11	1.89*	2.26*	.57	1.87*	1.65
12	2.37*	.46	1.74*	.52	3.44*
13	.79	1.95*	.53	1.31	.28
14	.03	3.42*	.40	1.58	.61
15	4.43*	.01	1.34	.90	1.21
16	.77	1.00	1.54	2.05*	2.33*
17	.76	.55	1.29	.68	.78
18	.97	.29	.14	.12	1.12
19	1.86*	1.52	1.87*	2.12*	.50
20	1.77*	1.56	1.63	.23	2.89*

[a]The values with asterisks were statistically significant ($p < 0.05$); t-test values $\geqq 1.67$ needed to achieve statistical significance for df = 59.

TABLE 10.- SUMMARY OF t-TEST COMPARISONS OF DISCOMFORT RATINGS OF SUCCESSIVE FREQUENCIES FOR EACH SESSION[a]

[Comparisons represent division of variance associated with session-frequency interaction]

Frequencies compared, Hz	t-test value of session –					
	1	2	3	4	5	6
2 and 3	4.45*	7.42*	3.63*	7.33*	5.40*	5.29*
3 and 4	6.13*	4.10*	7.97*	5.82*	4.66*	4.38*
4 and 5	1.02	.62	2.76*	.77	.66	.46
5 and 6	2.38*	1.46	1.94	1.12	1.37	1.46
6 and 7	4.11*	1.54	.28	1.19	1.36	.24
7 and 8	.60	.78	2.05*	3.07*	2.68*	4.24*
8 and 9	4.65*	4.48*	4.26*	3.32*	3.49*	1.09
9 and 10	4.37*	4.30*	5.81*	5.22*	2.64*	5.38*
10 and 11	3.35*	5.73*	1.42	4.47*	3.70*	1.94
11 and 12	.05	.42	4.82*	.68	3.89*	1.94
12 and 13	1.40	1.00	.47	1.14	.93	3.32*
13 and 14	1.25	.38	1.46	1.22	.79	1.29
14 and 15	1.05	3.64*	.44	1.25	1.83	.12
15 and 16	4.68*	.46	.90	.82	.92	3.00*
16 and 17	.71	.31	1.42	.14	2.20*	.85
17 and 18	1.24	1.18	.96	.47	.09	.38
18 and 19	.05	.90	.68	2.18*	.14	.40
19 and 20	1.15	1.03	1.86	.38	2.02*	.13

[a]The values with asterisks were statistically significant ($p < 0.05$); t-test values $\geqq 2.00$ needed to achieve statistical significance for $df = 59$.

TABLE 11

SUMMARY FOR SIXTH SESSION OF CORRELATIONS BETWEEN DISCOMFORT RATINGS AND VARIOUS FACTORS, MULTIPLE CORRELATIONS BETWEEN DISCOMFORT RATINGS AND A COMPOSITE OF THESE FACTORS, AND t-TEST COMPARISONS OF FLOOR AND SEAT ACCELERATION CORRELATIONS FOR SUCCESSIVE FREQUENCIES[a]

f, Hz	Correlation between discomfort ratings and –					Multiple correlation	t-test value
	Floor acceleration	Seat acceleration	Age	Weight	Sex		
2	-0.123	-0.094	0.019	-0.008	0.031	0.196	0.384
3	.630*	.664*	.009	-.061	.105	.693*	.162
4	.593*	.541*	.036	-.080	.069	.617*	.477
5	.557*	.557*	-.050	-.038	.049	.580*	.000
6	.568*	.572*	-.248	-.061	-.094	.646*	.039
7	.404*	.449*	.063	.183	.263	.508*	.424
8	.244*	.371*	-.197	-.052	.000	.510*	2.282*
9	.328*	.423*	-.050	.033	.218	.526*	1.396
10	.557*	.556*	-.156	-.052	.023	.598*	.020
11	.559*	.534*	.040	-.048	-.077	.578*	.490
12	.656*	.657*	-.061	-.012	.062	.677*	.024
13	.441*	.413*	-.019	.063	.099	.453	.466
14	.573*	.513*	.006	-.038	.036	.577*	1.082
15	.599*	.480*	.160	-.051	.138	.648*	2.228*
16	.511*	.447*	-.068	.017	.162	.563*	.941
17	.476*	.441*	-.153	-.140	-.038	.532*	.494
18	.494*	.328*	.130	-.002	.156	.538*	2.034*
19	.473*	.480*	.004	-.149	.063	.565*	.091
20	.648*	.532*	.087	.016	.164	.677*	1.566

[a]The values with asterisks were statistically significant ($p < 0.05$); correlation values $\geqq 0.243$ needed to achieve statistical significance for df = 46; multiple correlation values $\geqq 0.484$ needed to achieve statistical significance for df = 42; t-test values $\geqq 2.021$ needed to achieve statistical significance for df = 45.

TABLE 12.- SEAT ACCELERATION LEVELS IN VERTICAL DIRECTION FOR FREQUENCIES AT WHICH χ^2 VALUES WERE COMPUTED FOR TABLE 15

f, Hz	Seat acceleration level, g units		
	First comparison (a)	Second comparison (a)	Third comparison (a)
1	0.0546	0.1116	0.1576
2	.0550	.1183	.1710
3	.0506	.1326	.1900
4	.0600	.1100	.1600
5	.0593	.1200	.1700
6	.0563	.1200	.1750
7	.0593	.1100	.1600
8	.0576	.1000	.1300
9	.0506	.0900	.1300
10	.0420	.0800	.1100

[a]First comparison, second comparison, and third comparison refer to approximate seat accelerations of 0.05g, 0.10g, and 0.15g, respectively.

TABLE 13.- SEAT ACCELERATION LEVELS IN LATERAL DIRECTION FOR FREQUENCIES AT WHICH χ^2 VALUES WERE COMPUTED FOR TABLE 17

f, Hz	Seat acceleration level, g units		
	First comparison (a)	Second comparison (a)	Third comparison (a)
1	0.0500	0.0950	0.1400
2	.0600	.1000	.1400
3	.0500	.0950	.1100
4	.0500	.0900	.1250
5	.0450	.0850	.1250
6	.0450	.0900	.1300
7	.0500	.1050	.1650
8	.0650	.1000	.1500
9	.0650	.1050	.1650
10	.0700	.1200	.1850

[a]First comparison, second comparison, and third comparison refer to approximate seat accelerations of 0.05g, 0.10g, and 0.15g, respectively.

TABLE 14.- χ^2 VALUES BETWEEN COMFORT RESPONSES OF PASSENGERS IN DIFFERENT SEATS FOR THREE VERTICAL FLOOR ACCELERATIONS[a]

f, Hz	χ^2 values between comfort responses in –								
	Bus and tourist-class aircraft seats for floor accelerations of –			Bus and first-class aircraft seats for floor accelerations of –			Tourist-class and first-class aircraft seats for floor accelerations of –		
	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g
1	0.0038	0.3097	0.1326	0.0601	0.1301	0.0291	0.0144	0.3758	0.0054
2	.0121	.0898	.1008	.1680	.0131	.0315	.0361	.0018	.0190
3	.1884	3.2337	.8971	.0221	.6136	.7221	.0003	.1101	.1179
4	.1980	1.6162	.1896	.0046	2.0671	.2150	.7734	.0101	.4311
5	.0181	1.1825	1.5007	.0012	1.8915	.4428	.0054	.0618	.9676
6	.0641	.2075	.9409	.1856	.2036	.0824	.2552	.0939	.2904
7	.0104	.0663	.0281	.0011	.0091	.5661	.0909	.0366	.0281
8	.0520	.0023	.1708	.2222	.1991	.2808	.0520	.0365	.0164
9	.0250	.0022	.1402	.1850	.1216	.1677	.0528	.0108	.2314
10	.0185	.0898	.0278	.1912	.0454	.0610	.0450	.0051	.0450

[a]No values were statistically significant ($p < 0.05$); χ^2 values $\geqq 3.8410$ needed to achieve statistical significance for $df = 1$.

