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# MULTIDIMENSIONAL STIMULUS DIFFERENCES AND ACCURACY OF DISCRIMINATION

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## FOREWORD

This report is the result of experiments performed by Charles W. Eriksen under contract No. AF 33(038)-22642 at the Institute for Cooperative Research, The Johns Hopkins University. The contract was initiated under a project identified by Research and Development Order Nos. 694-45, Presentation of Data on Radar Scopes, and 694-43, Human Engineering Analysis of Multiple Operator Air-Ground Systems, and was administered by the Psychology Branch of the Aero Medical Laboratory, Directorate of Research, Wright Air Development Center, with Julien M. Christensen acting as Project Engineer.

## ABSTRACT

The present report is concerned with the effect of stimulus variation in several dimensions simultaneously upon the accuracy of discrimination in absolute judgment. The dimensions were size, hue and brightness. The discrimination measures for these dimensions were obtained separately and were compared with discrimination measures obtained by compounding these dimensions in various ways. Discriminability was better for the multidimensional series of stimuli than for any of the compounded dimensions used alone. It was further shown that the discrimination accuracy for a compounded or multidimensional series can be predicted if the discrimination accuracy of the separate dimensions is known. This prediction is based on the assumption that the accuracy of discrimination on the several dimensions is independent when simultaneously judged.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

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## I. INTRODUCTION

Can a series of stimuli be more accurately discriminated from one another if they differ on two or three dimensions than if they differ along a single dimension? And, can the discrimination accuracy for such multidimensional stimuli be predicted from the discriminability of the component dimensions? Little experimental work has been performed on these specific questions, but there are several reports in the literature that indicate multidimensional cues facilitate learning and reduce reaction time. Eninger (3) found that rats learned a discrimination problem more rapidly when visual and auditory cues were compounded than when either auditory or visual cues were used alone. Similar findings were obtained by Miller using compounds of visual and auditory modalities in a classical conditioning study (8). In both these studies compounding was across different sense modalities. However, two studies have shown that reaction time is reduced when two dimensions within the same sense modality are compounded. Grant (6) found in a card sorting task that sorting was more rapid if the cards differed in both number and configuration than if they differed in number alone. And Weitz (9) found that reaction time to control levers was more rapid if the knobs differed in both hue and form than if they differed only on hue or only on form.

Several other studies have indicated, however, that the overall perceptual situation determines in some cases whether or not compounded or multidimensional cues contribute to discrimination. Eriksen (4) found that compounding cues on the dimensions of hue, form, size and brightness did not increase the speed with which objects could be located in a visual display. He found that this failure to improve location time was attributable to a perceptual heterogeneity factor that resulted from introducing more dimensions of variation into the display. More recently Bricker (1) has shown that redundant position cues did not contribute in learning to associate labels to a set of visual forms.

In general the results of work in this area have been to suggest that the effects of compounding dimensional cues depends in some measure upon the response studied and the nature of the task. In none of the cases has there been a direct effort to assess the effects of compounding dimensions in terms of accuracy of discrimination or the number of discriminable steps in a stimulus series that can be obtained. In the present study both discrimination accuracy and the number of reliably discriminable steps have been determined for a series of stimuli varying along the dimension of size, hue and brightness. The discrimination measures obtained for stimuli varying along these single dimensions were then compared with the discrimination measures obtained when a stimulus series varied on size and hue, size and brightness, hue and brightness, and size, hue and brightness.

## II. METHOD

Design. Discrimination was determined by the method of absolute judgment, or as it is sometimes called, the method of stimulus rating. The method requires the subjects to identify by a name, number or value each member of a set of individually presented stimuli. In the present study subjects used the numbers from

1-20 in order to identify which stimulus had occurred. The absolute method was chosen as a measure of discrimination since it is amenable to an analysis in terms of information theory. Garner and Hake (5) have shown that the information transmitted by a series of stimuli along a dimension is interpretable as the number of stimuli that can be selected from this dimension to yield perfect discrimination under absolute conditions.

Seven different series of stimuli were judged in the present study. In three of these series the stimuli composing the series differed from one another along a single dimension. These dimensions were respectively, size, hue and brightness. In the remaining four stimulus series multidimensional stimulus differences were employed. In three of these four remaining series each stimulus in the series could be uniquely specified on each of two dimensions, and in the fourth series each stimulus could be specified on all three dimensions. The brightness and the size-brightness series each contained 17 stimuli and 20 stimuli were used in each of the remaining series.

