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An Investigation of Ride Quality Rating Scales

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SUMMARY

An experimental investigation was conducted for the combined purposes of determining the relative merits of various category scales for the prediction of human discomfort response to vibration and for determining mathematical relationships whereby subjective data are transformed from one scale to other scales. There were 16 category scales analyzed in this study representing various parametric combinations of polarity, that is, unipolar and bipolar, scale type (continuous or discrete), and number of scalar points (three, five, seven, or nine). Sixteen subject groups (12 subjects per group) were used, and each subject group evaluated their comfort or discomfort to vertical sinusoidal vibrations by using one of the rating scales. The experimental apparatus utilized was the Langley passenger ride quality apparatus which can expose six subjects simultaneously to predetermined vibrations. For this study, the vibration stimuli were composed of repeats of eight selected sinusoidal frequencies (1, 2, 4, 5, 8, 10, 15, and 20 Hz) applied at each of nine peak floor acceleration levels (0.05, 0.075, 0.10, 0.125, 0.15, 0.175, 0.20, 0.225, and 0.25 g).

Results indicated that unipolar continuous-type scales containing either seven or nine scalar points provide the greatest reliability and discriminability. Furthermore, transformations of subjective data between category scales were found to be feasible with unipolar scales of a larger number of scalar points providing the greatest accuracy of transformation. The results contain coefficients for transformation of subjective data between the category scales investigated. A result of particular interest was that the comfort (or positive) half of a bipolar scale was seldom used by subjects to describe their subjective reaction to vibration.

INTRODUCTION

The ride quality literature over the past 50 years is reviewed in reference 1 and emphasizes the importance of passenger reactions to vibration in the development of comfort criteria for use in vehicle design. This review of the literature points out that previous investigations have resulted in widespread disagreement as to comfort criteria, for example, the g × Hz needed to produce constant discomfort, and that a major contributing factor to these large differences is the use of widely varying category scales. Similarly, during ride quality meetings (refs. 2 and 3), rating scales are discussed and viewed as a major (if not the greatest) cause of this criteria variability. The large number of rating scales that have been used in ride quality research and discussed at these meetings can be characterized according to (1) the adjectives or adverbs that are used for anchoring scalar points, (2) polarity - whether the scale is of a unipolar type that allows a passenger to provide only negative reactions (discomfort) to a vehicle vibration or whether the scale is bipolar and allows passengers to record both positive (comfort) and negative (discomfort) reactions to a vibration, (3) scale type - either the category scale is of a line variety and continuous in nature or consists of category boxes of a discrete nature, and (4) the number of scalar points or category demarcations provided on the scale. A point of concern and discussion has centered upon the question of which of these scales is the "most applicable" for use in the development of ride quality criteria. This paper answers this question by presenting the results of a systematic investigation of a large number of category scales that differ from one another in terms of polarity, number of scalar points, and whether the scale is discrete or continuous. The various scales are compared on the basis of scale reliability, discriminability, and flexibility. Reliability refers to how well the scale allows subjects to repeat subjective evaluations to identical vibrations. Discriminability, on the other hand, is an assessment of how well the scale allows subjects to provide discrimination between vibration spectrum characteristics. Flexibility of a scale refers to how well the subjective responses of a scale can be transformed to the subjective responses of another scale, and consequently eliminate what is actually an artificial variability among comfort criteria.

The investigation of different adjective anchors for rating scales is not considered in the present paper since it would present an almost endless search for the "most applicable" subjective scale. (For example, see ref. 4.) Consequently, the present study selected the adjective "comfort-discomfort" for all scales since it is probably the simplest and most frequently occurring adjective used in this type of study. In addition, in order to avoid subject bias (error variance) in the data used to compare scales, each subject used one and only one type of scale during the testing.

The general purpose of the present investigation was to determine the applicability of various scales in assessing passenger discomfort/comfort response to vibration. This overall purpose can be viewed as twofold. The initial objective was to determine through a parametric investigation of scale polarity, scale type, and scalar points, the relative merits of these scales in terms of reliability and discriminability. The second purpose was to determine the mathematical relationships whereby subjective data are transformed from one scale to another scale.

METHOD

Simulator

The apparatus used was the Langley passenger ride quality apparatus (PRQA) shown in figure 1. The PRQA is described briefly in this section and a detailed description can be obtained from references 5 and 6. The photograph of figure 1 displays the exterior of PRQA which is a three-axis drive system. The actual mechanisms which drive the simulator (inclusive of supports, actuators, and restraints) are located beneath the pictured floor. The console for control of the simulator is located at the same level as the simulator to allow operators to constantly monitor subjects within the simulator. The interior of the simulator was fitted with tourist-class aircraft seats. To reduce the influence of extraneous low level noises (less than 60 dB A-weighted) produced by the equipment, music was played in the PRQA and each subject was requested to use ear plugs. (See ref. 7.)

Subjects

A total of 192 subjects participated in the study. The volunteer subjects were obtained from Old Dominion University (undergraduate students) and from a contractual subject pool and were paid for their participation in the study. Subject demographics are listed in table I, and it should be noted that a previous investigation (ref. 8) indicated these demographic factors were not important determiners of discomfort responses.

Subjective Evaluation Scales

A total of 16 different rating scales were investigated in the present study. These scales were parametric combinations of polarity (unipolar or bipolar), scale type (continuous or discrete), and number of scalar points (three, five, seven, or nine points). The exact scales are displayed in figure 2.

Subject Instruction

The subjects were instructed to base evaluations upon the comfort (or discomfort) of a vibration. Prior to the start of testing for each session, the subjects were exposed to a vibration (4 Hz at 0.25 peak g for 10 sec) and told the vibration usually resulted in a rating of maximum discomfort. The subjects were purposely not given a vibration typical of maximum comfort since such a vibration is difficult to specify and would, in fact, bias results related to polarity. The exact instructions are displayed in appendix A.

Procedure

Sixteen groups of subjects (composed of 12 subjects per group) were each assigned one (and only one) of the previously mentioned category scales to use in evaluating successive vibrations called "ride segments." A ride segment is defined as a stimulus combination composed of one of eight vertical vibration frequencies (1, 2, 4, 5, 8, 10, 15, and 20 Hz) at one of nine peak floor acceleration levels (0.05, 0.075, 0.10, 0.125, 0.15, 0.175, 0.20, 0.225, and 0.25 g). The factorial combination of these frequencies and acceleration levels resulted in a total of 72 separate ride segments each of which was presented to a subject twice in order to determine estimates of reliability for a total of 144 ride segments. The eight frequencies were randomized twice without replacement and were used to define the frequency of vibration of a short period of testing called a session. A session was a period of testing within which the subjects received a series of nine ride segments at a constant vibration frequency. The nine peak floor acceleration levels were randomized for each frequency and the resulting randomization defined segments of a session. A total of 16 sessions were used. The randomized sequence of 144 ride segments (frequencies by acceleration levels) was duplicated for groups of subjects using different rating scales. Through the use of a two-way auditory communication system, the subjects were instructed when to begin evaluation of a ride by the word "start" and when to end the evaluation by the word "stop." The rise and decay time of a vibration each lasted 5 seconds, the duration of the actual test vibration was 10 seconds, and the interstimulus interval was 5 seconds. The subjects were further instructed to ignore rise and decay vibrations that occurred prior and subsequent to the words "start" and "stop," respectively.

Each session lasted approximately 4 minutes, with a 1-minute rest period after each session. A 15-minute rest interval was provided after the eighth session instead of the 1-minute interval.

RESULTS AND DISCUSSION

The results presented herein are discussed in terms of the previously described factors of reliability, discriminability, and flexibility of response transformation. The scale characteristics of polarity, scale type, and number of scalar points are addressed in the reliability and discriminability subsections.

Scale Reliability

Reliability is the extent to which a category scale allows a subject to repeat evaluations to similar vibrations. This logically represents an initial requirement of a category scale that is applicable as a measuring instrument. The statistical reason that scale reliability is of particular importance is that it defines an upper limit to the discriminability of a scale. Specifically, the correlation coefficient between comfort responses and vibration acceleration level (that is, scale discriminability) cannot exceed the square root of the reliability correlation coefficient. (See ref. 9.) The effect of the unreliability of a scale on discriminability is that it increases the error variance in the discriminability correlation coefficient. Theoretically, figure 3 displays the minimum percent of unexplained variance (or error variance), as well as explained variance, in the discriminability correlation coefficient as a function of the reliability correlation coefficient. Thus, this figure displays the error variance present in comfort predictions that is due solely to the unreliability of a category scale. The minimum error variance shown can increase because of the inaccuracy of physical measurements, use of a scale in field rather than laboratory investigations, etc. It is important to note that systematic increases in the reliability correlation coefficient allow systematic reductions in the minimum error variance associated with the discriminability prediction. In other words, the selection and use of a category scale that is less reliable than another scale, by even a relatively small amount, will introduce unnecessary error variability in the development of vibration criteria.

Figure 4 provides a rank ordering of the 16 category scales according to the size of their associated reliability correlation coefficient. These results can be interpreted relative to figure 3. For example, the rating scale of lowest reliability (bipolar, discrete, three-point) will result in a minimum error variance of 42 percent when used to predict comfort, whereas the scale of highest reliability (unipolar, continuous, nine-point) will result in only a 20-percent error variance. In addition to supplying information as to the reliability of each category scale, figure 4 also indicates a trend that unipolar continuous scales of either seven or nine scalar points supply the greatest degree of reliability. However, since these trends are not readily apparent, the scale characteristics of polarity, scale type, and number of scalar points are addressed separately and in greater detail in the next sections. In order to obtain this information, the subsequent analyses are directed at scale characteristics rather than at specific scales. This is important since the absolute difference in reliability coefficients, for example, between unipolar and bipolar type scales, is reduced because of the consideration of response data across specific scales.

Polarity.- Figure 5 displays the test-retest reliability correlation coefficients for unipolar and bipolar scales. These correlations include all the paired (repeat) data of subjective responses for different frequencies, acceleration levels, scale type, scalar points, and subjects (N = 6912 pairs). A particular procedure was used for computation of these reliability correlation coefficients: A reliability correlation coefficient was first computed for 12 subjects that used a single scale as displayed in figure 3; then, in order to compare the reliability of unipolar and bipolar scales, the eight reliability correlation coefficients representing the unipolar scales were averaged, as were the eight for bipolar scales. This procedure was completed in order to avoid the application of a constant to the response data of scales with a different number of scalar points as well as to avoid inverting the negative response data of bipolar scales. Either the application of constants to response data (and inversion of negative data) to achieve a single reliability correlation coefficient or the averaging procedure described would use all the response data and achieve identical results. A z-score test between these test-retest reliability correlation coefficients (see appendix B) indicated there was a statistically ($z = 2.882$, $P < 0.05$; all analyses of the report are based on tests at this level of significance) higher degree of reliability obtained through the use of unipolar than through the use of bipolar scales.

Since the foregoing analysis indicated a difference in the reliability of unipolar and bipolar scales, a logical question could be raised as to whether the subjects use the scales in a similar fashion. Some information related to this question can be obtained by considering the responses recorded on bipolar scales. Figure 6 displays the percentage of responses to vibration (computed across subjects, frequencies, acceleration levels, and scalar points) that occurred within each area of the discrete and continuous bipolar scales. These results indicate that subjects generally use only the portion of bipolar scales associated with discomfort. In other words, the bipolar scales are being used as unipolar scales. Since the comfortable portion of the scale is the primary distinction between the unipolar and bipolar scales investigated, it would appear that the reduced reliability of the bipolar scales could partially be attributed to this portion of the scale. Further analyses of these response data indicated that when the neutral or comfortable portions of the bipolar scales were used, they were used almost exclusively to record subjective reactions to 15- and 20-Hz vibrations. Since these frequencies of vibration are known not to produce any appreciable discomfort (for example, see refs. 8 and 10) and are not of major interest for purposes of vehicle design, the use of bipolar scales is of questionable value for ride quality studies.

Scale type.- Figure 7 displays the test-retest correlation coefficients obtained for discrete and continuous type scales. In this case, each correlation was based on paired data for different frequencies, acceleration levels, polarity, scalar points, and subjects (N = 6912). The procedure used for computation of these reliability correlation coefficients was analogous to the procedure used to obtain reliability correlation coefficients for the bipolar scales. Consequently, the reliability correlation coefficients of figure 7 can be viewed, for purposes of simplicity, as the average of the eight reliability correlation coefficients of figure 3 for the continuous or discrete scales. A z-score of 6.412 indicated there was a statistical difference ($P < 0.05$) between these two correlations. The results, thus, indicate that a significantly higher degree of reliability will be obtained from the use of continuous rather than discrete type scales.

Scalar points.- Figure 8 displays the test-retest correlation coefficients obtained for three, five, seven, or nine scalar points. In this case, each correlation was based on paired data for different frequencies, acceleration level, polarity, scale type, and subjects (N = 3456 pairs). Again, for purposes of simplicity, the data of figure 8 can be viewed as an average of the reliability correlation coefficients of figure 3 for the various number of scalar points. A series of z-score tests between these correlation coefficients indicated that there was no difference between three or five scalar points or between seven and nine scalar points. However, there was a statistically higher degree of reliability obtained for seven and nine scalar points in comparison with three or five scalar points (z-scores of 0.7469, 5.3527, 6.2656, 6.0996, 7.0124, and 0.9129 for scalar point comparisons of 3 against 5, 3 against 7, 3 against 9, 5 against 7, 5 against 9, and 7 against 9, respectively).

Reliability summary.- The results from these analyses indicate that higher degrees of reliability are obtained from certain category scales for evaluation of vibration than from other scales investigated. The scales that display the greater reliability are of a unipolar continuous nature with seven or nine scalar points.