TABLE 15.- χ^2 VALUES BETWEEN COMFORT RESPONSES OF PASSENGERS IN DIFFERENT SEATS FOR THREE VERTICAL SEAT ACCELERATIONS[a]

[For exact values of seat accelerations used for χ^2 values, see table 12]

f, Hz	χ^2 values between comfort responses in –								
	Bus and tourist-class aircraft seats for seat accelerations of approximately –			Bus and first-class aircraft seats for seat accelerations of approximately –			Tourist-class and first-class aircraft seats for seat accelerations of approximately –		
	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g
1	0.0244	0.0117	0.0093	0.0616	0.0756	0.1170	0.1745	0.0690	0.0413
2	.0421	.0043	.0610	.1046	.0793	.0205	.0545	.0465	.0098
3	.0006	.0652	.4409	.0462	.0191	.0953	.0895	.0048	.2891
4	.0691	.0019	.0403	.0059	.0000	.0191	.4457	.2802	.3411
5	.0928	.0401	.0002	.0002	.0000	.0007	.0266	.0018	.1098
6	.0310	.0668	.2396	.0176	.0040	.1549	.2077	.0302	.0227
7	.1074	.0531	.0077	.1110	.1116	.3293	.0872	.0128	.0148
8	.0240	.0785	.1432	.1467	.0005	.2182	.0074	.0046	.4581
9	.0020	.1041	.0174	.0286	.0313	.1750	.0985	.0138	.0018
10	.0228	.0001	.2396	.1936	.0744	.9513	.0530	.0083	.1409

[a]No values were statistically significant ($p < 0.05$); χ^2 values $\geqq 3.8410$ needed to achieve statistical significance for $df = 1$.

TABLE 16.- χ^2 VALUES BETWEEN COMFORT RESPONSES OF PASSENGERS IN DIFFERENT SEATS FOR THREE LATERAL FLOOR ACCELERATIONS[a]

f, Hz	χ^2 values between comfort responses in –								
	Bus and tourist-class aircraft seats for floor accelerations of –			Bus and first-class aircraft seats for floor accelerations of –			Tourist-class and first-class aircraft seats for floor accelerations of –		
	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g
1	1.0714	0.2063	3.0741	3.2723	0.0971	1.4937	0.8016	0.2649	0.9041
2	.2789	.6418	3.0741	.4174	4.2847*	.0000	.0004	.1235	2.2815
3	1.5315	.4989	.0000	.9796	.3277	.0000	.1129	.0102	.0000
4	.9358	.0140	.1218	.4191	.5033	.0000	.1173	.1163	.0127
5	.0052	.3302	.0107	.0179	.2840	1.2543	.1196	.5929	.0393
6	.0006	.8813	.0315	.0052	.4662	4.2847*	.2364	.0628	.0758
7	.0115	2.6606	.0784	.0848	.6303	.3751	.0457	.2178	.0104
8	4.1265*	1.6854	1.4094	3.7153*	.8948	.1470	.0000	.0301	.1774
9	.0152	3.0213	3.0043	.0241	.1226	.1224	1.6139	1.0358	1.3410
10	3.2872	.9688	1.9186	.7236	.1073	.1238	.0518	1.0041	2.2981

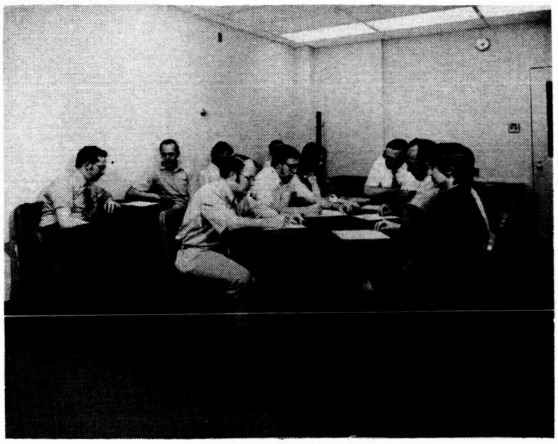
[a]The values with asterisks were statistically significant ($p < 0.05$); χ^2 values $\geqq 3.410$ needed to achieve statistical significance for $df = 1$.

TABLE 17.- χ^2 VALUES BETWEEN COMFORT RESPONSES OF PASSENGERS IN DIFFERENT SEATS FOR THREE LATERAL SEAT ACCELERATIONS[a]

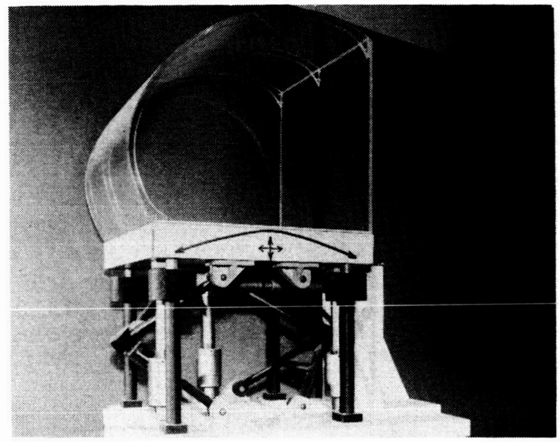
[For exact values of seat accelerations used for χ^2 values, see table 13]

f, Hz	χ^2 values between comfort responses in –								
	Bus and tourist-class aircraft seats for seat accelerations of approximately –			Bus and first-class aircraft seats for seat accelerations of approximately –			Tourist-class and first-class aircraft seats for seat accelerations of approximately –		
	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g	0.05g	0.10g	0.15g
1	0.7182	0.3419	0.0081	3.2935	1.1444	0.2122	1.2330	0.2309	0.0360
2	.2917	.1272	.0163	.4461	.0299	.0039	.0001	.0500	.2436
3	.5060	.1371	.1164	.7646	.2180	.1048	.0053	.5468	1.3103
4	.1193	.0959	.0022	.3170	.0361	.0211	.0060	.1263	.7033
5	.0196	.0084	.5044	.0722	.1365	.2015	.1352	.0157	.7549
6	.1750	.0002	.3163	.0798	.0150	.0026	.3150	.7190	2.4219
7	.1067	.0037	.4743	.1701	.0921	.1243	.0270	.0513	.6995
8	.1485	.1116	.2381	.2652	.4172	1.1083	.6122	.9259	2.7533
9	.0079	.1384	.7746	.1134	.3881	1.4858	.0013	.0152	.1044
10	.4202	.0140	.1117	.2712	.0205	.5032	.0205	.0058	.0816

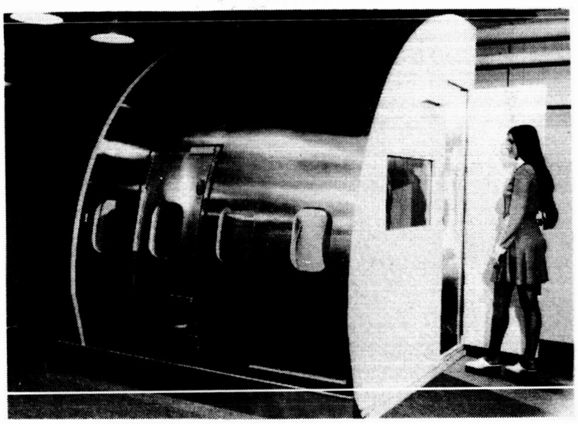
[a]No values were statistically significant ($p < 0.05$); χ^2 values $\geqq 3.410$ needed to achieve statistical significance for $df = 1$.



(a) Waiting room.

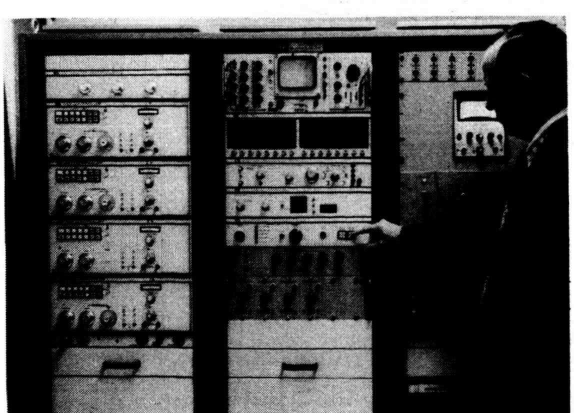


(b) Model of PRQA.