Each of six subjects made one hundred judgments of each stimulus in each of the seven stimulus series. Subjects completed all judgments of a series before beginning their judgments on the next series. To control for practice effects, subjects made their judgments of the seven stimulus series in a counter-balanced order.1/

<u>Materials and apparatus.</u> Table 1 defines the stimuli used in the size, hue, brightness, and the hue-brightness series and shows the response number that was assigned to each. The other three multidimensional series are not represented in this table since they were constructed by compounding stimuli of the single dimensional series. In constructing these multidimensional series the component single dimension stimuli were superimposed one on top of the other. Thus for the series size-hue, stimulus 1 was a 1/8 in. 5 R 5/6 square, stimulus 2 was a 2/8 in. 10 R 5/6 square, stimulus 3 a 3/8 in. 5 YR 5/6 square, etc.2/ In constructing the multidimensional series of size-hue-brightness, the hue-brightness stimuli were compounded with the size stimuli in the manner described above for size-hue.

As can be seen in Table 1 the response numbers were assigned to stimuli in such a manner that the serial order of the response numbers conformed to the position of the stimuli along the dimension(s).

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1/ The design followed a 7 x 7 latin square which was not quite realized due to the seventh subject failing to complete the experiment. However, statistical examination of the data revealed no evidence of systematic practice effects from one series to the next.

2/ The multidimensional series of hue-brightness was an exception to this method of construction and as a result has been presented in Table 1. This exception was necessitated by the non-independence of hue and brightness and the inability to obtain Munsell hue in half brightness steps. It will also be noted in the table that the hues in this series have a saturation of four in the Munsell system while in the hue and the size-hue series all hues have a saturation of six. Since the hues are of a different saturation and the brightness differences between adjacent stimuli are a full brightness step, the results obtained with this multidimensional series are not directly comparable to those obtained with the other multidimensional series.

Table 1

Specification of the stimulus categories used for size, hue, brightness and hue-brightness. The specifications for hue and brightness are given in the Munsell notation. For example, 10 R 5/6 indicates that the hue is red with a brightness value of 5 and a saturation of 6 on the Munsell scales.

| Response | Stimulus Dimensions | | | |
|---|---|---|---|---|
| | Size (in. square) | Hue | Brightness | Hue-Brightness |
| 1 | 1/8 | 5 R 5/6 | N 1/ | 5 R 4/4 |
| 2 | 2/8 | 10 R 5/6 | N 1.5/ | 10 R 5/4 |
| 3 | 3/8 | 5 YR 5/6 | N 2/ | 5 YR 6/4 |
| 4 | 4/8 | 10 YR 5/6 | N 2.5/ | 10 YR 7/4 |
| 5 | 5/8 | 5 Y 5/6 | N 3/ | 5 Y 8/4 |
| 6 | 6/8 | 10 Y 5/6 | N 3.5/ | 10 Y 7/4 |
| 7 | 7/8 | 5 GY 5/6 | N 4/ | 5 GY 6/4 |
| 8 | 8/8 | 10 GY 5/6 | N 4.5/ | 10 GY 5/4 |
| 9 | 9/8 | 5 G 5/6 | N 5/ | 5 G 4/4 |
| 10 | 10/8 | 10 G 5/6 | N 5.5/ | 10 G 3/4 |
| 11 | 11/8 | 5 BG 5/6 | N 6/ | 5 BG 2/4 |
| 12 | 12/8 | 10 BG 5/6 | N 6.5/ | 10 BG 3/4 |
| 13 | 13/8 | 5 B 5/6 | N 7/ | 5 B 4/4 |
| 14 | 14/8 | 10 B 5/6 | N 7.5/ | 10 B 5/4 |
| 15 | 15/8 | 5 PB 5/6 | N 8/ | 5 PB 6/4 |
| 16 | 16/8 | 10 PB 5/6 | N 8.5/ | 10 PB 7/4 |
| 17 | 17/8 | 5 P 5/6 | N 9/ | 5 P 8/4 |
| 18 | 18/8 | 10 P 5/6 | ------ | 10 P 7/4 |
| 19 | 19/8 | 5 RP 5/6 | ------ | 5 RP 6/4 |
| 20 | 20/8 | 10 RP 5/6 | ------ | 10 RP 5/4 |

The stimuli for the size series were cut from a dark gray paper and for the hue, brightness, and hue-brightness series 7/8 in. squares of Munsell papers were used. For all series the stimuli were mounted in the center of 3 in. white cardboard squares to facilitate handling.