Scale Discriminability

This section addresses the problem of which category scale in terms of polarity, scale type, or number of scalar points allows subjects to provide maximum discrimination between ride spectrum characteristics. A comparison of the discriminability accuracy of the various scales was based on discriminability correlation coefficients. These correlations were computed between the subjective responses (for a particular rating scale) and vibration acceleration level, for a given frequency of vibration. However, there are a variety of mathematical relationships that could exist between the subjective responses (for an individual rating scale) and a particular physical measure. The four mathematical relationships (psychophysical formulations) studied are

Linear

$$y = a + bx \tag{1}$$

Logarithmic

$$y = a + b \log x \tag{2}$$

Exponential

$$y = a10^{bx} \tag{3}$$

Power

$$y = ax^{b} \tag{4}$$

where y is the subjective response, x is the physical measurement of peak acceleration level at a particular frequency of vibration, and a and b are coefficients determined from appropriate least-square fitting techniques. Note that the correlation coefficients for these mathematical relationships were computed separately for each frequency of vibration. An average of these correlation coefficients across frequency was used to represent the discriminability correlation coefficient of a rating scale. Therefore, the accuracy of discrimination as defined was determined for variations of polarity, scale type, and number of scalar points for each of the mathematical formulations.

An overview of the discriminability results (similar to reliability) for each scale of interest is presented in figures 9 to 12, based on equations (1) to (4), respectively. Each figure provides a rank ordering of the category scales according to the size of the discriminability correlation coefficients. There is not an appreciable difference between the correlations for any one scale when computed according to the various equations. Consequently, the simple linear equation can be selected for the description of the relationship between responses and vibration acceleration level. Consistent with the reliability data, the unipolar, continuous, nine-point scale allows the greatest accuracy of discrimination. These results are explored in more detail in the following sections in terms of the scale characteristics rather than in terms of specific scales.

Polarity.- Figure 13 displays the correlation coefficients between subjective responses and vibration measures for both unipolar and bipolar scales for each of the previously mentioned mathematical formulations (eqs. (1) to (4)). The data for each correlation were based on paired data (subjective responses and vibration acceleration levels) for different frequencies, acceleration levels, repeats of both frequencies and acceleration levels, scale type, scalar points, and subjects (N = 13 824). The procedure for computation of discriminability correlation coefficients was analogous to the procedure for computation of reliability correlation coefficients. Subsequent to computation of the average discriminability correlation coefficients across frequency (described earlier), the average discriminability correlation coefficients were derived for each scale characteristic and for each of the mathematical formulations. For example, in order to compare the discriminability of unipolar and bipolar scales, the eight discriminability correlation coefficients (for a single mathematical formulation) representing the unipolar scales (for example, from fig. 9) were averaged as were the eight discriminability correlation coefficients for the bipolar scales. The reasons for doing this are identical to those given in the preceding discussion of reliability coefficients. Despite the fact that the correlations were based on twice the number of data pairs as were certain estimates of reliability, the number of pairs used for computation of z-score tests was 144 (eight frequencies times nine acceleration levels times repeated measurements; for example, $8 \times 9 \times 2 = 144$). This number was selected so as not to artificially inflate the degrees of freedom despite the fact that the correlation coefficients were based on the total number of data pairs. The z-score tests indicated that there was no statistical difference between the discriminability correlation coefficients of unipolar and bipolar scales for any of the mathematical formulations (z-scores = 1.327, 0.957, 1.327, and 1.066 for the linear, logarithmic, exponential, and power comparison of scale polarity, respectively). However, there is a systematic trend in figure 13, although not significant, of unipolar scales offering a greater accuracy of discrimination between vibration measures than bipolar scales. In fact, the z-scores indicate that by chance, such differences between correlation coefficients would occur only 10 to 15 percent of the time.

Additional z-score tests were computed between the responses of different mathematical descriptions of the same type of scale. For example, it was problematical whether there was any statistical difference between a linear or logarithmic description of the relationship between responses and the vibration measure for either unipolar or bipolar scales. There were no statistical differences obtained between any mathematical formulations of these relationships for either scale. The implication of these results strongly suggests that the linear relationship can be selected for description of the mathematical relationship, especially in lieu of the simplicity afforded by such a relationship.

Scale type.- Figure 14 displays the discriminability correlation coefficients between subjective responses and vibration measures for both continuous and discrete scales for each of the mathematical formulations. These discriminability correlation coefficients can be viewed, for purposes of simplicity, as the averages of the eight discriminability correlation coefficients of figure 9, 10, 11, or 12 for continuous or discrete scales for equations (1) to (4), respectively. The actual number of data pairs for computation of these correlations and restriction of the degrees of freedom for computation of z-score tests are identical to those for polarity analyses.

There was no statistical difference between the correlations for continuous and discrete type scales for any of the mathematical formulations (z-scores = 0.865, 0.957, 0.999, and 1.066 for linear, logarithmic, exponential, and power comparisons of continuous and discrete scales, respectively). However, the figures do indicate a trend that continuous-type scales allow a greater accuracy of discrimination than discrete scales. In addition, the z-scores for the comparison were of sufficient magnitude to indicate that differences between the scales would occur by chance only 15 to 20 percent of the time. The implication is that the evidence (although not conclusive) suggests that a continuous- rather than a discrete-type scale should be used for the investigation of subjective reactions to vibration.

Similar to polarity analyses, there were no statistical differences between various psychophysical descriptions. Again, for simplicity, selection of the simpler linear relationship is appropriate for description of the psychophysical relationship between responses and vibration measure.

Scalar points.- Figure 15 shows the discriminability correlation coefficients between subjective responses and vibration measures for category scales of three, five, seven, or nine scalar points, for each of the mathematical formulations. These correlations can also be viewed as the averages of the discriminability correlations of figure 9, 10, 11, or 12 for the various number of scalar points. Information and restrictions regarding the number of data pairs are identical to those for polarity and scale-type analyses.

The z-scores obtained from comparison of the discrimination accuracy of these category scales (with different number of scalar points) are displayed in table II. These results indicate that the nine-point scale allows a significantly ($P < 0.05$) greater degree of discrimination accuracy than three-point or five-point (for some comparisons) scales. Analogous to comparisons between scalar points for reliability, these data for discrimination indicate a trend of no difference between three- or five-point scales, or between seven- and nine-point scales, but point toward a trend of a higher degree of discrimination accuracy for seven- or nine-point than for three- or five-point scales.

Similar to polarity and scale-type analyses, there were no statistical differences among the four mathematical descriptions for any of the category scales varying in number of points. Consequently, several types of analyses indicate that the linear law is preferred because it is simpler to apply and is equally as accurate for description of the psychophysical relationship as are other mathematical formulations.

Discriminability summary.- The discriminability analyses were not as conclusive as those for reliability because of the limited number of degrees of freedom. There were, however, strong trends for discriminability essentially in agreement with those for reliability. Specifically, the category scales that display trends of greater discriminability are of a unipolar continuous nature with either seven or nine scalar points.

Scale Transformation

The flexibility of a category scale in the transformation of the subjective responses to other scales is addressed in this section. Figure 16 shows typical transformation data. The figure displays cross plotting of responses from two different category scales, the responses of which were reactions to the same vibration (for example, frequency by acceleration level). The cross-plotted data represent the mean response of 12 different subjects for each of the scales. The correlation coefficient between the responses of the two scales was -0.98 and the standard error of estimate (standard deviation about the regression line) was 0.325. This latter value could be considered to represent the accuracy of a particular scale in predicting responses of other scales. Prior to a discussion of the relative flexibility of different category scales in allowing transformation of data between scales, a general overview of the scale transformation data is presented.

The data of figure 16, mentioned earlier as typical, display that a high degree of accuracy is possible in transforming the subjective responses of one scale to another. Consequently, table III has been included to provide a summary of the coefficients (least-squares curve fitting) that are needed for the transformations between any two scales. In addition, the table provides the standard error of estimates associated with each transformation. These standard error of estimates can be used to evaluate the degree of accuracy expected for a computed transformation. For example, the smaller the standard error of estimate, the greater the transformation accuracy. The results of table III will allow various types of comparisons between the results of different studies. Most important, the transformations lead to the elimination of response differences or contradictions between studies that are fundamentally a difference in rating scales. Although the transformation coefficients developed in this report have provided a high level of confidence in the interpretation of data collected with different scales, the determination of their universal applicability is beyond the scope of this paper. Therefore, caution should be exercised in application of the transformation coefficients because (1) the transformations may not apply to subjective scales with adjective anchors other than those used in the present study; and (2) since the transformations were based on mean responses, they may not apply to the data of unique subjects.

The standard error of estimates mentioned previously were further used to evaluate the flexibility of scale transformation, namely, the relative flexibility of transforming the subjective data of a particular scale to the remaining scales. However, in order to compare standard error of estimates of different scales, the criterion (predicted scale scores) was adjusted to a nine-point scale by the application of a constant to the response data of scales having a different number of scalar points, and through inversion of the negative response data of bipolar scales. The mean standard error of estimate was then computed for each scale; this estimate was based on the error estimates that resulted when the scale was used to predict responses from the other scales. Table IV lists a summary of these mean standard error of estimates associated with each scale. The mean values were then used to provide a rank ordering of the category scales in terms of transformation accuracy. Generally, as displayed in table IV, these data indicate that unipolar scales of a higher number of scalar points (that is, seven or nine) allow the greatest accuracy of transformation.

CONCLUDING REMARKS

A number of major conclusions can be derived from this investigation of ride quality rating scales. Higher degrees of reliability and discriminability were obtained for unipolar continuous type scales of either seven or nine scalar points than for other scales investigated. Regardless of the rating scale investigated, the psychophysical relationship (mathematical formulation) between subjective responses and vibration acceleration level can be described as linear, as opposed to logarithmic, exponential, or power relationships. Probably more important, transformation of subjective data between category scales was demonstrated to be feasible. Unipolar scales of a higher number of scalar points allowed the greatest accuracy of response data transformation. In addition, a point of interest was that the comfort or positive end of a bipolar scale is not generally used by subjects for description of their sensations to vibration.

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APPENDIX A

INSTRUCTIONS TO SUBJECTS

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 seatbelt 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 the 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 comfort (or 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 comfort (or discomfort) of a vibration contained in a ride segment in terms of the following scale:

[One of the 16 scales is inserted here.]

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

Evaluation marks.- You should record your evaluation of the comfort (or discomfort) associated with the vibration of each ride segment by placing either a checkmark (✓) or an X depending upon the scale type being used. If a checkmark is used, the point of the checkmark will be used for your interpretation of the distance along the scale. If an X is used, be sure that the X is placed in the box you intended to mark.

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The scale should be conceived as representing the total comfort (or discomfort) values you may associate with vibration. In addition, it should be emphasized that your evaluation should be based only upon vibration. Certainly, you could evaluate the comfort (or discomfort) of a ride segment based upon other factors as temperature, pressure, etc. However, restrict your comfort (or discomfort) evaluations to variations of vibration.

The scale will be more meaningful when you are given a practice ride segment. The practice segment will be a vibration that usually results in a rating of maximum discomfort.

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 comfort (or discomfort) you associate with such a ride.

3. Carefully record your evaluation mark. 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 seated.) 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.

APPENDIX B

REVIEW OF STATISTICAL CONCEPTS

This appendix provides a brief review of the correlation coefficient and z-score 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. 11.)

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:

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

where

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

For the reliability correlation coefficient computations, the X and Y values were subjective responses to the same vibration. The meaning of X and Y was different for computation of discriminability correlation coefficients. 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 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

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

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.

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TABLE I.- SUBJECT DEMOGRAPHICS

Subject		Age, yr		Weight, kg (lb)	
Sex	Number	Median	Range	Mean	Standard deviation
Males	61	21	18 to 46	75.34 (165.98)	9.93 (21.88)
Females	131	21	18 to 55	58.58 (129.05)	11.03 (24.31)
All subjects	192	21	18 to 55	63.90 (140.78)	13.23 (29.15)

TABLE II.- SUMMARY OF z-SCORES FROM COMPARISON OF CATEGORY SCALES OF DIFFERING NUMBERS OF SCALAR POINTS

Psychophysical relationship	Scalar points compared					
	3 with 5	3 with 7	3 with 9	5 with 7	5 with 9	7 with 9
Linear	0.092	-1.511	-1.763*	-1.419	-1.671*	-0.252
Logarithmic	.000	-1.545	-1.688*	-1.545	-1.688*	-.143
Exponential	.185	-1.511	-1.763*	-1.327	-1.579	-.252
Power	.109	-1.545	-1.545	-1.436	-1.436	-.000

*$P < 0.05$; z-score value ≥ 1.64 or ≤ -1.64 needed to achieve statistical significance.