(c) Simulator exterior.

(d) Simulator interior.

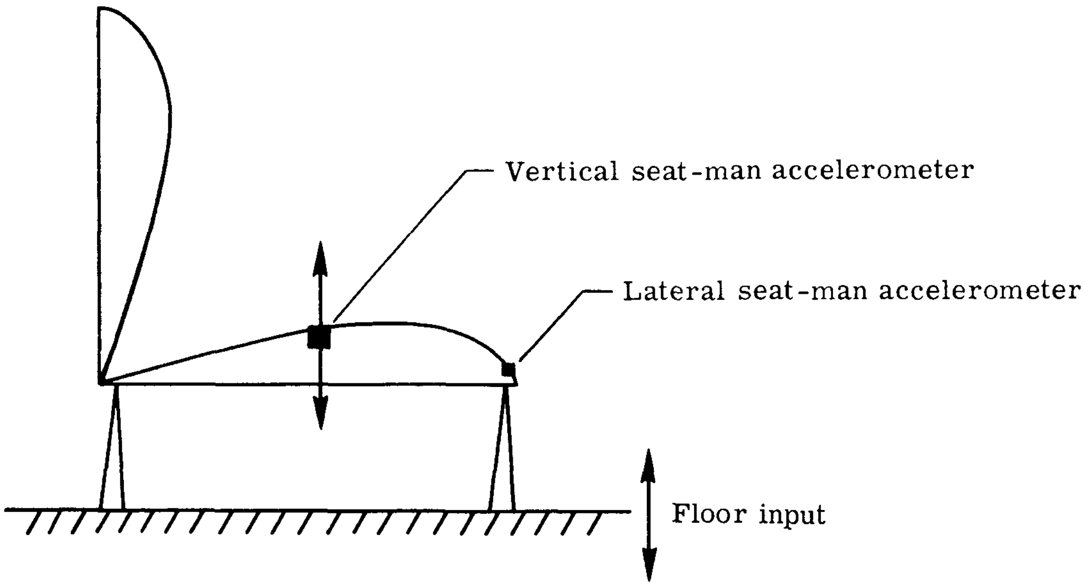


(e) Control console.

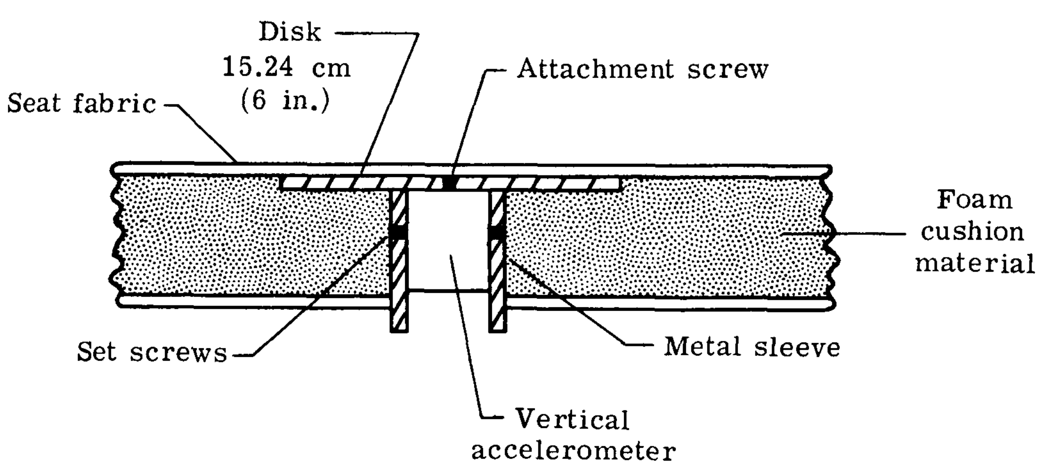
L-75-218

(f) Tourist-class seats.

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



(a) Vertical accelerometer location.



(b) Accelerometer installation detail.

Figure 2.- Details of accelerometer location and installation.

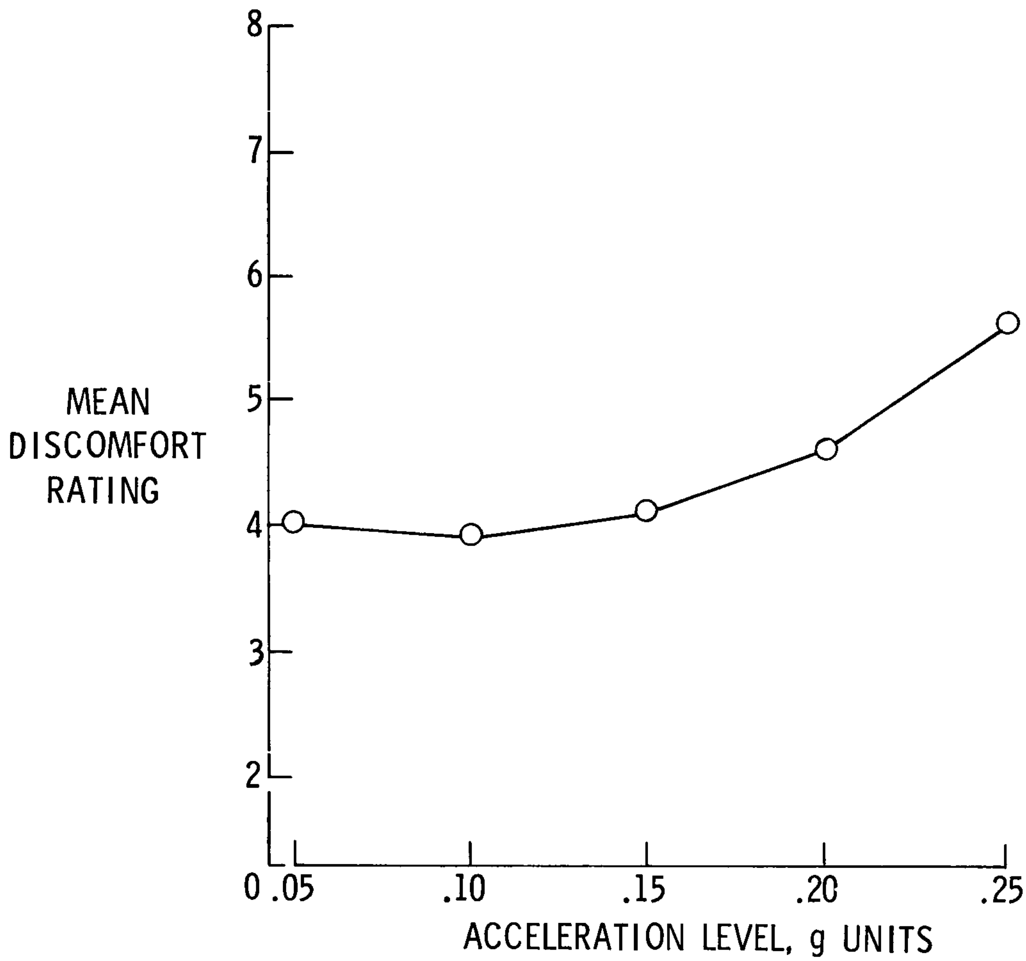


Figure 3.- Mean discomfort ratings (averaged across subjects, vertical sinusoidal frequency, and sessions) as a function of floor acceleration level.