Procedure. The subjects were run individually with an average of five one hour sessions being required to judge the stimuli in any one series. Prior to beginning the experimental judgments on a given series, each subject made eight practice judgments with correction of each stimulus in the series. Following the practice judgments one hundred judgments of each stimulus were obtained during the experimental sessions. In all each subject made a total of 13,400 experimental judgments over the seven stimulus series during the experimental sessions.

As was mentioned above, all stimuli were mounted on white cardboard squares. Four of these stimulus cards were constructed for each stimulus. The stimulus cards were presented to the subject one at a time and his judgment recorded. The experimental sessions were broken up into blocks of judgments where a block was defined as four judgments on each stimulus in the particular series. Between blocks the subject was given a short rest while the experimenter thoroughly reshuffled the stimulus cards in order to insure a random order of appearance of the different stimuli.

Subjects. The six subjects were male undergraduate students at The Johns Hopkins University. None had previously served as a subject in a psychophysical experiment. All were screened by a shortened version (2) of the Ishihara Color Vision test to insure that they were color normal.

## III. RESULTS

Two different methods have been used to express the discrimination accuracy obtained with the three single and the four multidimensional stimulus series. The first of these was to determine the information transmitted in bits ($I_t$) between the stimuli and responses in each series. Garner and Hake (5) have shown that the antilogarithm to the base 2 of $I_t$ is interpretable as the maximum number of stimulus values that could be selected from a series of stimuli if errorless discrimination were desired. The second method consisted of computing the average percent of correct responses given to the stimuli within each series.

As a first step in evaluating the results an overall test of the significance of differences in discrimination accuracy between the different series was made. The value of $I_t$ for each subject was computed for each of the seven series. These $I_t$ values were then subjected to a two-way analysis of variance (stimulus series and subjects). The resulting F of 20.48 ($P > .0001$) demonstrated that the variation in accuracy between series was much greater than could be reasonably attributed to chance.

The discrimination accuracy obtained with each of the seven series is shown in Table 2. The first column of this table gives the average value of $I_t$ for the six subjects. In the second column the antilog of the $I_t$ value to the base 2 for

Table 2

Discrimination accuracy for the three single and the four multidimensional stimulus series

| Stimulus Series | $I_t$* | Number of Stimuli Absolutely Discriminable | Average Percent Correct Judgments | |
|---|---|---|---|---|
| | | | Observed | Predicted |
| Size | 2.84 | 7.19 | 47.5 | |
| Hue | 3.08 | 8.45 | 53.4 | |
| Brightness | 2.34 | 5.06 | 41.3 | |
| Size-Hue | 3.55 | 11.90 | 76.2 | 72.6 |
| Size-Brightness | 2.98 | 7.89 | 59.8 | 59.5 |
| Hue-Brightness | 3.76 | 13.55 | 84.2 | |
| Size-Hue-Brightness | 4.11 | 17.28 | 96.5 | 90.7 |

* Based upon error term for the analysis of variance, differences of .38 and .52 in $I_t$ are significant at the .05 and the .01 level, respectively.

each subject has been averaged through subjects. Thus the values in this column represent the best estimate of the maximum number of stimulus categories or values that could be selected from the different series if errorless discrimination were to be obtained. The third column shows the average percent of correct responses obtained with each series.

As can be seen from Table 2 there is a marked gain in discrimination when two or three dimensions are compounded. This is true irrespective of which measure of discrimination is considered. The multidimensional series of size-hue results in significantly more accurate discrimination than is obtained by either the size or the hue dimension used alone. The size-brightness and the hue-brightness series also yield better discrimination than is obtained by any of the component dimensions used singly and in the case of the series size-hue-brightness where stimuli differed from adjacent stimuli in the series on each of these dimensions discrimination was nearly perfect for all 20 stimuli.

This improvement in discrimination obtained by compounding dimensions indicates at least a moderate degree of independence in the accuracy with which two or more dimensions are simultaneously judged. That is to say, the accuracy with which a subject judges or rates a hue at a given moment is less than perfectly correlated with the accuracy with which he rates a particular size or brightness value. In fact the present data suggest that the value of this correlation is close to zero.