TABLE III.- A SUMMARY OF INTERCEPT (a) AND SLOPE (b) COEFFICIENTS FOR TRANSFORMATION OF SUBJECTIVE DATA BETWEEN SCALES

[The standard error of estimates associated with the transformation provide information as to the accuracy of the transformation]

Predictor scale (X)			Criterion scale (Y)					
			Unipolar; discrete; 3 points			Unipolar; discrete; 5 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	-------	-------	------	1.6318	0.3474	0.2775
		5	0.5643	-0.1102	0.1632	------	------	------
		7	.4051	-.3566	.1427	.6890	-.3339	.2422
		9	.3222	-.3786	.1627	.5529	-.3940	.2449
	Continuous	3	1.3897	-0.4310	0.1551	2.3842	-0.4829	0.2312
		5	.5337	.0530	.1695	.9327	.3144	.1821
		7	.4112	-.2363	.1579	.7087	-.1594	.2181
		9	.3465	-.5682	.1445	.5922	-.7076	.2262
Bipolar	Discrete	3	-1.0246	0.5556	0.2426	-1.6800	1.2499	0.4761
		5	-.6528	.5835	.1897	-1.1156	1.2611	.3092
		7	-.5670	.2991	.1594	-.9587	.7892	.2895
		9	-.4056	.4652	.1588	-.6860	1.0695	.2870
	Continuous	3	-1.8797	0.0023	0.2146	-3.2583	0.2413	0.3171
		5	-.6976	.5669	.2395	-1.2041	1.2238	.3762
		7	-.5622	.3763	.1557	-.9607	.9070	.2476
		9	-.3913	.4841	.2067	-.6674	1.0932	.3446

TABLE III.- Continued

Predictor scale (X)			Criterion scale (Y)					
			Unipolar; discrete; 7 points			Unipolar; discrete; 9 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	2.3189	1.0423	0.3415	2.8596	1.4403	0.4849
		5	1.3638	.6698	.3408	1.6971	.9486	.4290
		7	------	------	------	1.2098	.2383	.4098
		9	.7801	.0142	.3291	------	------	------
	Continuous	3	3.3535	-0.0999	0.3266	4.1583	0.0069	0.4351
		5	1.2853	1.0728	.3755	1.5923	1.4638	.4971
		7	.9886	.3813	.3534	1.2491	.5291	.3341
		9	.8407	-.4531	.2607	1.0549	-.4900	.2485
Bipolar	Discrete	3	-2.5119	2.2607	0.5075	-3.0410	2.9720	.7357
		5	-1.6067	2.3243	.3257	-1.9563	3.0404	.5372
		7	-1.3836	1.6407	.2714	-1.6759	2.2203	.5188
		9	-.9729	2.0714	.3671	-1.2323	2.6599	.3365
	Continuous	3	-4.5314	0.9483	0.4882	-5.8095	1.1970	0.4616
		5	-1.7379	2.2678	.4403	-2.0485	3.0216	.7614
		7	-1.3689	1.8329	.2739	-1.6909	2.4118	.4031
		9	-.9681	2.0719	.3583	-1.1693	2.7477	.6037

TABLE III.- Continued

Predictor scale (X)			Criterion scale (Y)					
			Unipolar; continuous; 3 points			Unipolar; continuous; 5 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	0.6681	0.3659	0.1075	1.7136	0.0744	0.3038
		5	.3964	.2513	.0943	1.0356	-.2597	.1919
		7	.2817	.0886	.0947	.7210	-.6320	.2812
		9	.2252	.0676	.1013	.5760	-.6833	.2990
	Continuous	3	------	------	------	2.5060	-0.8000	0.2540
		5	0.3752	0.3653	0.0983	------	-------	------
		7	.2850	.1751	.1101	.7380	-.4379	.2770
		9	.2418	-.0630	.0897	.6169	-1.0098	.2828
Bipolar	Discrete	3	-0.6940	0.7323	0.1855	-1.7570	1.0259	0.5138
		5	-.4539	.7422	.1286	-1.1552	1.0463	.3735
		7	-.3967	.5410	.0973	-1.0113	.5320	.3014
		9	-.2794	.6638	.1183	-.7103	.8481	.3545
	Continuous	3	-1.3112	0.3356	0.1430	-3.3819	-0.0142	0.3747
		5	-.4889	.7277	.1570	-1.2867	.9782	.3617
		7	-.3891	.6004	.1104	-.9986	.6750	.3088
		9	-.2747	.6691	.1307	-.7036	.8534	.3619

TABLE III.- Continued

Predictor scale (X)			Criterion scale (Y)					
			Unipolar; continuous; 7 points			Unipolar; continuous; 9 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	2.2516	0.7703	0.3696	2.7067	1.8343	0.4040
		5	1.3420	.3710	.3001	1.5997	1.3829	.3717
		7	.9459	-.1524	.3456	1.1474	.6882	.3045
		9	.7706	-.2877	.2624	.9284	.5535	.2331
	Continuous	3	3.2461	-0.3277	0.3714	3.9294	0.4847	0.3616
		5	1.2586	.7794	.3618	1.5009	1.8687	.4410
		7	------	-------	------	1.1730	1.0017	.3050
		9	.8223	-.7100	.2554	------	------	------
Bipolar	Discrete	3	-2.3765	1.9855	0.5908	-2.8914	3.2774	0.6463
		5	-1.5213	2.0448	.4591	-1.8491	3.3508	.4668
		7	-1.3083	1.4001	.4319	-1.5966	2.5583	.4025
		9	-.9624	1.7425	.2995	-1.1536	3.0082	.3321
	Continuous	3	-4.5629	0.5854	0.3628	-5.4171	1.6511	0.4657
		5	-1.6056	2.0209	.6033	-1.9777	3.3024	.6206
		7	-1.3326	1.5337	.2975	-1.5982	2.7566	.3246
		9	-.9185	1.8032	.4740	-1.1214	3.0495	.4657

TABLE III.- Continued

Predictor scale (X)			Criterion scale (Y)					
			Bipolar; discrete; 3 points			Bipolar; discrete; 5 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	-0.8051	0.3572	0.2150	-1.3678	0.7161	0.2746
		5	-.4565	.4504	.2482	-.8082	.9439	.2632
		7	-.3448	.7106	.1880	-.5881	1.3247	.1970
		9	-.2692	.7066	.2189	-.4617	1.3298	.2610
	Continuous	3	-1.1343	0.7210	0.2371	-1.9779	1.3897	0.2684
		5	-.4299	.3151	.2542	-.7538	.6897	.3017
		7	-.3410	.5794	.2238	-.5820	1.1025	.2840
		9	-.2908	.8712	.2050	-.4959	1.5982	.2418
Bipolar	Discrete	3	-------	-------	------	1.5426	0.0289	0.2752
		5	0.5785	-0.0721	0.1686	------	------	------
		7	.4796	.1483	.2044	.8246	.3749	.2169
		9	.3428	.0075	.2050	.5803	.1189	.2603
	Continuous	3	1.6318	0.4234	0.2134	2.7530	0.8177	0.2865
		5	.5981	-.0722	.2432	1.0294	-.0035	.3117
		7	.4875	.0980	.1720	.8194	.2649	.2041
		9	.3447	.0128	.1910	.5770	.1179	.2578

TABLE III.- Continued

Predictor scale (X)			Criterion scale (Y)					
			Bipolar; discrete; 7 points			Bipolar; discrete; 9 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	-1.6303	0.3831	0.2704	-2.2808	0.9465	0.3766
		5	-.9532	.6330	.2887	-1.3341	1.2976	.4003
		7	-.6951	1.0874	.1924	-.9559	1.8732	.3639
		9	-.5429	1.0806	.2953	-.7807	2.0188	.2678
	Continuous	3	-2.3729	1.2026	0.2380	-3.2688	2.0377	0.4046
		5	-.9056	.3654	.2852	-1.2440	.8776	.4691
		7	-.6869	.8216	.3129	-.9884	1.6480	.3035
		9	-.5877	1.4181	.2442	-.8305	2.4342	.2817
Bipolar	Discrete	3	1.7552	-0.4791	0.3910	2.4534	-0.2607	0.5483
		5	1.1317	-.5166	.2540	1.5576	-.3318	.4265
		7	------	-------	------	1.3226	.3051	.4467
		9	.6762	-.3523	.3194	------	-------	------
	Continuous	3	3.1427	0.4243	0.3946	4.6561	1.1535	0.3328
		5	1.2443	-.4619	.2821	1.5819	-.3532	.6759
		7	.9534	-.1841	.2638	1.3445	.1665	.3266
		9	.6864	-.3321	.2530	.9143	-.1243	.5375

TABLE III.- Continued

Predictor scale (X)			Criterion scale (Y)					
			Bipolar; continuous; 3 points			Bipolar; continuous; 5 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	-0.4591	-0.0778	0.1061	-1.1889	0.5477	0.3126
		5	-.2752	.0069	.0922	-.7096	.7606	.2888
		7	-.1933	.1121	.1009	-.5174	1.0989	.2403
		9	-.1598	.1503	.0766	-.3933	1.0446	.3337
	Continuous	3	-0.6661	0.1507	0.1020	-1.7333	1.1484	0.2956
		5	-.2572	-.0785	.1033	-.6829	.5783	.2635
		7	-.2035	.0780	.0766	-.4997	.8634	.3365
		9	-.1694	.2321	.0823	-.4315	1.3163	.2899
Bipolar	Discrete	3	0.5072	-0.3139	0.1190	1.2974	-0.0721	0.3582
		5	.3209	-.3294	.0978	.8374	-.0992	.2811
		7	.2669	-.2059	.1150	.7375	.2797	.2172
		9	.2022	-.2669	.0693	.4794	-.0096	.3721
	Continuous	3	------	-------	------	2.2530	0.5554	0.3952
		5	0.3229	-0.3361	0.1496	------	------	------
		7	.2732	-.2315	.0919	.7044	.1454	.2887
		9	.1866	-.2895	.1242	.5289	.0696	.1922

TABLE III.- Concluded

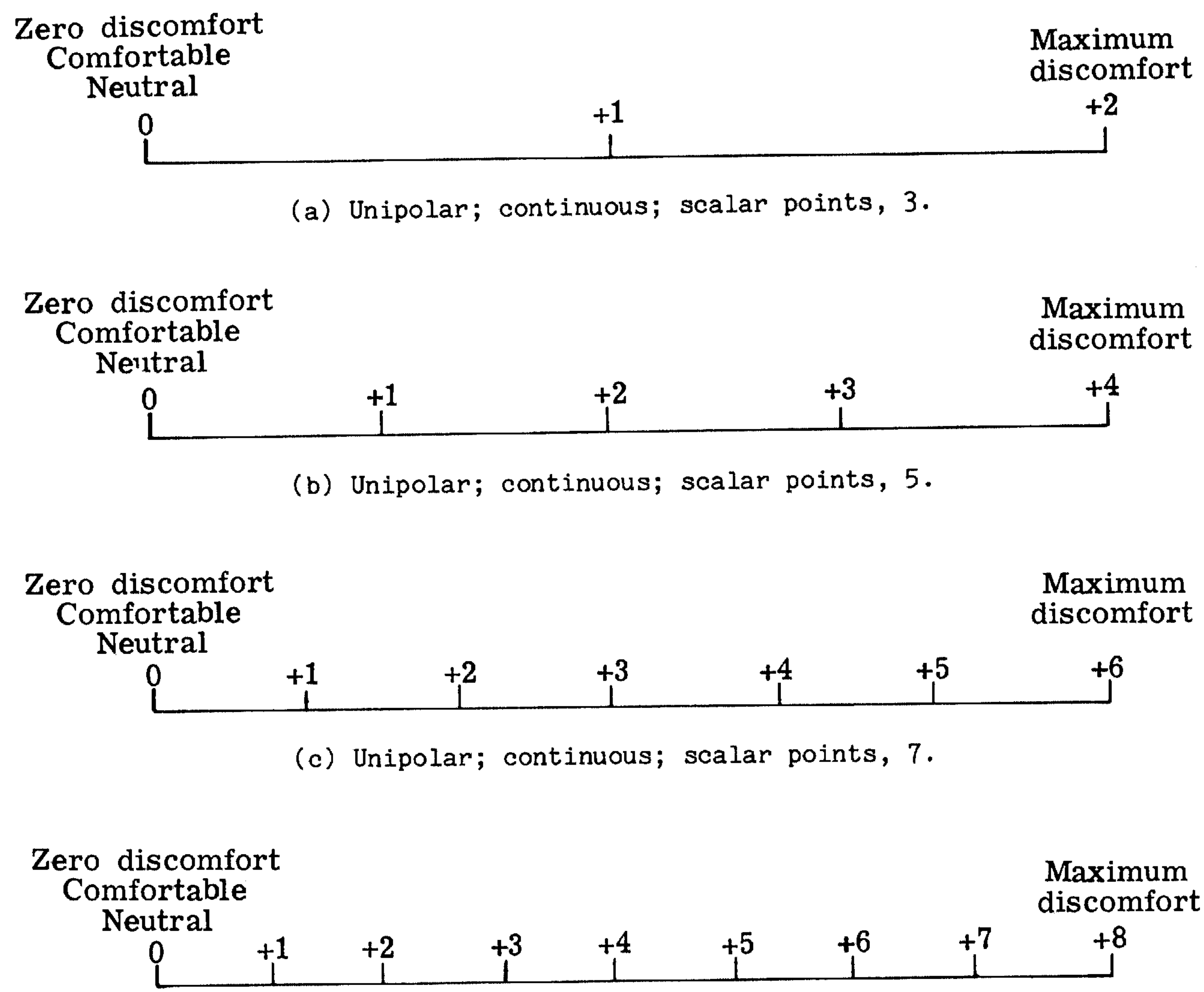
Predictor scale (X)			Criterion scale (Y)					
			Bipolar; continuous; 7 points			Bipolar; continuous; 9 points		
Polarity	Scale type	Scalar points	Slope	Intercept	Standard error	Slope	Intercept	Standard error
Unipolar	Discrete	3	-1.6504	0.5303	0.2668	-2.2304	0.8850	0.4935
		5	-.9752	.8052	.2494	-1.3153	1.2508	.4838
		7	-.7020	1.2377	.1962	-.9640	1.8951	.3575
		9	-.5592	1.2801	.2318	-.7508	1.8758	.4838
	Continuous	3	-2.3760	1.3315	0.2729	-3.2560	2.0168	0.4500
		5	-.9129	.5051	.2953	-1.2488	.8800	.4821
		7	-.7143	1.0351	.2178	-.9559	1.5367	.4835
		9	-.6006	1.6052	.1990	-.8181	2.3684	.3978
Bipolar	Discrete	3	1.8213	-0.3195	0.3325	2.5002	-0.2435	0.5145
		5	1.1482	-.3785	.2416	1.5696	-.3296	.4253
		7	.9734	.0887	.2665	1.3605	.3504	.3562
		9	.7018	-.1878	.2360	.9266	-.1189	.5411
	Continuous	3	3.2839	0.6310	0.3186	4.3534	0.9725	0.6000
		5	1.2132	-.3594	.3789	1.7688	-.2218	.3515
		7	------	------	------	1.3376	.1509	.3877
		9	.6890	-.2026	.2782	------	------	------

TABLE IV.- A SUMMARY OF CATEGORY SCALES RANKED FROM HIGHEST TO LOWEST IN TERMS OF MEAN STANDARD ERROR OF ESTIMATES

Rank	Scale	Mean standard error of estimate
1	Bipolar; discrete; 3 points	0.687
2	Bipolar; continuous; 5 points	.662
3	Bipolar; continuous; 3 points	.598
4	Bipolar; continuous; 9 points	.556
5	Bipolar; discrete; 5 points	.522
6	Unipolar; continuous; 5 points	.509
7	Bipolar; discrete; 9 points	.506
8	Unipolar; discrete; 3 points	.498
9	Bipolar; discrete; 7 points	.491
10	Unipolar; continuous; 3 points	.489
11	Unipolar; continuous; 7 points	.474
12	Unipolar; discrete; 5 points	.474
13	Unipolar; discrete; 9 points	.466
14	Bipolar; interval; 7 points	.451
15	Unipolar; discrete; 7 points	.429
16	Unipolar; continuous; 9 points	.425

L-73-4381

Figure 1.- NASA Langley passenger ride quality apparatus.