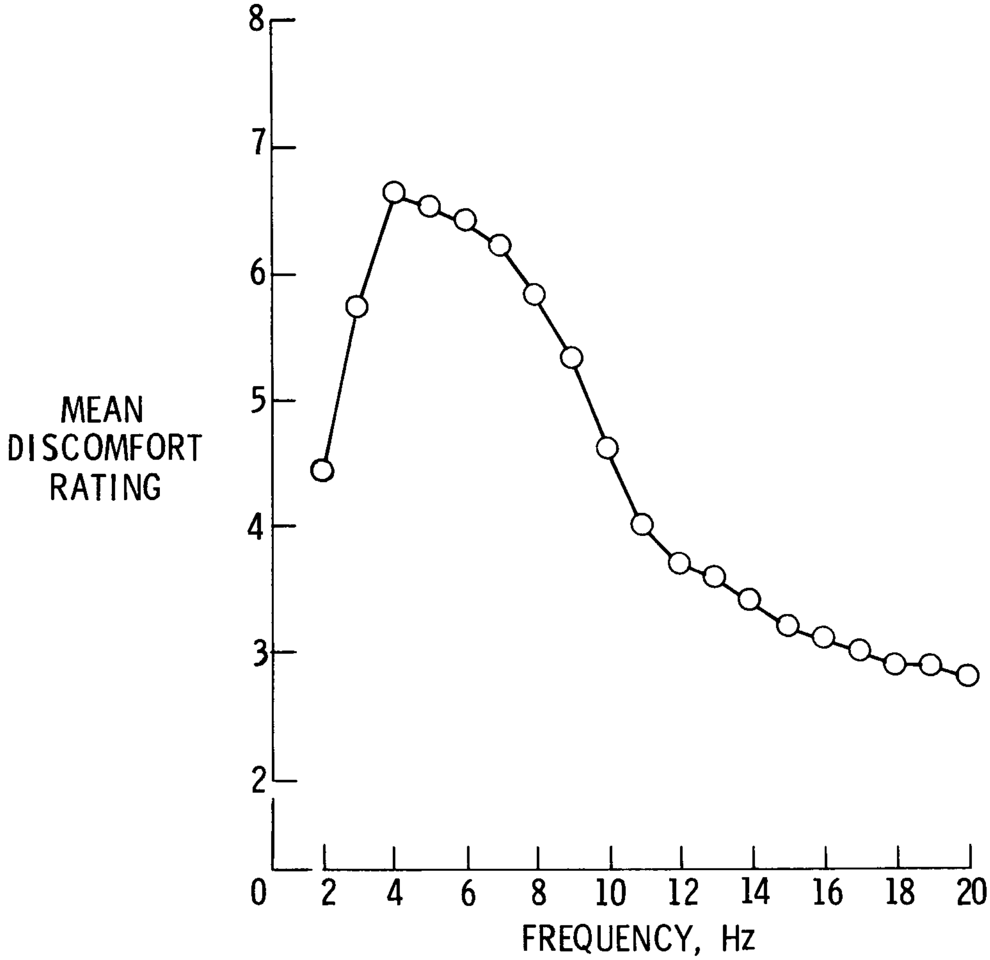


Figure 4.- Mean discomfort ratings (averaged across subjects, acceleration levels, and sessions) as a function of vertical sinusoidal frequency.

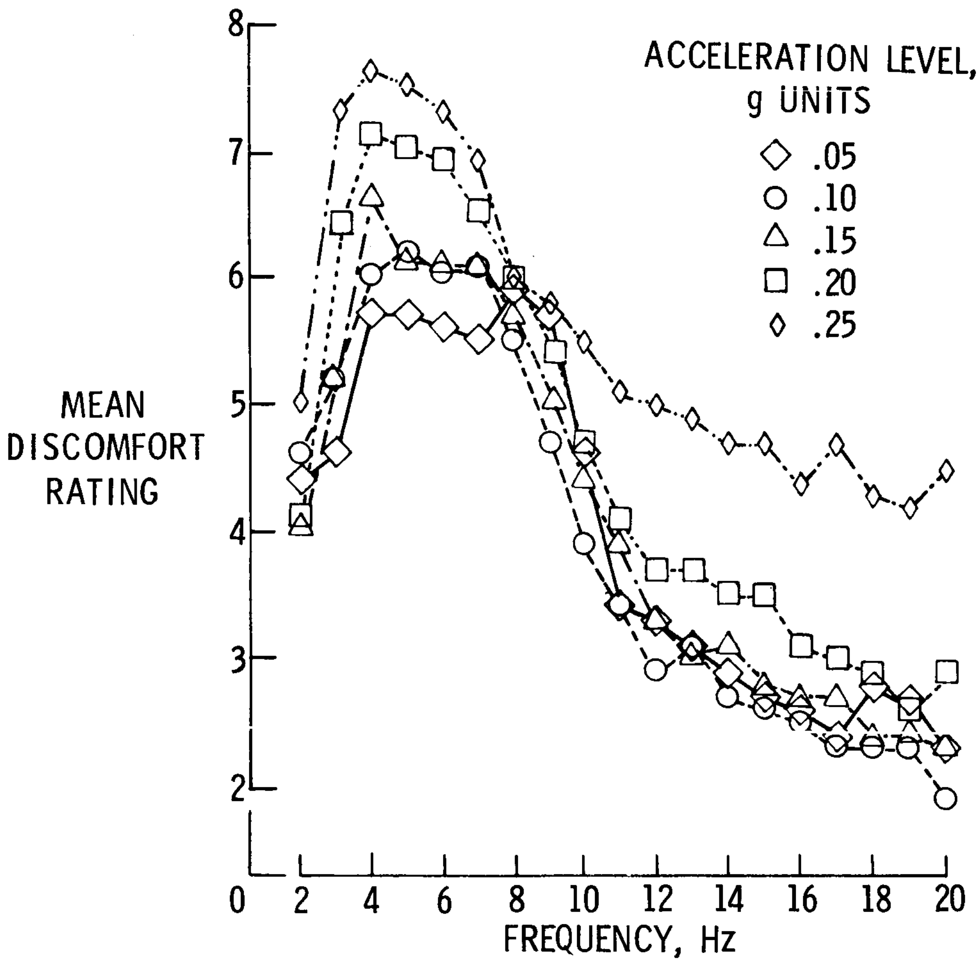


Figure 5.- Mean discomfort ratings (averaged across subjects and sessions) for each level of acceleration as a function of vertical sinusoidal frequency.