The results obtained with the multidimensional series can be predicted rather well by the use of three assumptions concerning discrimination behavior under the present conditions. They are:

1. At a given moment in time, the response tendency (rating) to a magnitude on one dimension is independent of the response tendency to magnitudes on other dimensions.

2. The distribution of response frequencies to a stimulus magnitude is a measure of the relative strengths of response tendencies elicited by that magnitude.

3. In the case of competing response tendencies the stronger tendency will be evoked as a response.

In Table 3 these assumptions have been used to predict the distribution of responses to stimulus number 8 (8/8 in. 10 GY square) in the multidimensional size-hue series.

The first column of this table shows the response distribution obtained for this hue (10 GY) when it occurred as stimulus number 8 in the hue series and the second column shows the distribution of responses to this size (8/8 in. square) when it occurred as stimulus 8 in the size series. The third column is the response distribution to the compound of these two stimulus magnitudes.

If we consider the first two columns as reflecting the strength of response tendencies to these two stimulus magnitudes when viewed separately, we would expect that 16.8% of the time when this size occurred in the size-hue series the response tendency 7 would occur and 49.6% of the time this particular hue would tend to elicit the response 8. In keeping with the first assumption of independence, it would be expected that 49.6% of the time when this size magnitude tended to elicit the response 7, this hue magnitude would tend to elicit the response 8. In keeping with assumption 3, the occurrence of this event would give rise to the response 8 since the response 8 to the hue magnitude is a stronger response (has a higher relative frequency) than 7 is to the size magnitude. In other words for this particular event, accuracy of discrimination for the size-hue compound would increase by 8.3% over what would have been obtained by size alone.

In a similar way we may consider all the other possible events that could arise from these two distributions. This essentially reduces to multiplying each response percentage for the size or hue magnitude by the response percentage for the other dimensional magnitude and assigning the product to the response category that has the highest percentage value. Thus 0.3% for response 5 for size would be multiplied by 0.8% for response 7 for hue and the product, 0.0024%, would be assigned to response 7 since it has the greatest response strength of the two responses.

Column four in Table 3 is the predicted response distribution for stimulus number 8 in the size-hue series. It was obtained by following the above procedure through the 48 multiplications involved and then summing the products assigned to each response category. As can be seen from the table, the predicted distribution is a fair approximation to the empirical one.

The distribution predicted in Table 3, however, is for only one of the compounded stimuli and is not an adequate test of the predictive model. Accordingly the above described procedure was carried out for each stimulus in the size-hue, size-brightness and the size-hue-brightness series.3/ The predicted percent correct judgments for each stimulus was then averaged for each series. These average predicted percent correct responses are shown in column four of Table 2 where they can readily be compared with the obtained values.

Comparison shows the predicted percent correct responses are very close to the empirical results. The biggest discrepancy is 5.8% for the multidimensional series size-hue-brightness, but it is less than 1% for size-brightness. The closeness of the fit can be further demonstrated by computing the rank order correlation between the predicted percent correct judgments for each stimulus in a series and the obtained percentage correct judgments. For the size-hue series this rank order correlation is .86 for the 20 stimuli, and for the 17 stimuli in the size-brightness series, rho is .77. A similar rank order correlation for the size-hue-brightness was not practicable since the discrimination accuracy for this series was nearly perfect and there was little or no variation among the predicted or the obtained judgments for the stimuli in this series.

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3/ It was not possible to obtain such predictions for the hue-brightness series since, as was pointed out in the section on Procedure, this multidimensional series was not a simple compound of the stimuli used in the hue and brightness series. Due to limitations of Munsell hues it was necessary to use a full brightness step between adjacent hues in this multidimensional series whereas in the brightness series alone, half-brightness steps were employed. Also, as a consequence it was necessary for the same brightness values to be compounded with several different hues.