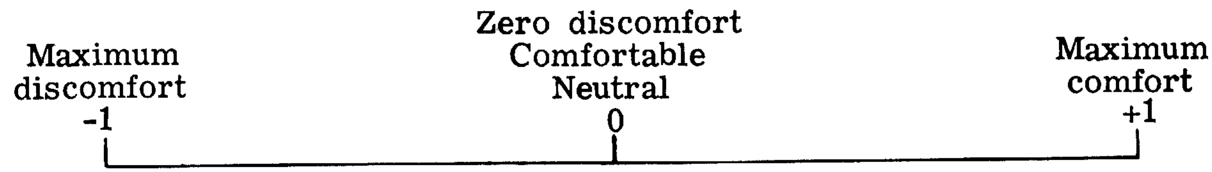
(a) Unipolar; continuous; scalar points, 3.

(b) Unipolar; continuous; scalar points, 5.

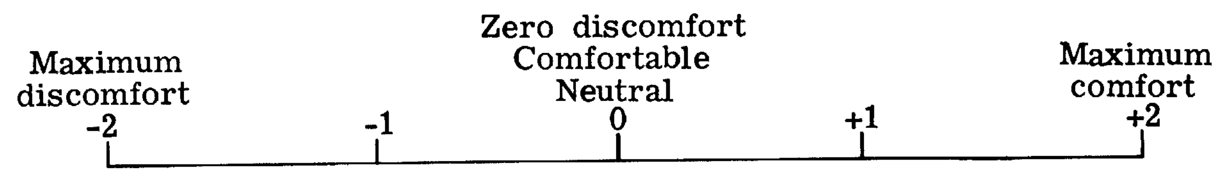
(c) Unipolar; continuous; scalar points, 7.

(d) Unipolar; continuous; scalar points, 9.

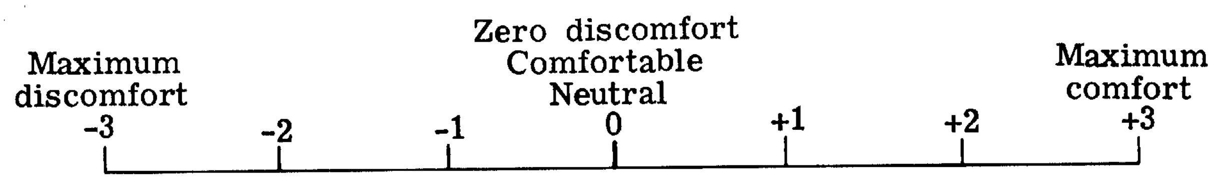
Figure 2.- Category scales.



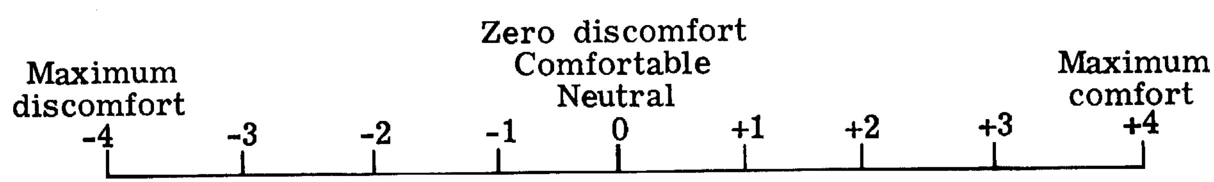
(e) Bipolar; continuous; scalar points, 3.



(f) Bipolar; continuous; scalar points, 5.

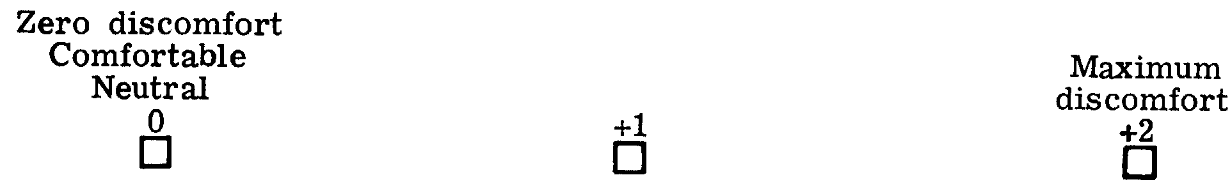


(g) Bipolar; continuous; scalar points, 7.

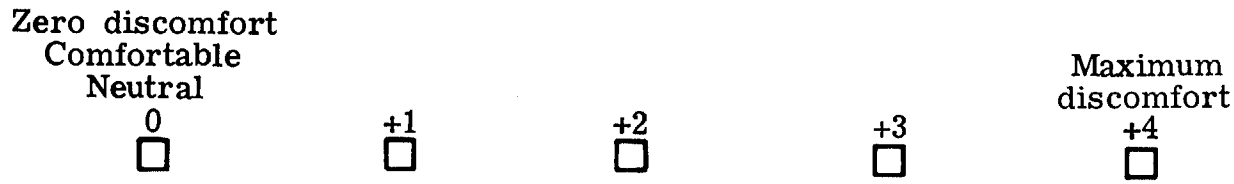


(h) Bipolar; continuous; scalar points, 9.

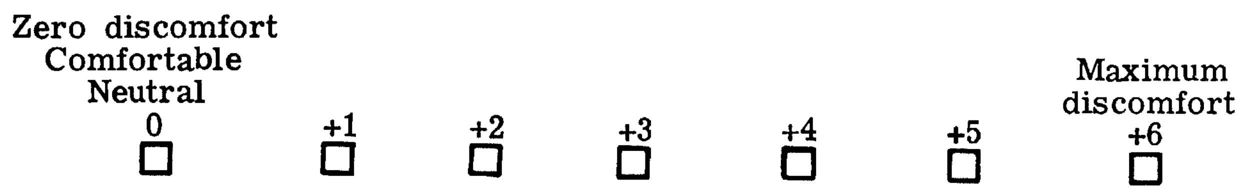
Figure 2.- Continued.



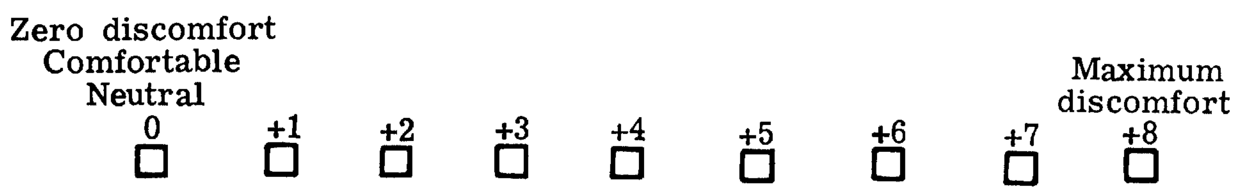
(i) Unipolar; discrete; scalar points, 3.



(j) Unipolar; discrete; scalar points, 5.

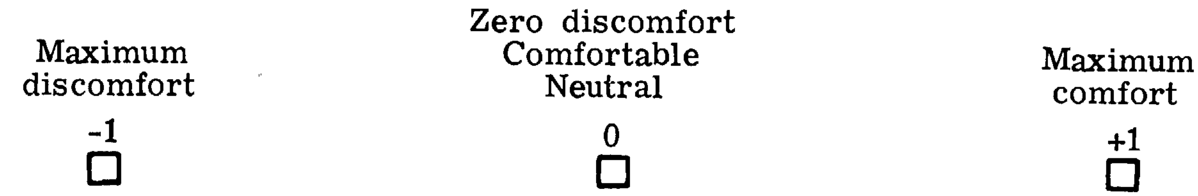


(k) Unipolar; discrete; scalar points, 7.

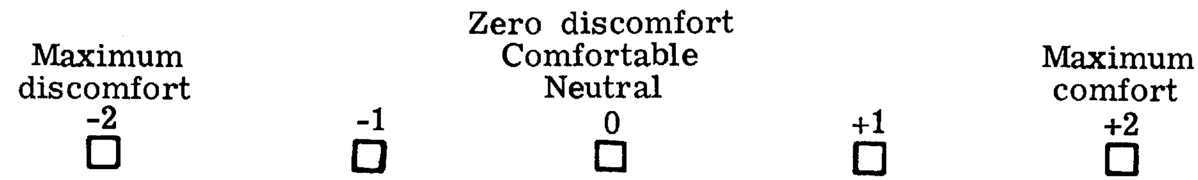


(l) Unipolar; discrete; scalar points, 9.

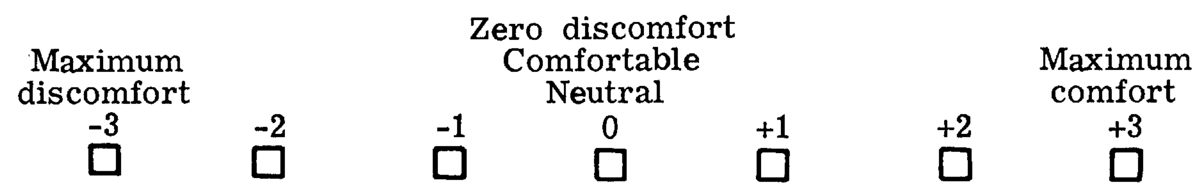
Figure 2.- Continued.



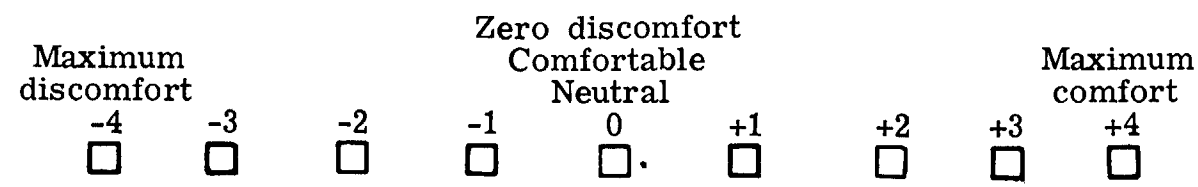
(m) Bipolar; discrete; scalar points, 3.



(n) Bipolar; discrete; scalar points, 5.



(o) Bipolar; discrete; scalar points, 7.



(p) Bipolar; discrete; scalar points, 9.

Figure 2.- Concluded.

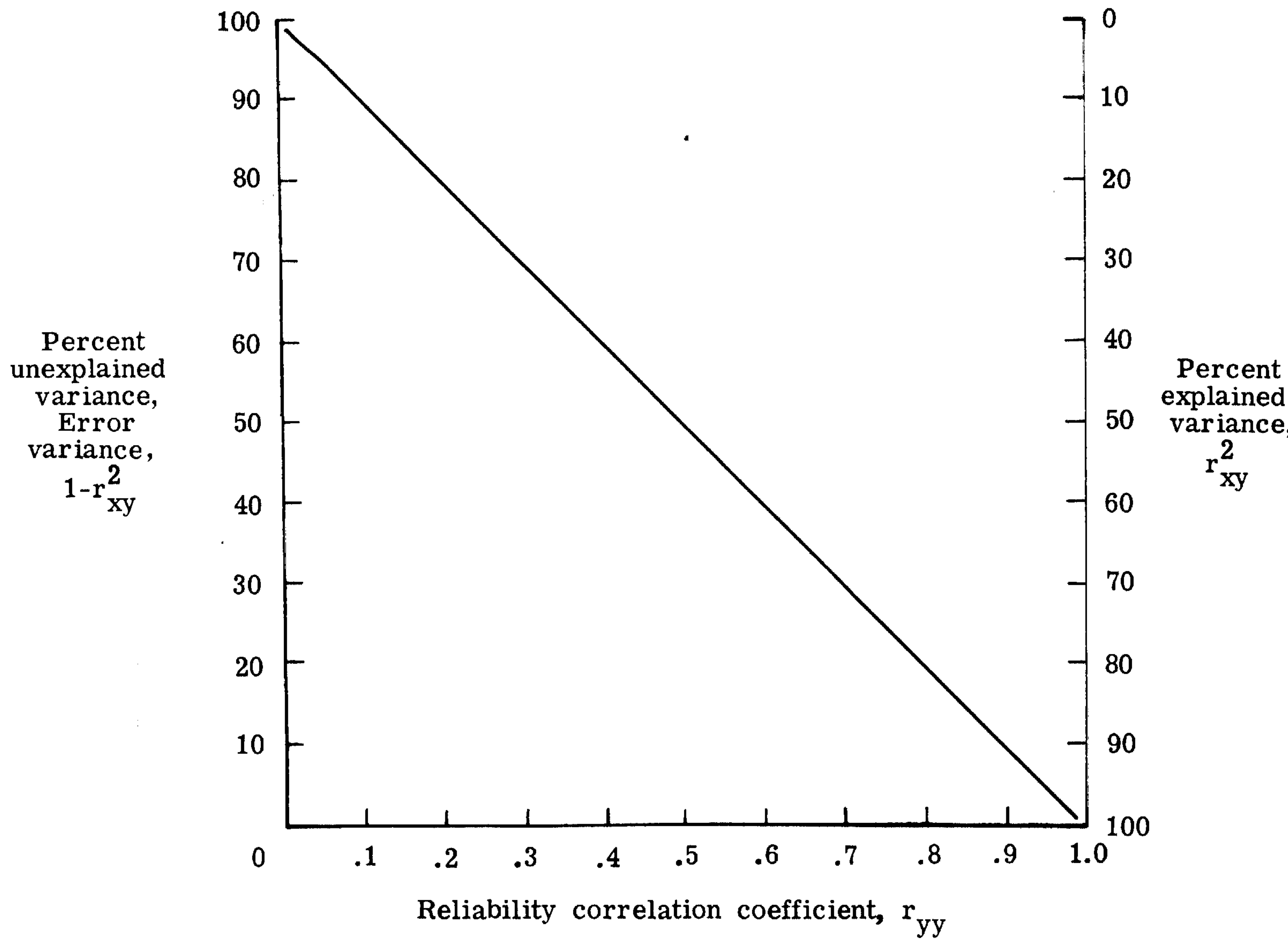


Figure 3.- Percent of unexplained variance or error variance $(1 - r_{xy}^2)$ as well as explained variance (r_{xy}^2) of a discriminability prediction as a function of reliability correlation coefficient.