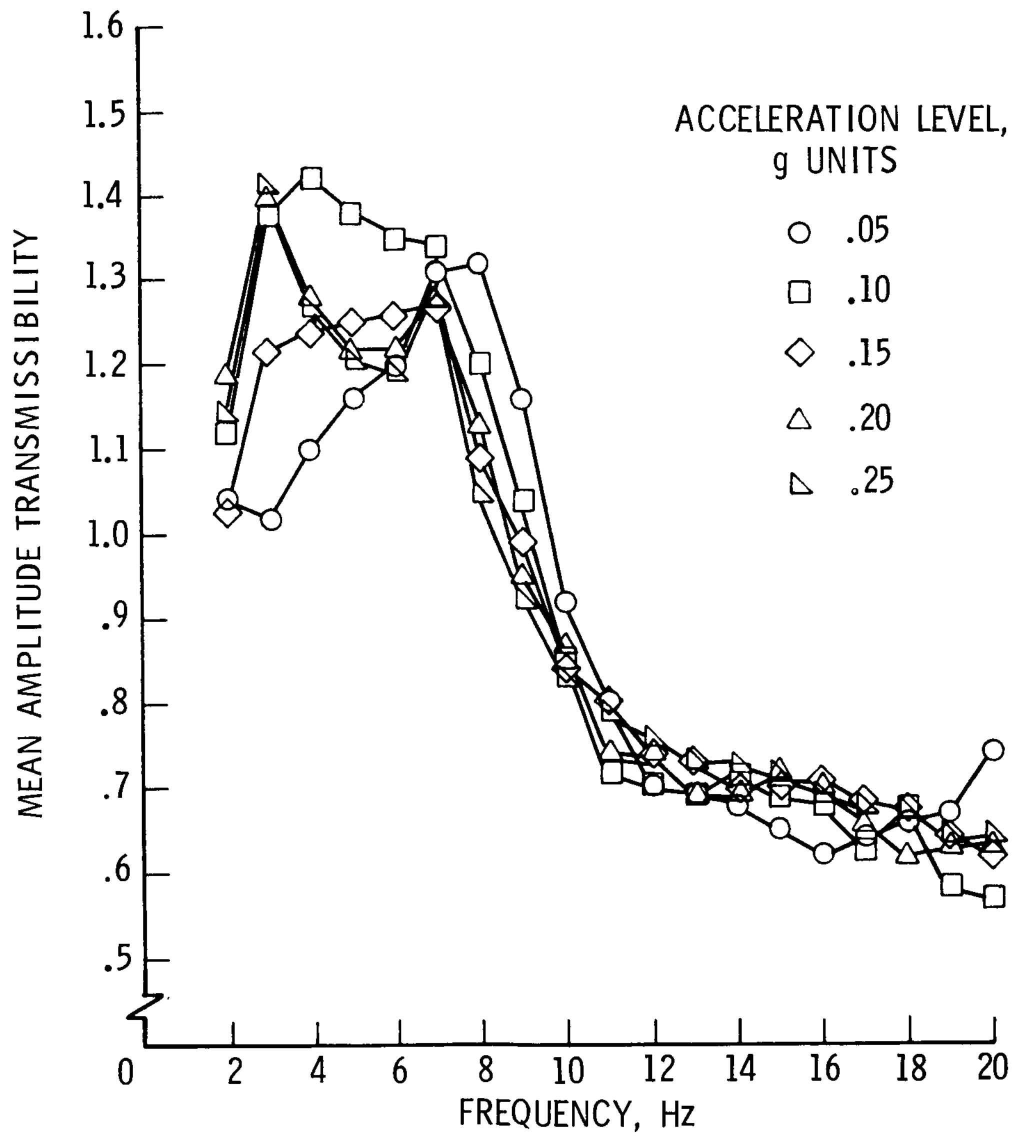


Figure 6.- Mean amplitude transmissibility (seat acceleration/floor acceleration) for five levels of peak floor acceleration as a function of frequency.

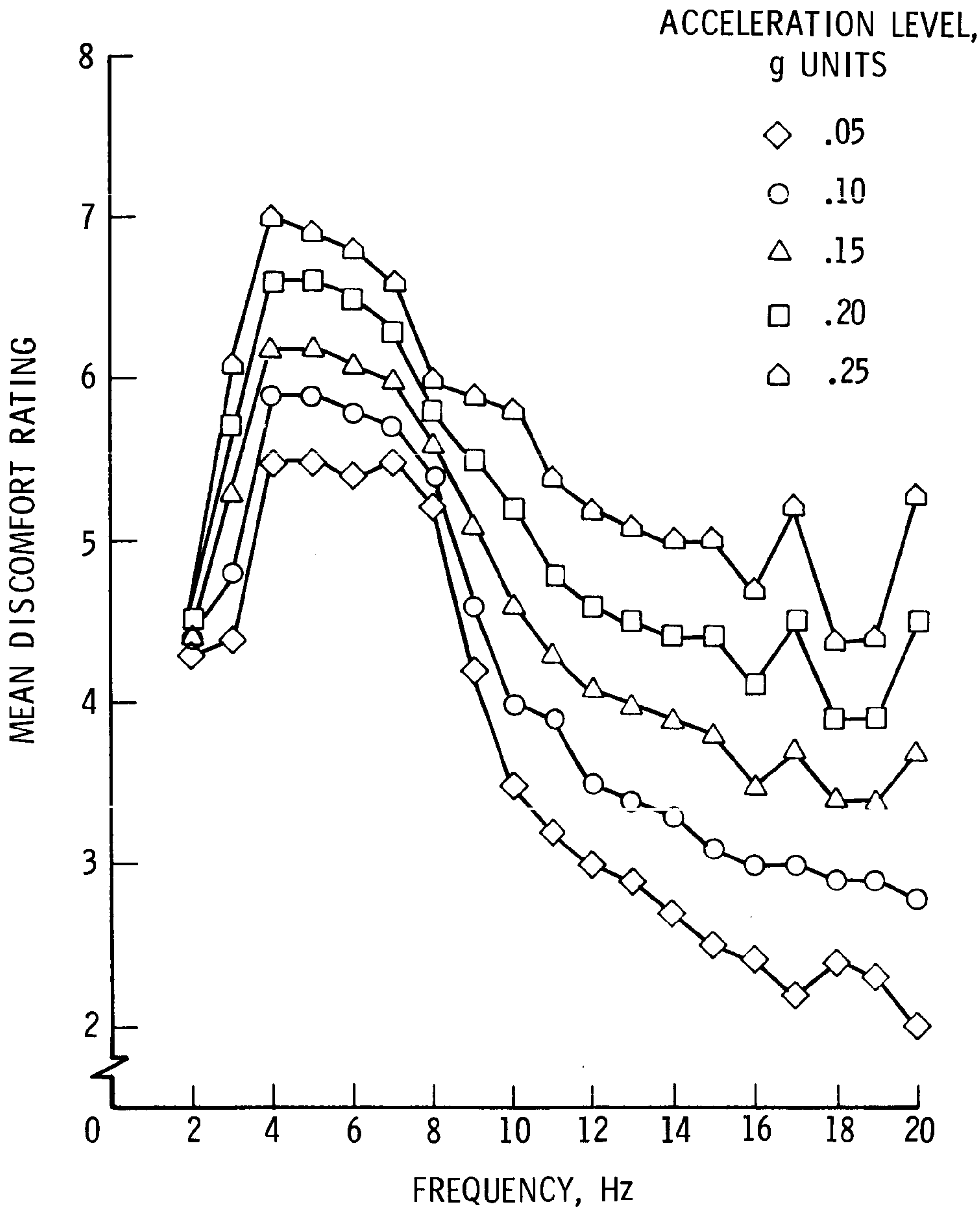


Figure 7.- Mean discomfort responses for five levels of seat acceleration as a function of vertical sinusoidal frequency.