Table 3

Distribution of responses in percent to the 8/8 in. square in the size series, the 10 GY in the hue series, and to the compound of these two values in the size-hue series (N = 600)

| Response | Size | Hue | Size-Hue Observed | Size-Hue Predicted |
|---|---|---|---|---|
| 5 | 0.3 | 0.0 | 0.0 | 0.0 |
| 6 | 0.7 | 0.0 | 0.0 | 0.0 |
| 7 | 16.8 | 0.8 | 1.7 | 2.1 |
| 8 | 46.2 | 49.6 | 81.5 | 72.8 |
| 9 | 24.0 | 19.8 | 12.3 | 18.3 |
| 10 | 8.8 | 17.5 | 4.3 | 5.6 |
| 11 | 3.0 | 9.5 | 0.2 | 1.2 |
| 12 | 0.2 | 2.7 | 0.0 | 0.0 |

## IV. DISCUSSION

The results of the present study show quite clearly that compounding dimensional differences between stimuli results in a large as well as a significant improvement in discrimination under the absolute method of judgment. This improvement in discrimination indicates at least a moderate degree of independence at a given time between a subject's ability to rate correctly a magnitude on one dimension and his ability to rate correctly magnitudes on other dimensions. In the present case it was possible by assuming complete independence of judgments to predict with reasonable accuracy the discriminability of compounded or multi-dimensional stimulus series from the discriminability of the component dimensions.

It should be noted, however, that the results obtained here are limited to the visual dimensions employed and to the type of discrimination that occurs under conditions of absolute judgment. The importance of the perceptual task and the performance measure studied has been pointed out earlier in this paper to be a factor in determining the effect of compounding dimensional differences between stimuli (1, 4). Also it seems quite reasonable to expect that there are psychological dimensions where judgmental accuracy at a moment in time is correlated in varying degrees with judgmental accuracy on other dimensions. The existence of such dimensions and the factors determining the correlations need to be determined.

It should be noted in the present study that the subjects were well aware of the different dimensions along which the compounded stimuli differed. Most of the subjects, when questioned after the experiment, stated that they were aware of the component dimensions in making their judgments of a compounded stimulus. This awareness must be considered as another restriction on the obtained results, since it is quite likely that certain other dimensions may combine in such a manner that the resultant stimulus is perceived as a whole where the observer is not aware of all the component dimensions. Possible examples are the dependence of pitch upon loudness and visual forms. In a similar way the compounding of a large number of dimensions may result in the loss of ready awareness of some of the dimensions involved in the compounding. If this latter case were true, it might set the upper limit on the amount of improvement in discrimination that can be obtained via compounding dimensions.

There is one other aspect of the present data that deserves comment. This concerns the number of absolutely identifiable or discriminable steps that can be obtained with the hue and brightness dimensions. Since the entire range of visible hue and nearly the entire range of brightness was used in these respective stimulus series, the number of absolutely discriminable steps obtained for these dimensions may be considered as close approximations to the maximum obtainable. As was seen above, very few values could be selected from the brightness dimension so as to satisfy the criterion of perfect discriminability under absolute conditions. The data suggest a maximum of about five values. The maximum number of values that could be selected from the hue dimension to meet this criterion is somewhat larger. Here the data indicate that at least eight hues of equal brightness and saturation could be so selected. This number for hue is somewhat less than the number that has been estimated by Halsey and Chapanis (7). Their data indicated that between ten and twelve hues could be absolutely discriminated.

This discrepancy between the two sets of data seems most likely to be due to differences in amount of practice given the subjects. Halsey and Chapanis practiced their subjects until there was no further learning from trial to trial. If only the last 20 judgments of each of the 20 hue stimuli are considered in the present experiment, it is found that the subjects were transmitting an average of 3.44 bits of information from the hue dimension. The antilog to the base 2 of this value is 11, which is quite comparable to the figure arrived at by Halsey and Chapanis. A comparable computation for the brightness series results in an average of 2.59 bits which indicates about six steps on the brightness dimension are absolutely discriminable.

## V. SUMMARY

The present study was concerned with the contribution of multidimensional stimulus differences to accuracy of discrimination. Discrimination accuracy was determined by the method of absolute judgment for a series of stimuli varying along the dimension of size, of hue, and of brightness. The discrimination measures obtained for these stimuli varying along these single dimensions were then compared with the discrimination measures obtained when a series of stimuli varied on size and hue, size and brightness, hue and brightness, and size, hue and brightness.

The results demonstrated that the discriminability for a multidimensional series of stimuli was considerably greater than that obtained for any of the compounding dimensions used alone. It was further shown that the discrimination accuracy for a compounded or multidimensional series of stimuli could be predicted with reasonable precision if the discrimination accuracy of the compounding dimensions was known. This predictability was based upon the assumption of independence in the accuracy with which magnitudes on two or more dimensions are simultaneously judged.

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