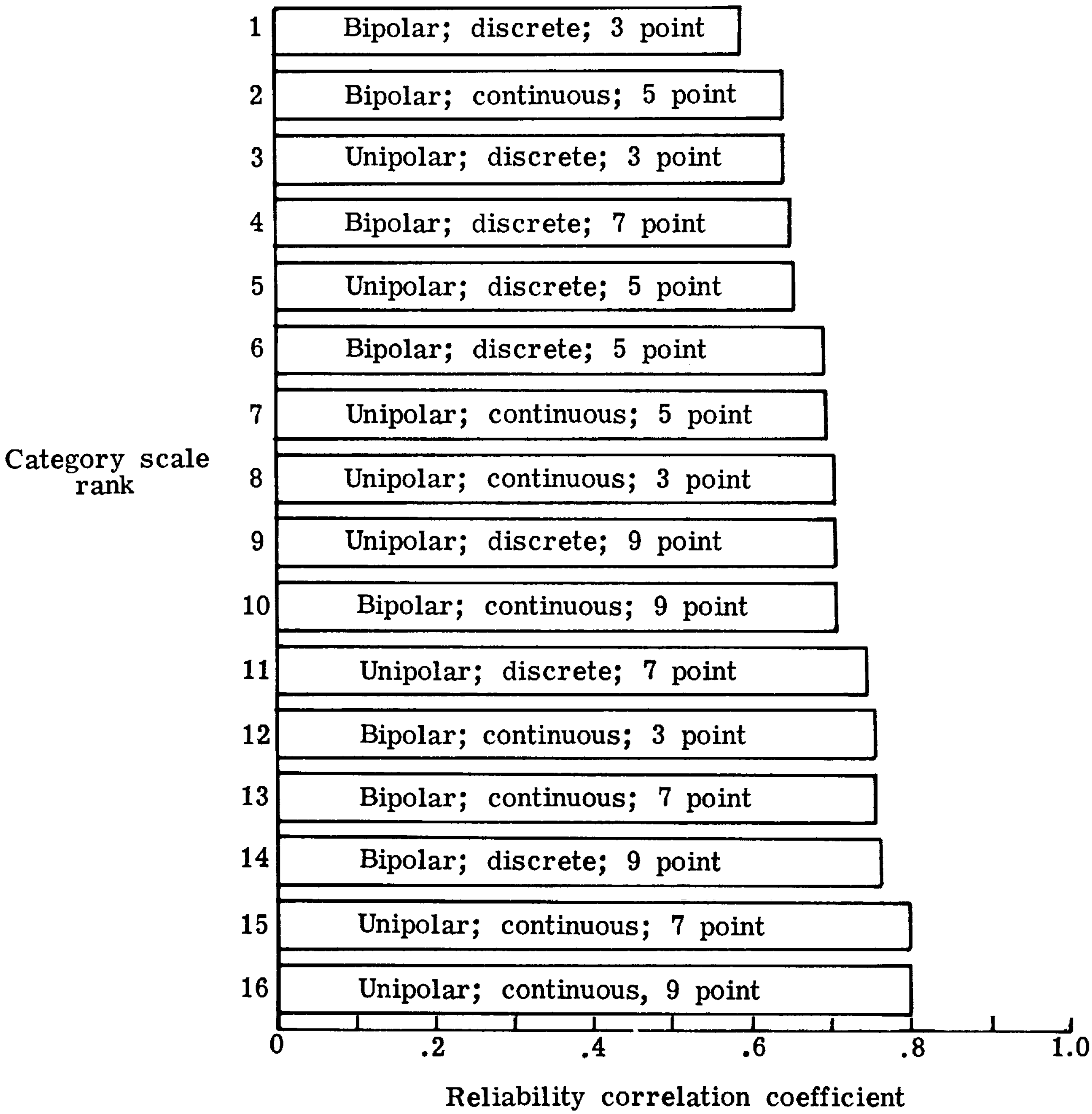


Figure 4.- Rank order of category scales as a function of reliability correlation coefficient.

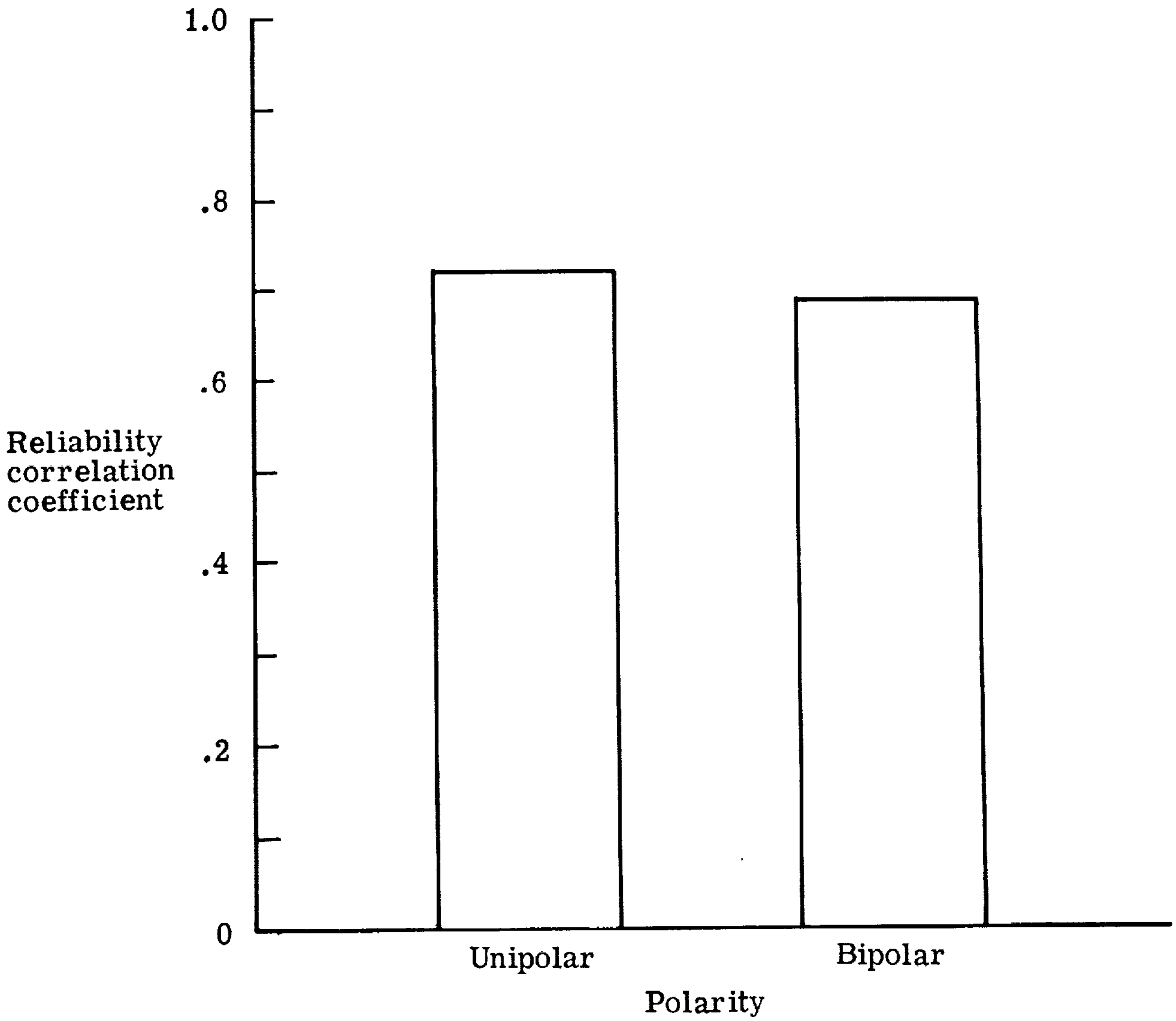


Figure 5.- Test-retest reliability correlation coefficients for unipolar and bipolar scales.

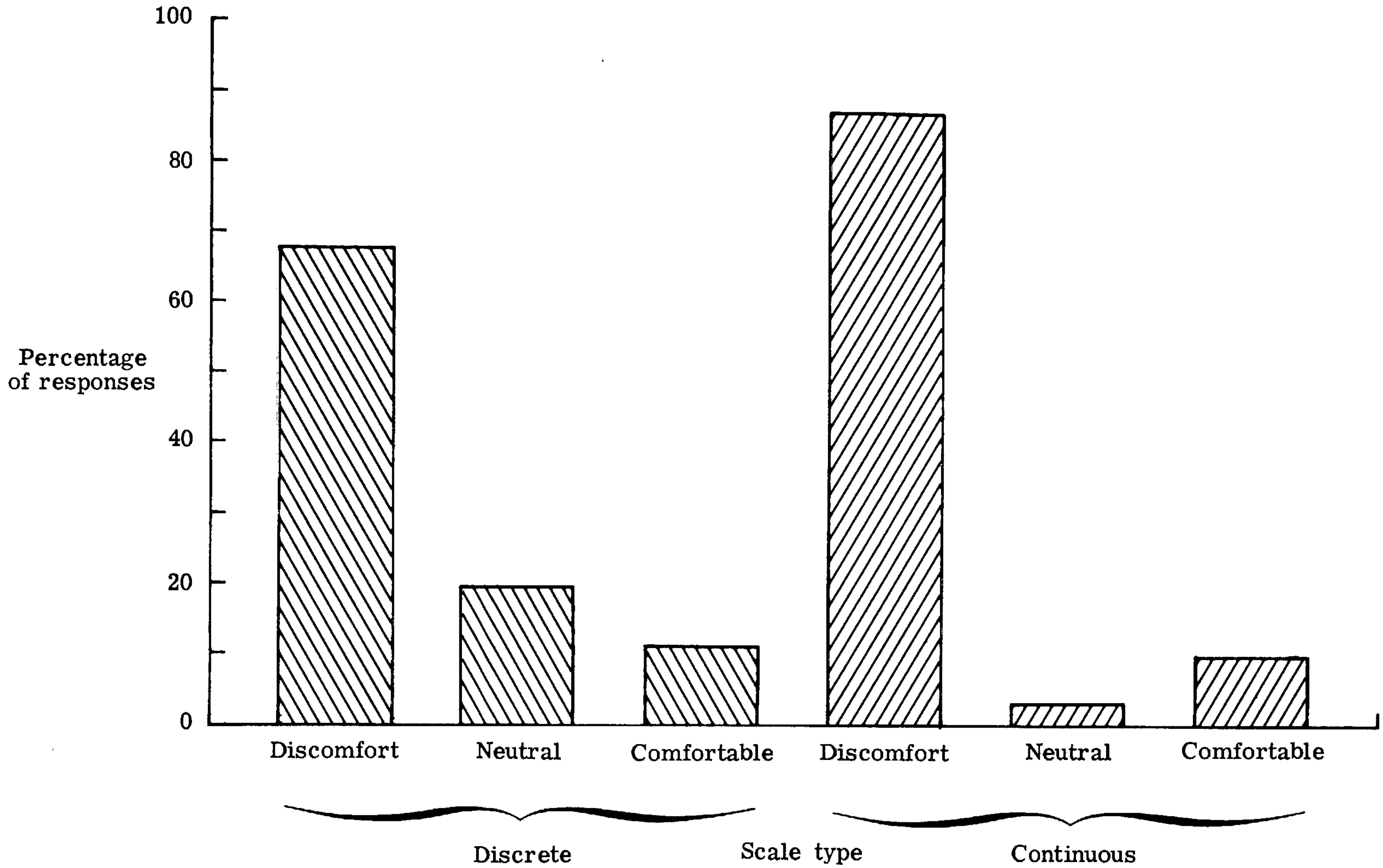


Figure 6.- Percentage of responses that occurred within each response area of both discrete and continuous bipolar scales.