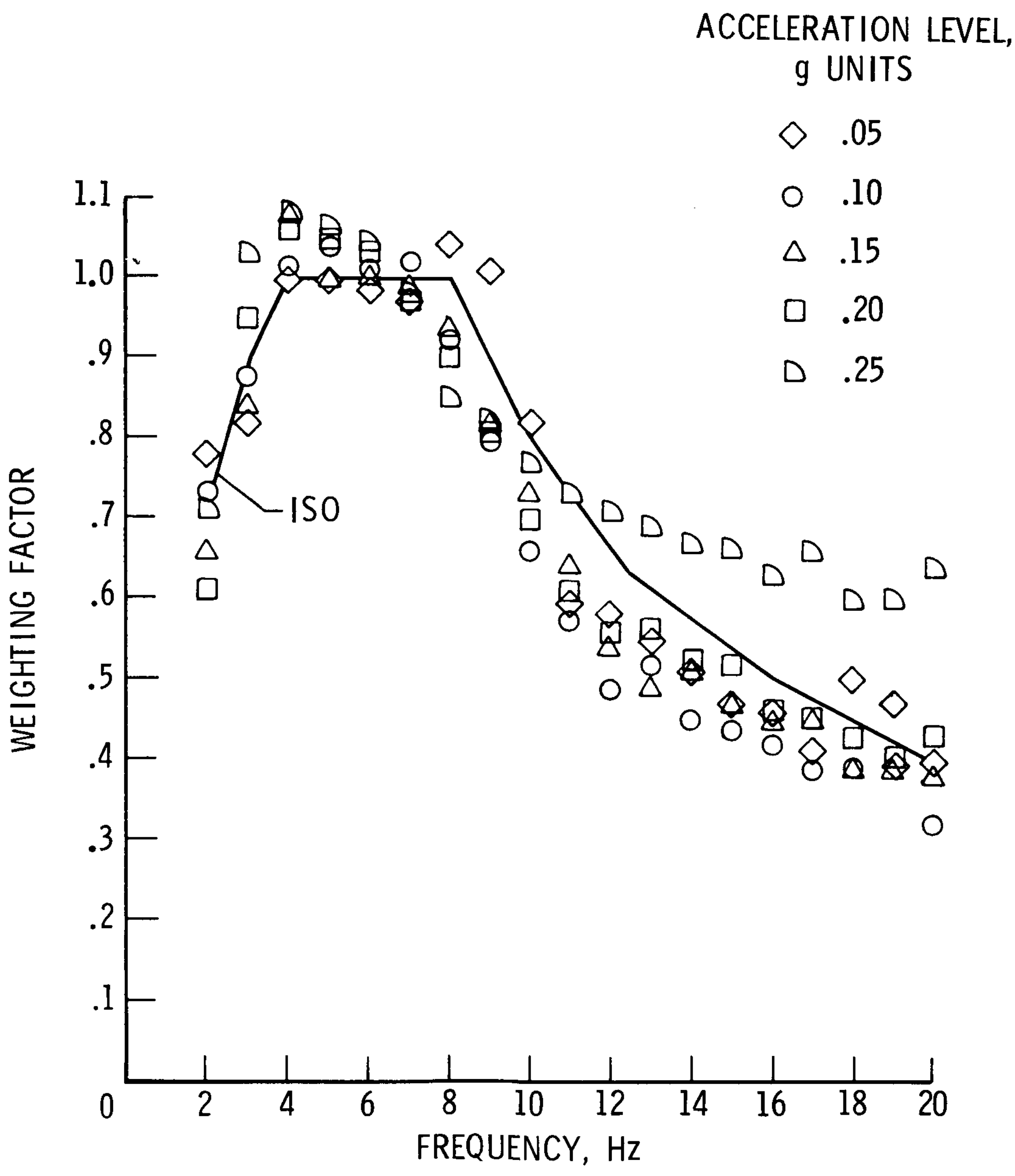


Figure 8.- Weighting factors (normalized discomfort) as a function of vertical sinusoidal frequency.

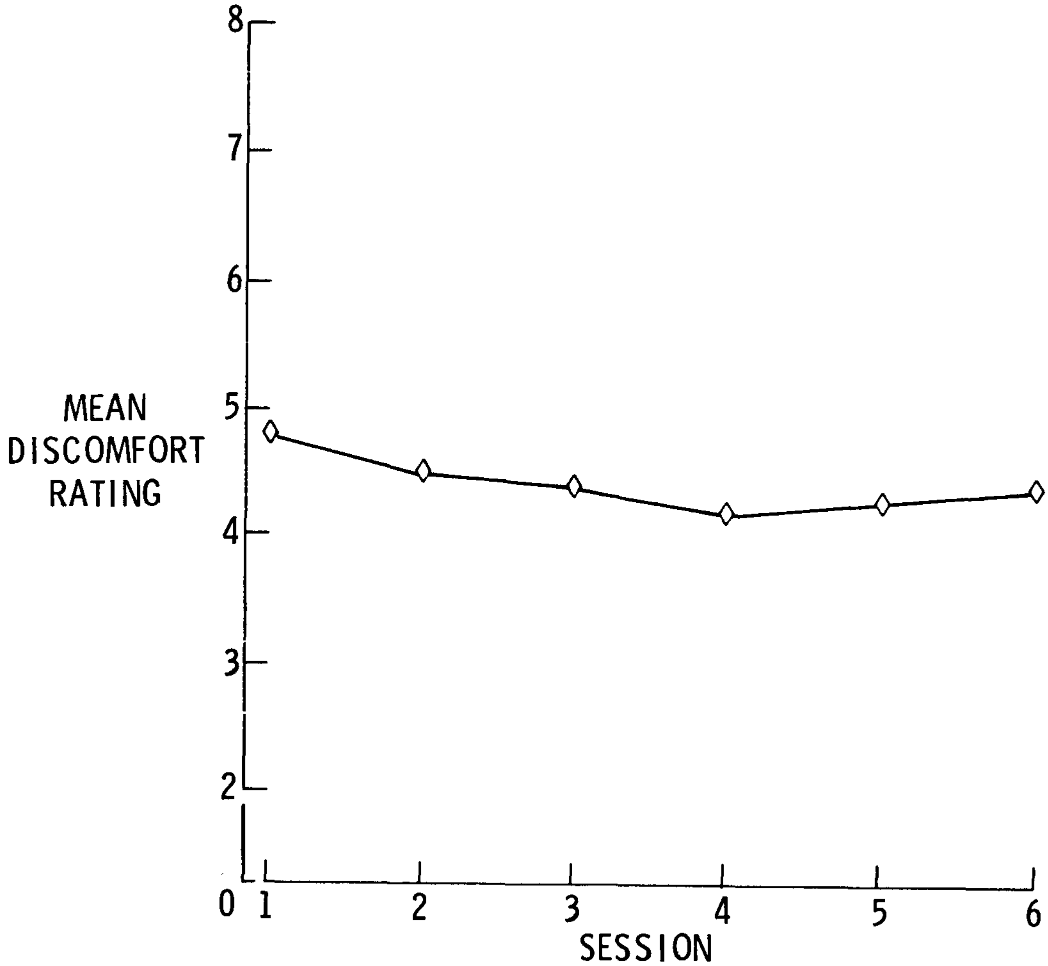


Figure 9.- Mean discomfort ratings (averaged across subjects, acceleration levels, and vertical sinusoidal frequency) as a function of session.

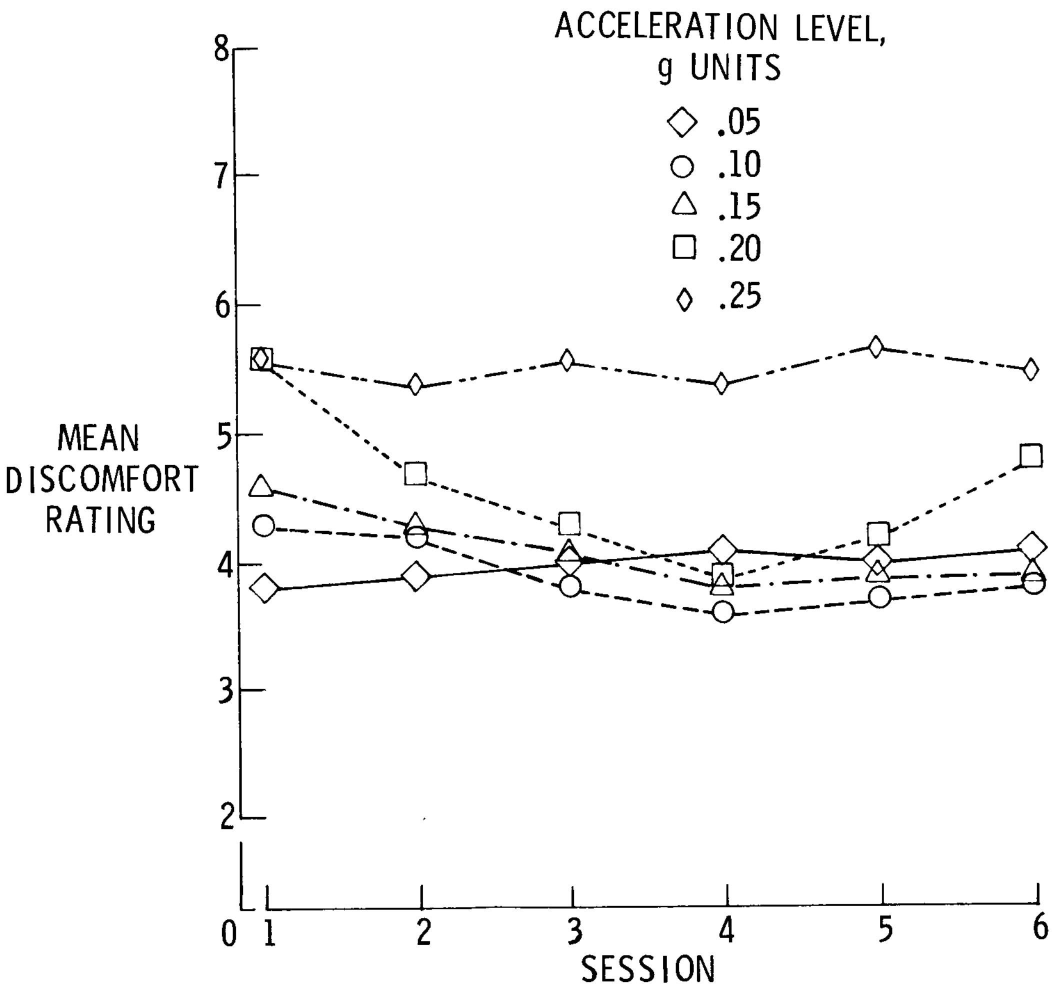


Figure 10.- Mean discomfort ratings (averaged across subjects and vertical sinusoidal frequency) for each level of acceleration as a function of session.

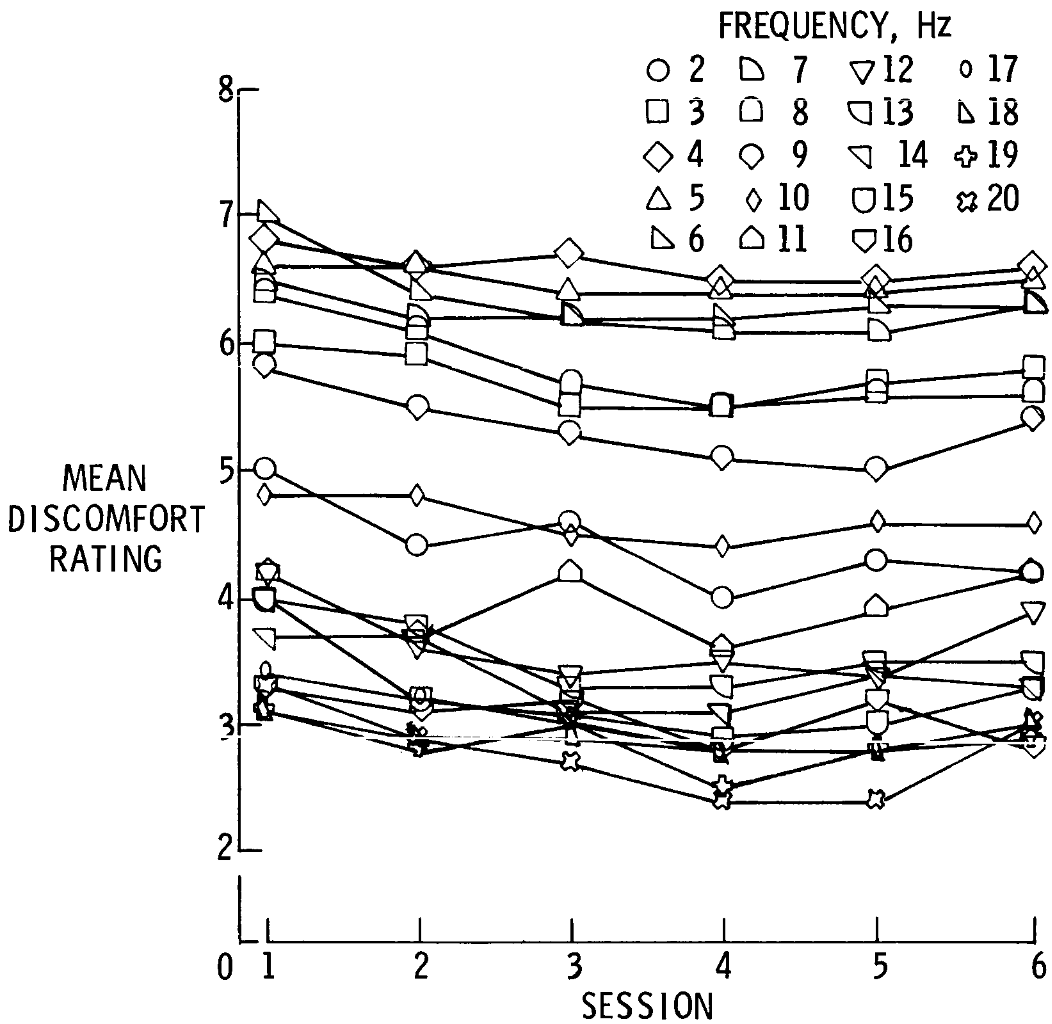


Figure 11.- Mean discomfort ratings (averaged across subjects and acceleration levels) for each vertical sinusoidal frequency as a function of session.

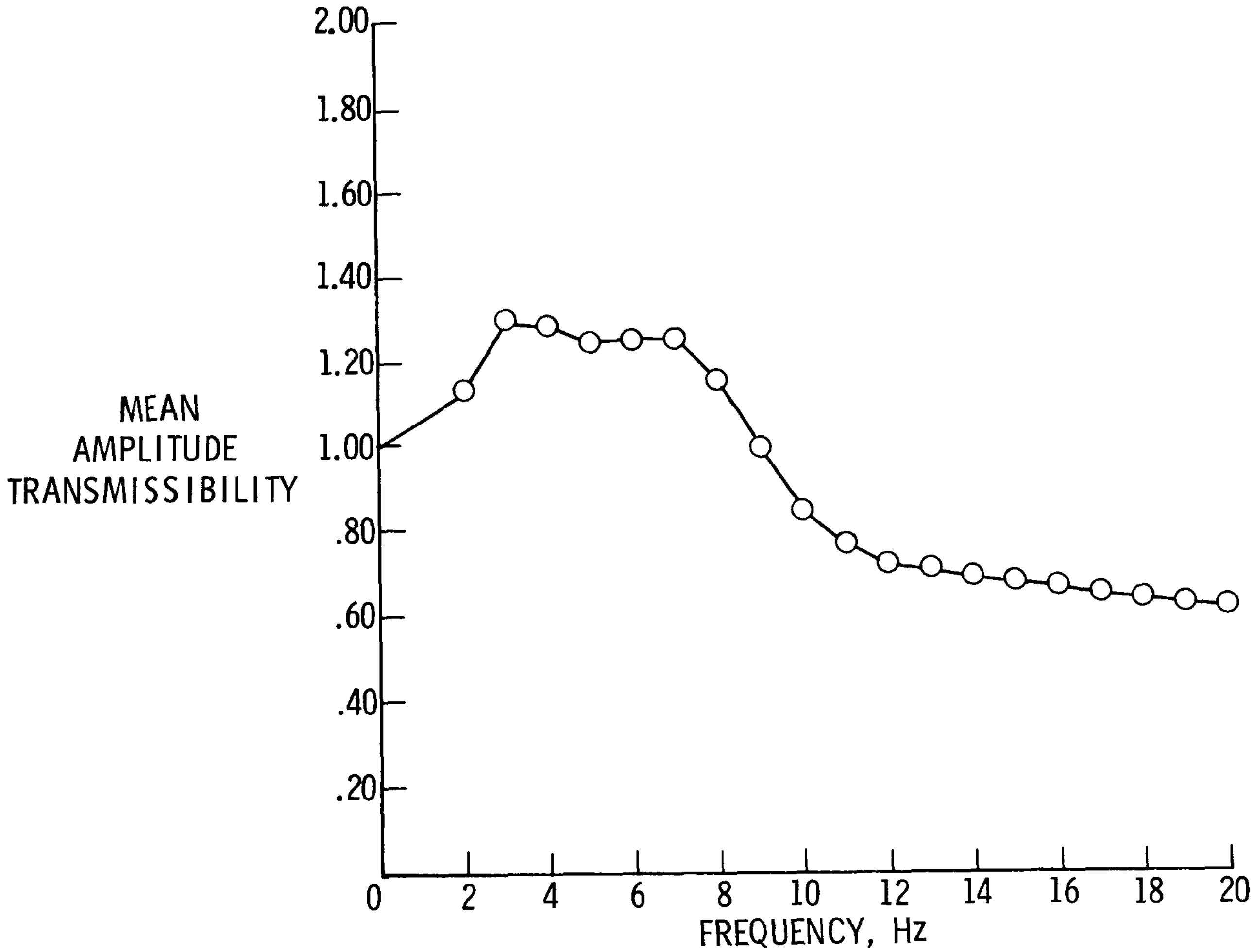


Figure 12. - Mean amplitude transmissibility (seat acceleration/floor acceleration) for tourist-class aircraft seats as a function of frequency.