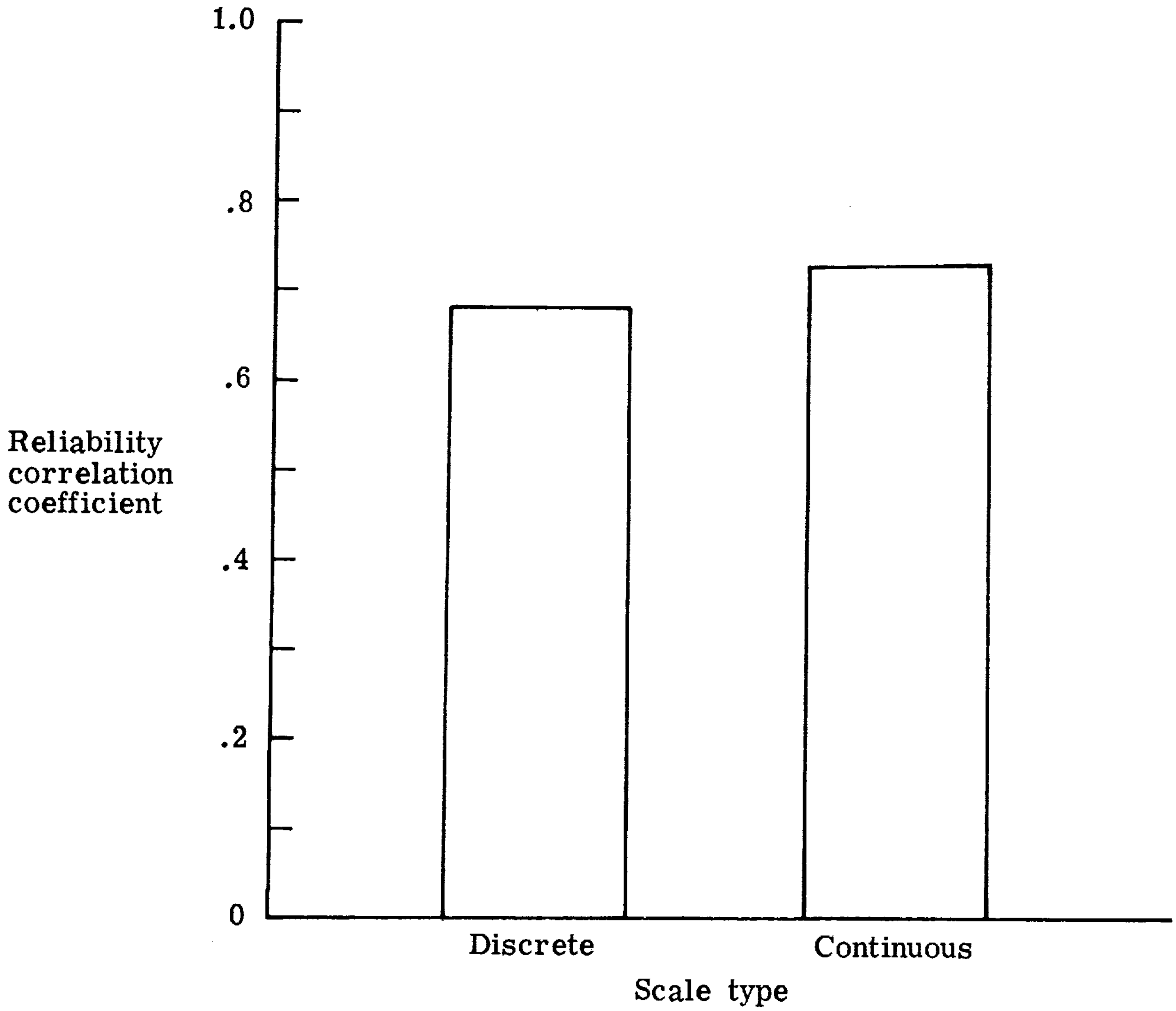


Figure 7.- Test-retest reliability correlation coefficients for discrete and continuous scales.

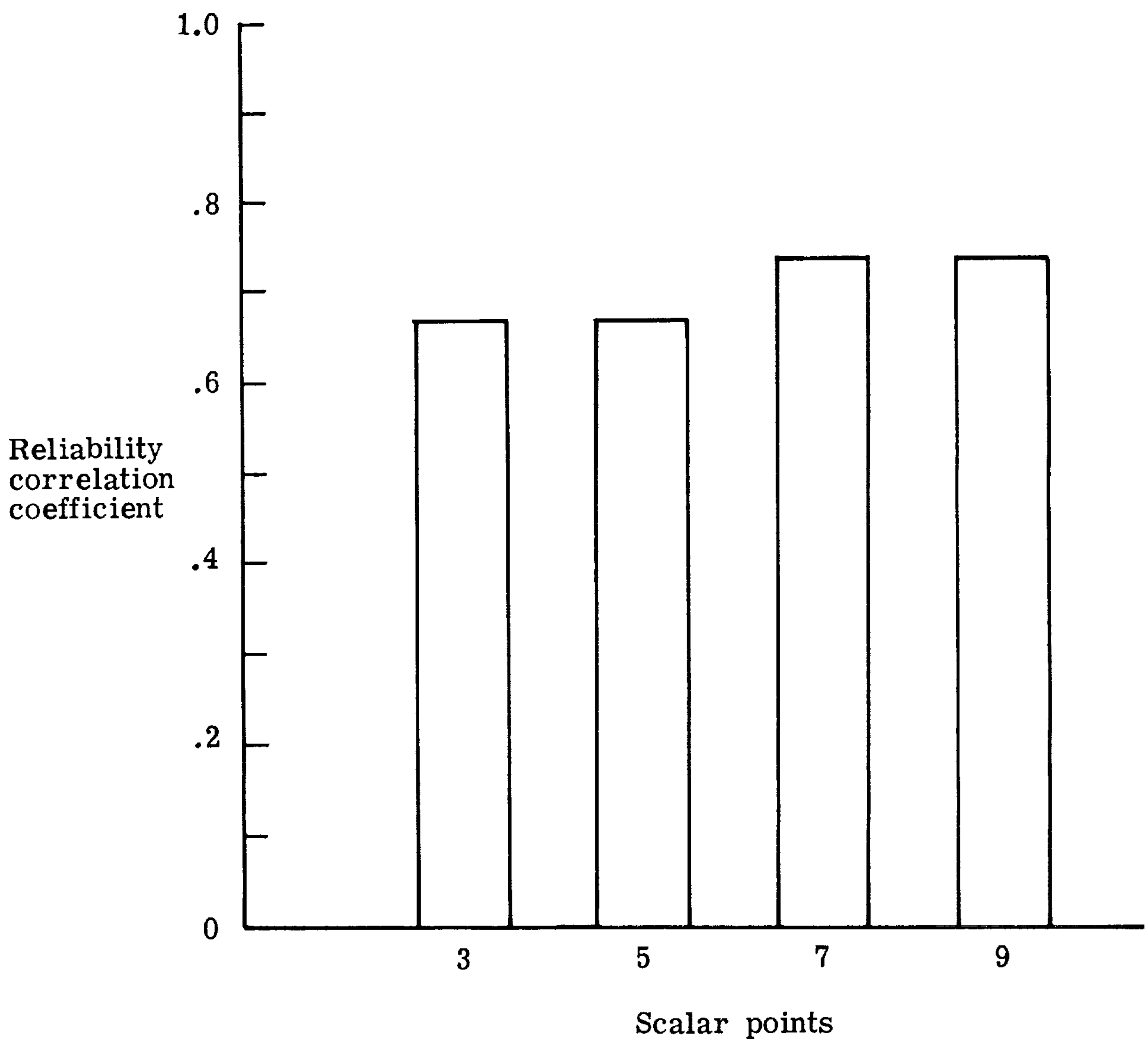


Figure 8.- Test-retest reliability correlation coefficients as a function of number of scalar points.

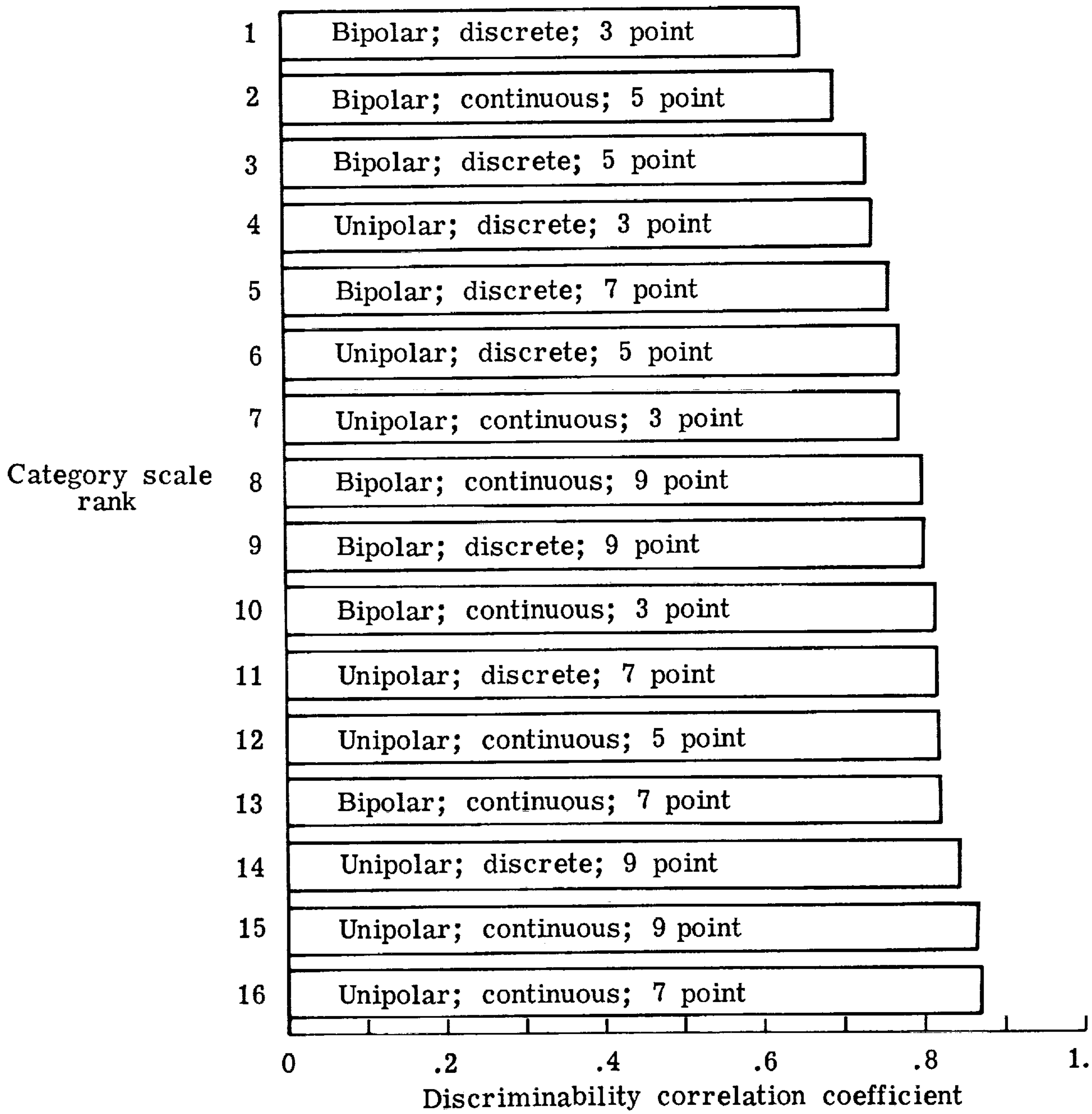


Figure 9.- Rank order of category scales as a function of discriminability correlation coefficient computed according to equation (1) (linear relationship).

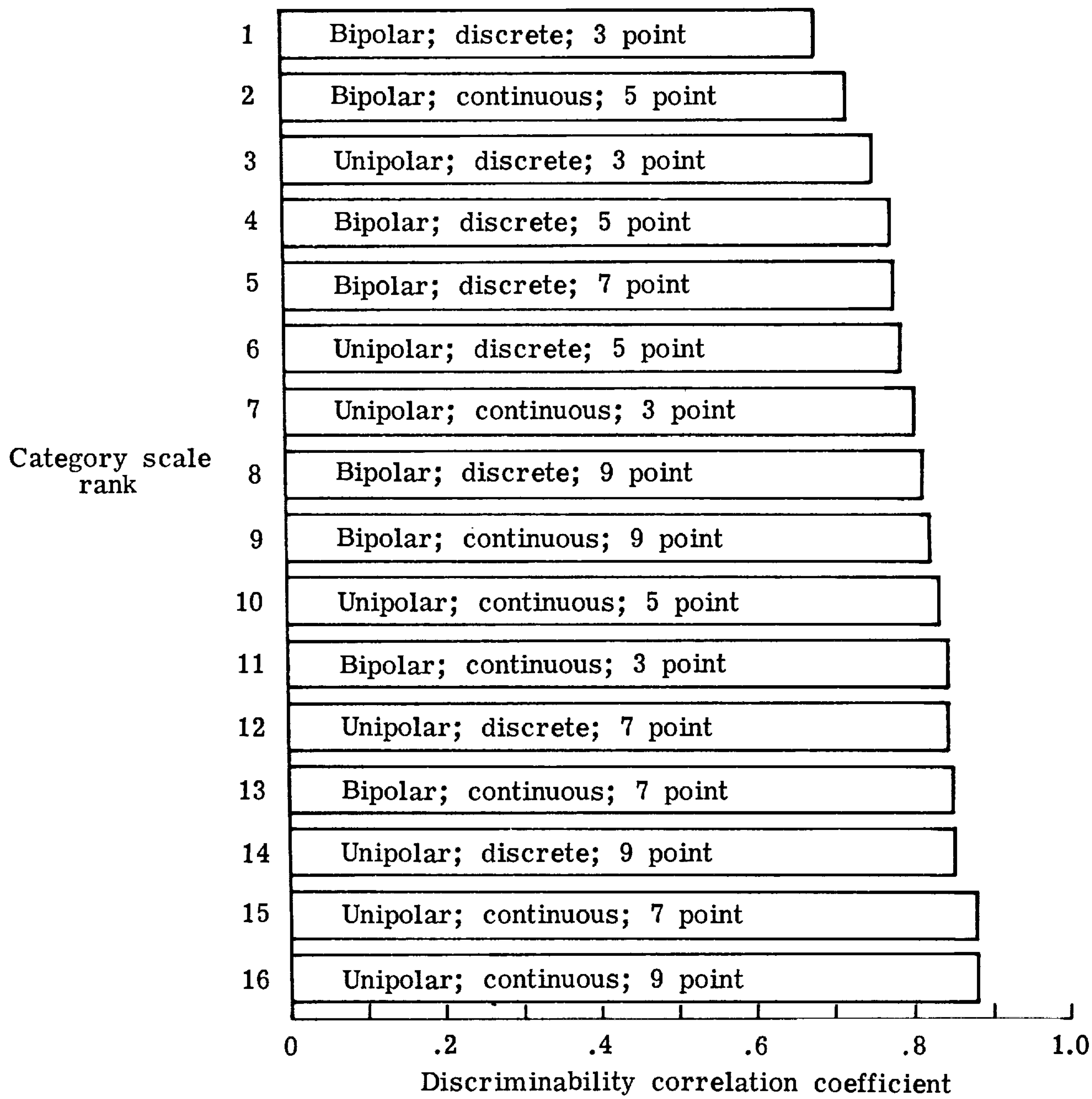


Figure 10.- Rank order of category scales as a function of discriminability correlation coefficient computed according to equation (2) (logarithmic relationship).