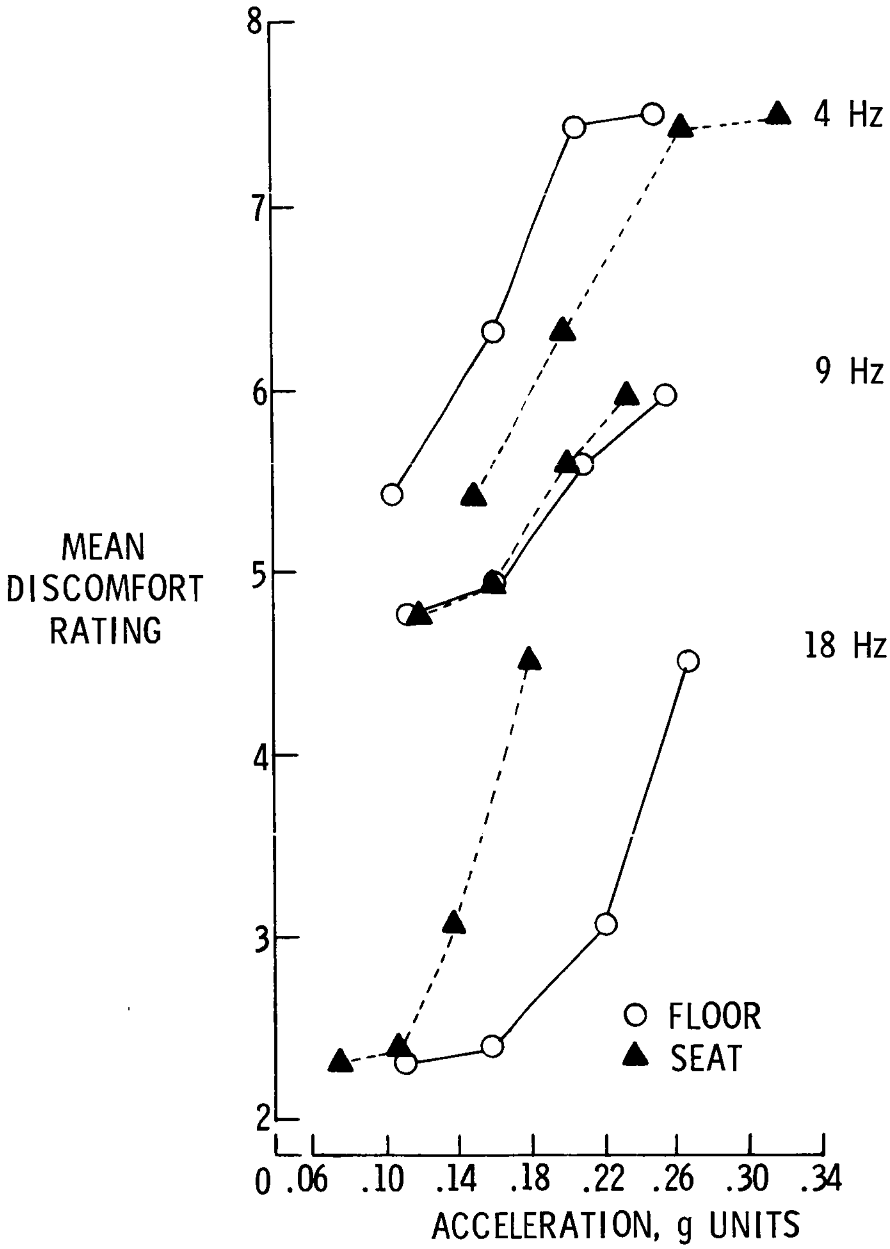


Figure 13. - Mean discomfort rating of session six as a function of floor and seat acceleration levels for selected vertical sinusoidal frequencies.

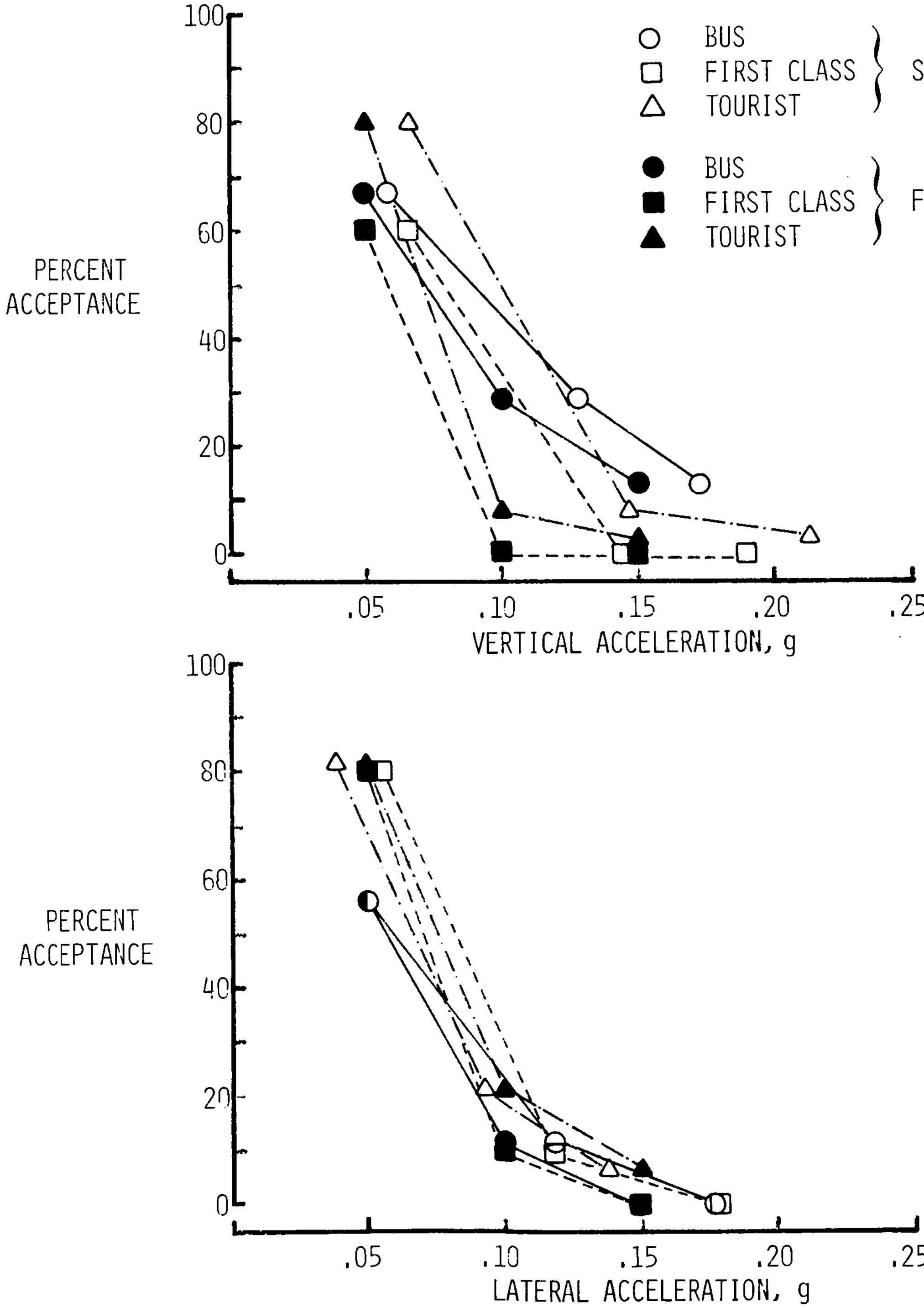


Figure 14.- Percent acceptance at 4 Hz for bus, tourist-class aircraft, and first-class aircraft seats as a function of floor and seat accelerations for vertical sinusoidal motion and lateral sinusoidal motion.

NASA-Langley, 1975 L-10264