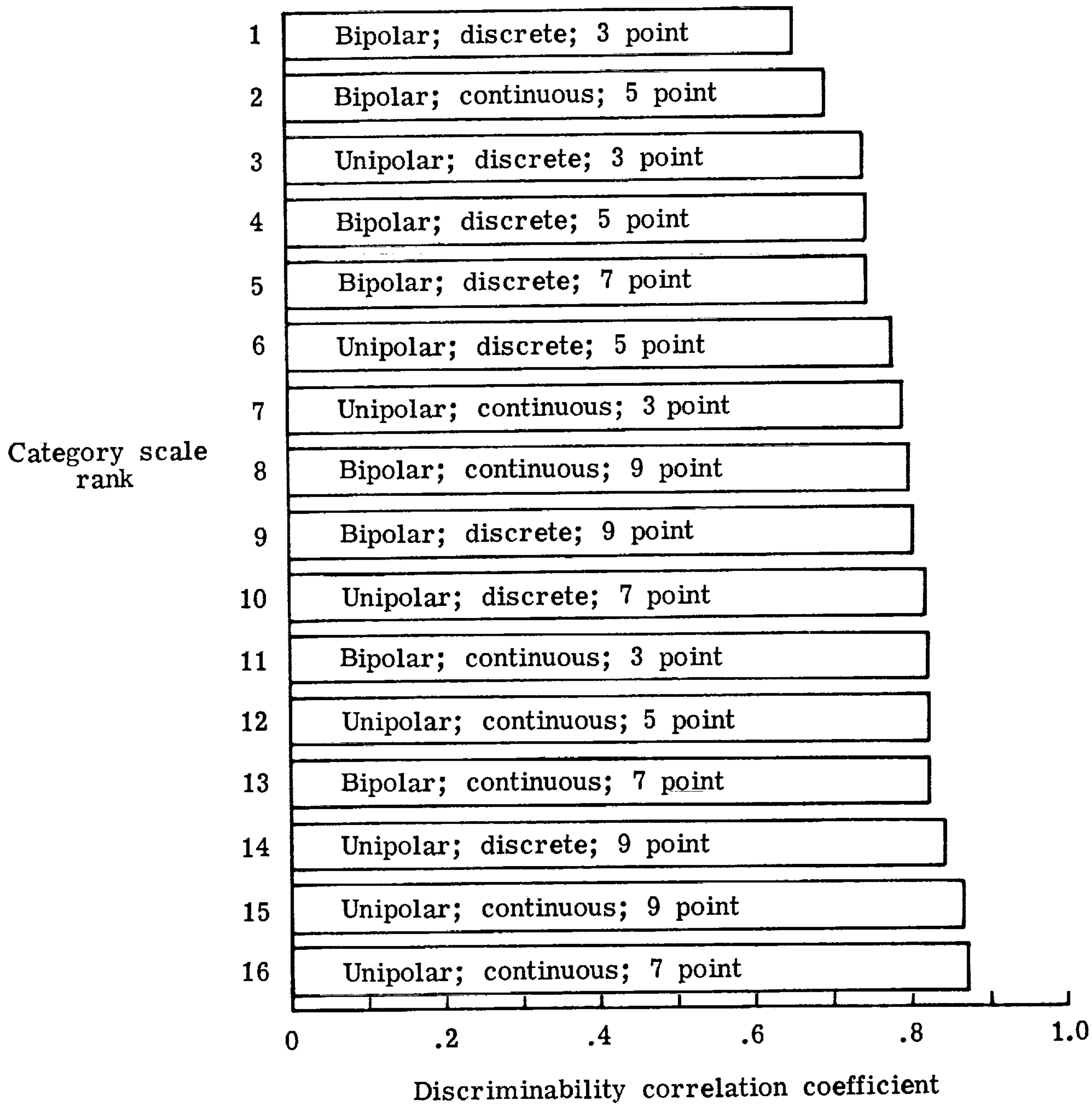


Figure 11.- Rank order of category scales as a function of discriminability correlation coefficient computed according to equation (3) (exponential relationship).

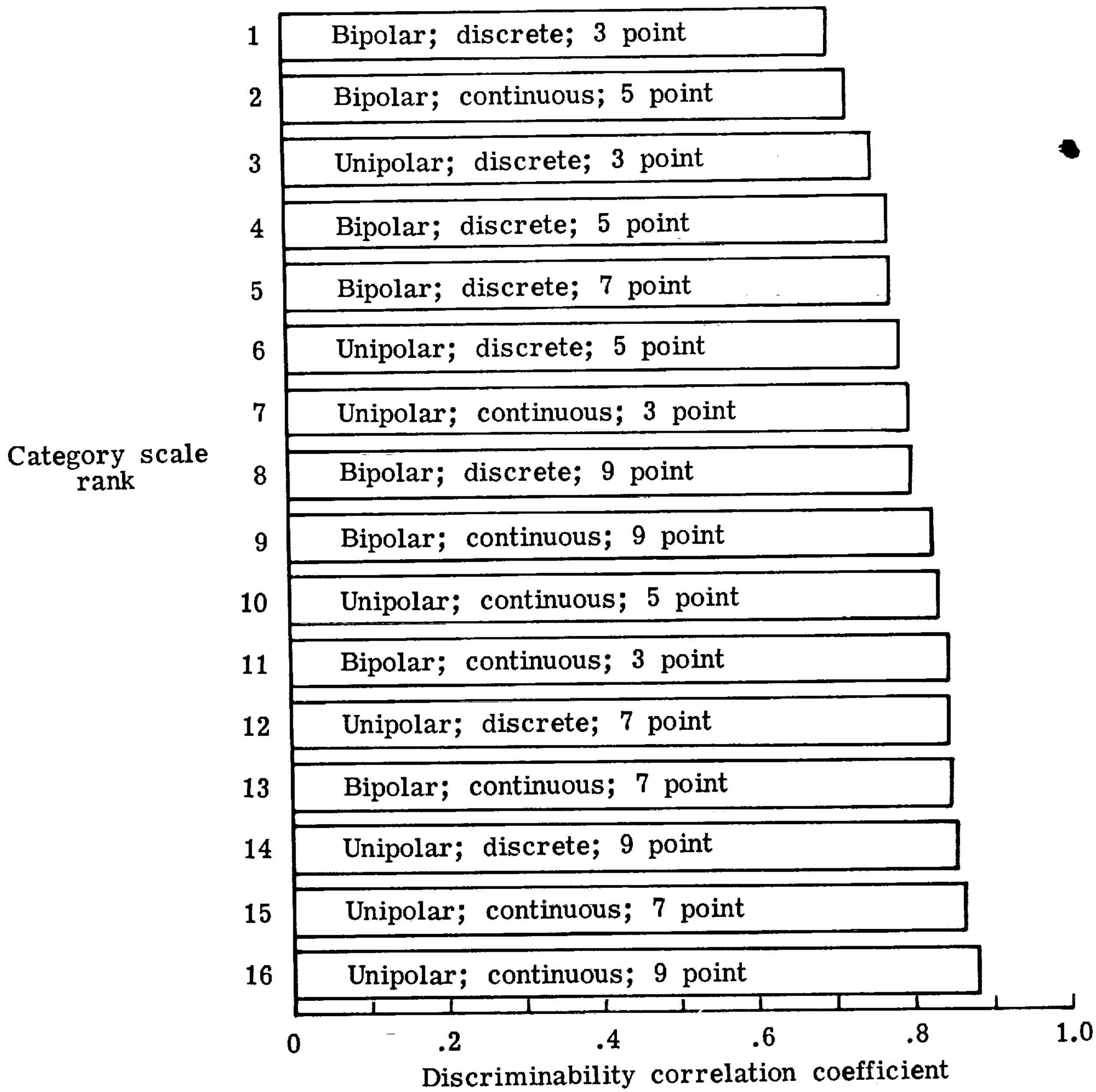


Figure 12.- Rank order of category scales as a function of discriminability correlation coefficient computed according to equation (4) (power relationship).

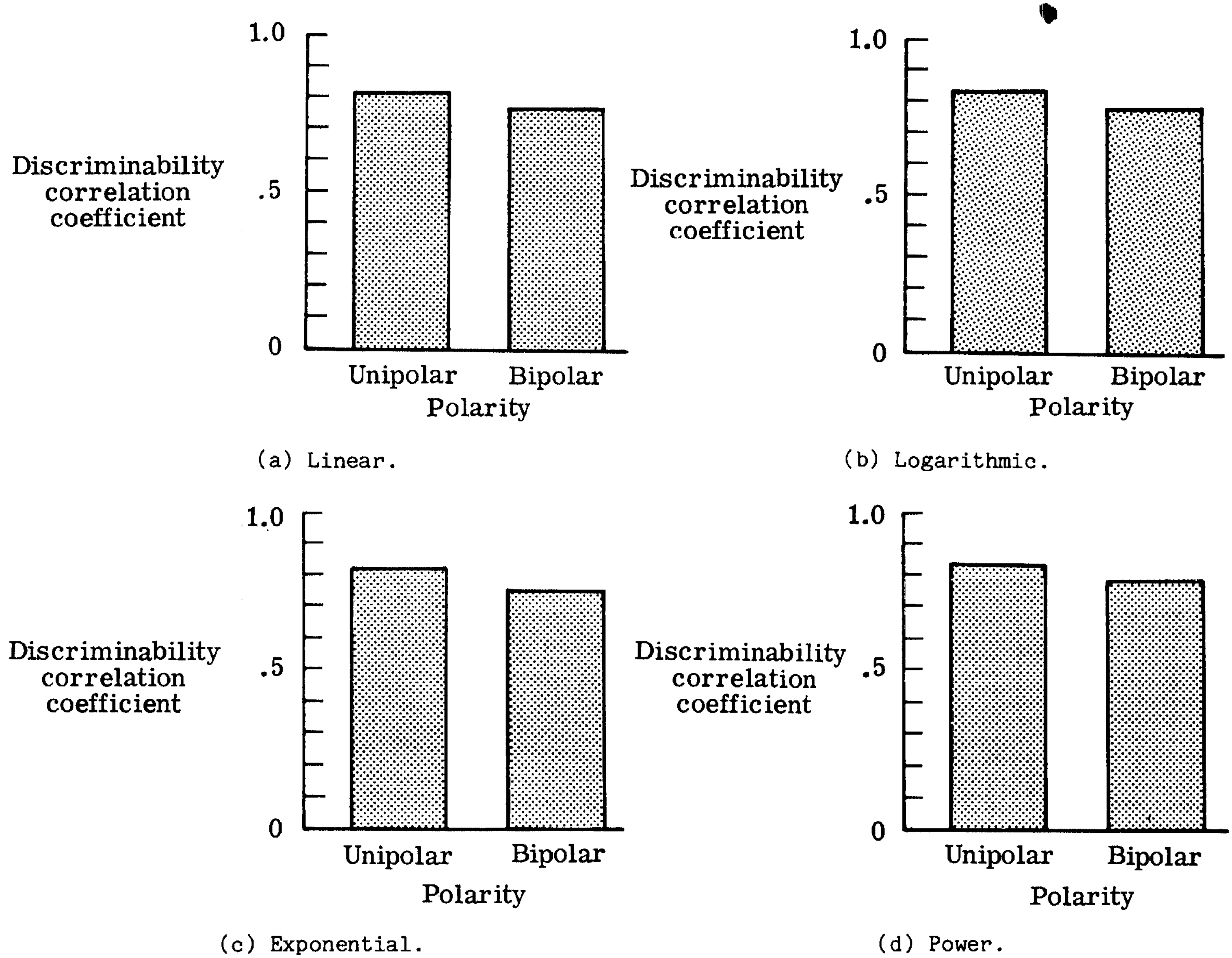
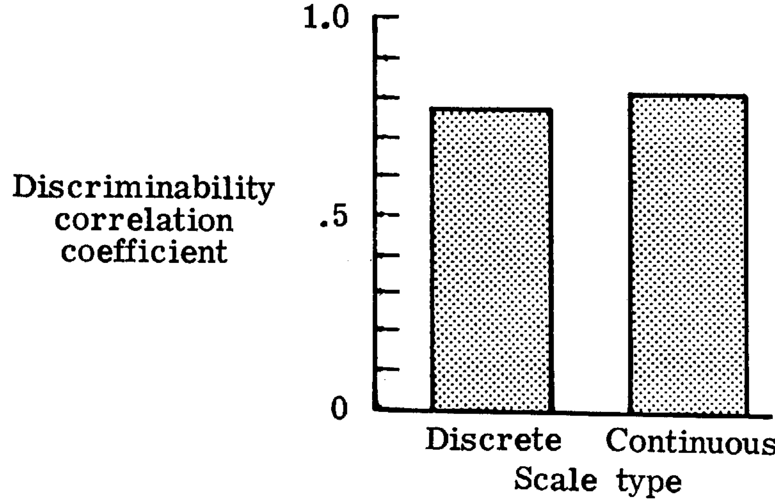
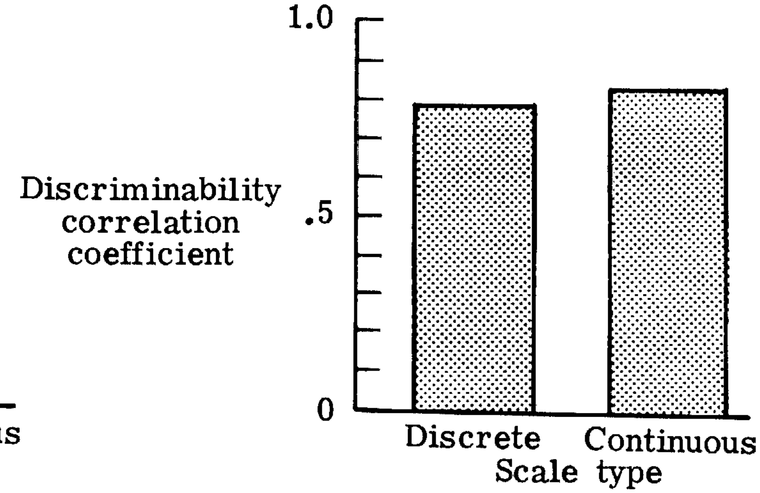


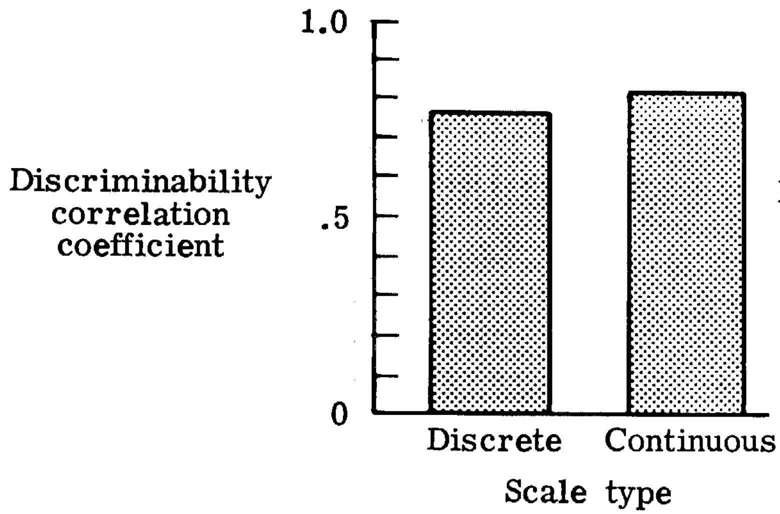
Figure 13.- Discriminability correlation coefficients for unipolar and bipolar scales for various psychophysical formulations.



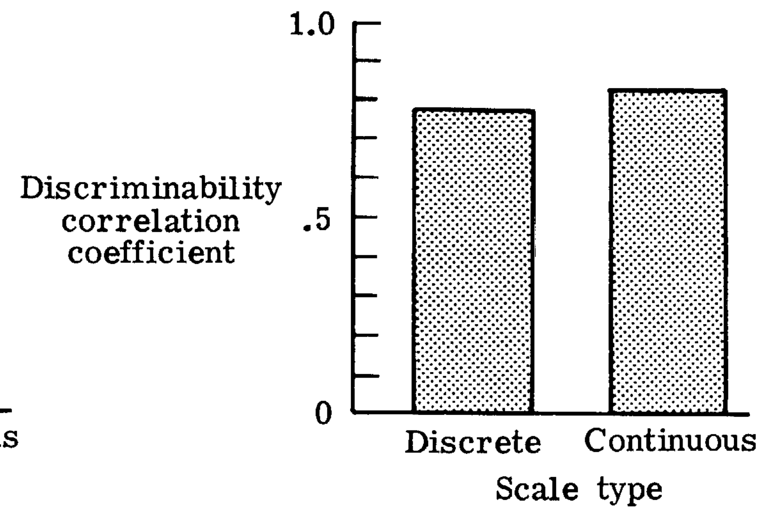
(a) Linear.



(b) Logarithmic.

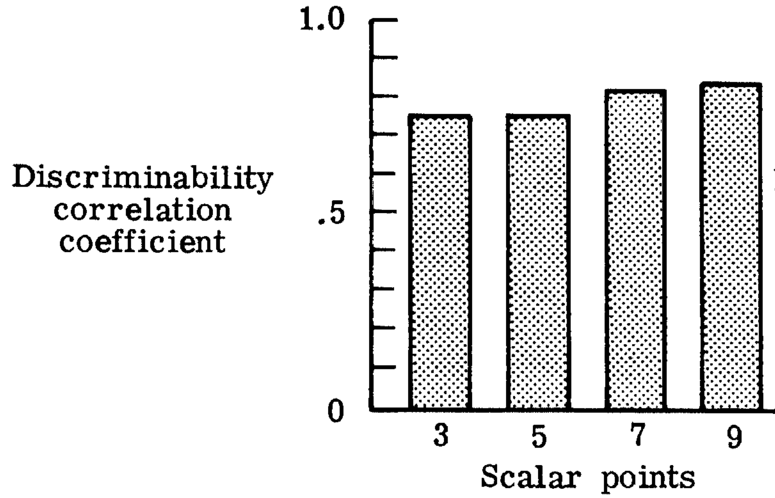


(c) Exponential.

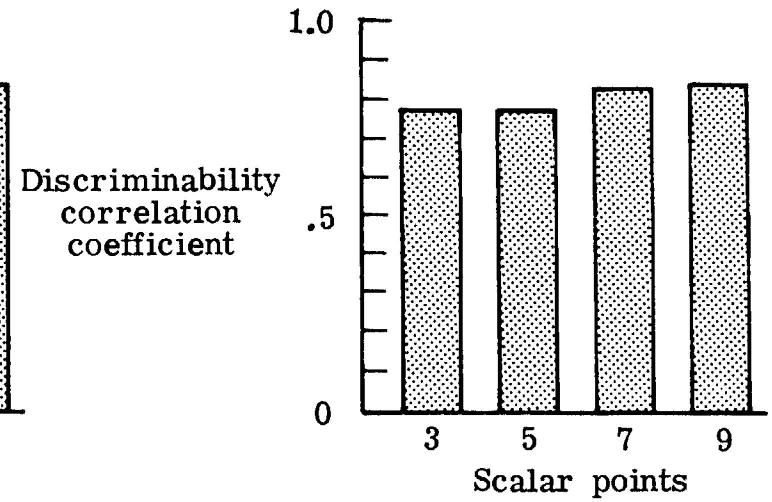


(d) Power.

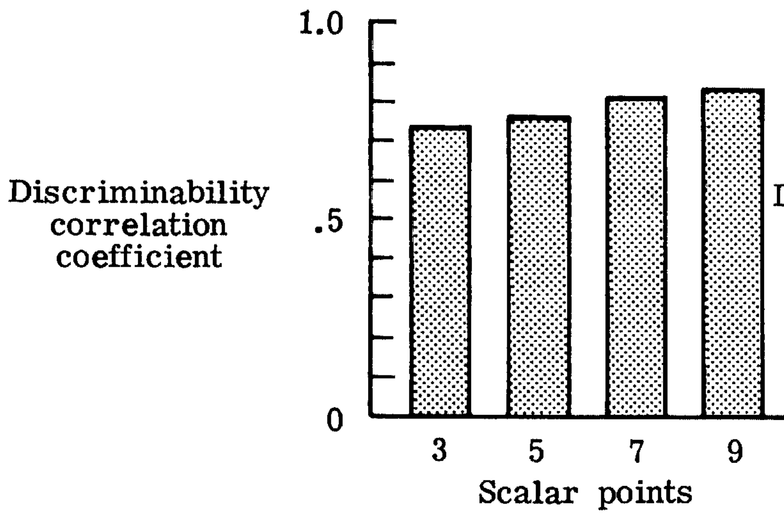
Figure 14.- Discriminability correlation coefficients for discrete and continuous type for various psychophysical relationships.



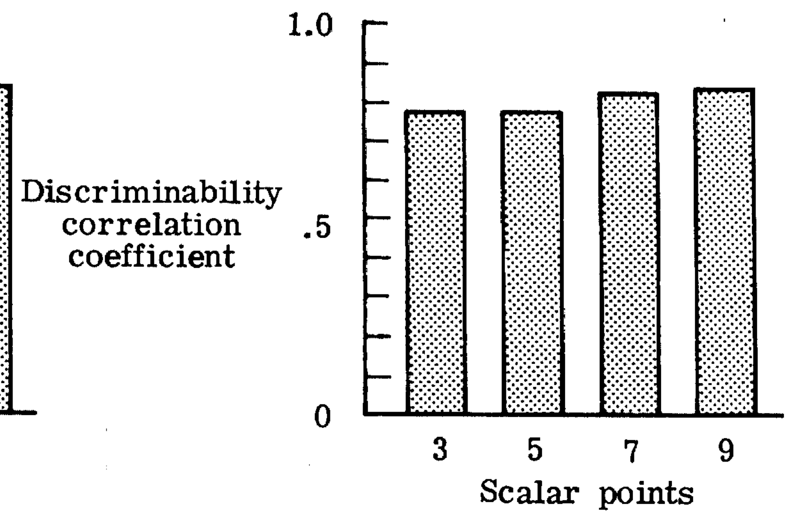
(a) Linear.



(b) Logarithmic.



(c) Exponential.



(d) Power.

Figure 15.- Discriminability correlation coefficients as a function of scalar points for various psychophysical formulations.

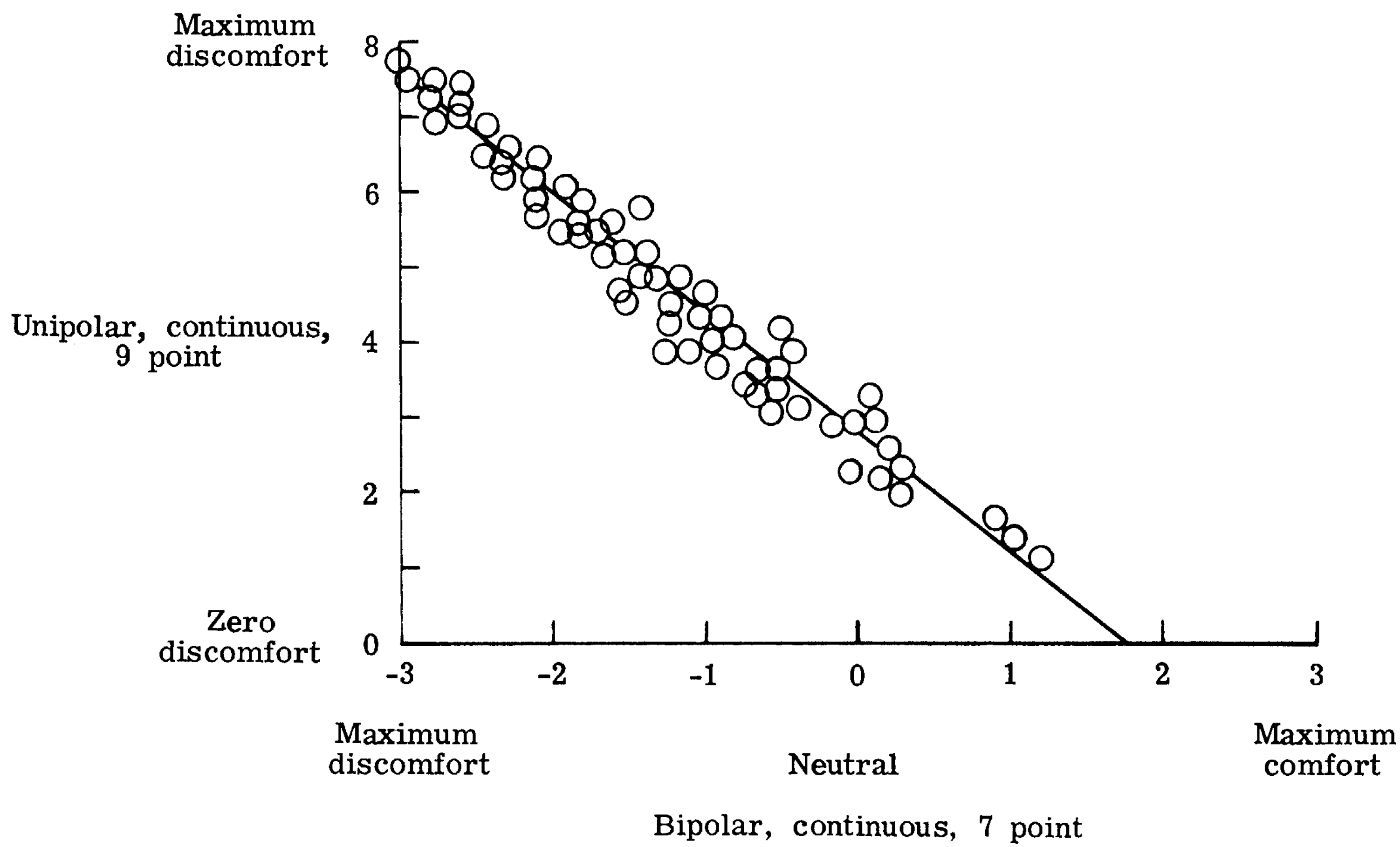


Figure 16.- Subjective responses of a unipolar, continuous, nine-point scale compared with responses of a bipolar, continuous, seven-point scale. The data represent cross plotting of responses from two different category scales, the responses of which were reactions produced to the same vibrations (for example, frequency by acceleration level).

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16. Abstract

An experimental investigation was conducted for the combined purposes of determining the relative merits of various category scales for the prediction of human discomfort response to vibration and for determining the mathematical relationships whereby subjective data are transformed from one scale to other scales. There were 16 category scales analyzed in this study representing various parametric combinations of polarity, that is, unipolar and bipolar, scale type (continuous or discrete), and number of scalar points (three, five, seven, or nine).

Results indicated that unipolar continuous-type scales containing either seven or nine scalar points provide the greatest reliability and discriminability. Furthermore, transformations of subjective data between category scales were found to be feasible with unipolar scales of a larger number of scalar points providing the greatest accuracy of transformation. The results contain coefficients for transformation of subjective data between the category scales investigated. A result of particular interest was that the comfort (or positive) half of a bipolar scale was seldom used by subjects to describe their subjective reaction to vibration.

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