Multidimensional encoding of visual form*

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The encoding of stimulus dimensions of visual form in the human S was investigated under conditions of threshold exposure durations. Three stimulus dimensions defined on a spatial grating were investigated: spatial line frequency, grating orientation, and orientation of a transverse break in the lines of grating. Results support the conclusion that, within the general category of visual form, different primary stimulus dimensions such as spatial frequency and orientation may be encoded simultaneously, whereas, when the two stimulus components for report are defined on the same dimension (orientation), overall performance is consistent with the predictions of a single channel model.

The concept of a limit to the capacity of a simple channel is generally inadequate in accounting for the upper bound on information processing in the human observer. For, when stimulus uncertainty is increased by increasing the dimensionality of the stimuli rather than the number of steps on the physical continuum, overall performance improves though performance on each individual dimension may be impaired (Garner, 1962). What the functional interrelations between the encoding of particular dimensions of a stimulus are remains an empirical question. We here distinguish four such possible interrelations: (1) Two dimensions may be "integral": information cannot be extracted on either dimension separately from the other (Garner & Felfoldy, 1970). While the dimensions are physically orthogonal, an error on one will be associated with chance performance on the other, and vice versa. (2) There is a second case in which processing on two dimensions would be mandatory, even though S's task is specified on only one of the two. This is if information extracted on one of the dimensions is necessary in order to extract information on the other, but the relation is not symmetrical ("serial dependence"). (3) Processing limitations for two dimensions may be defined by a common channel or a common analyzer. Where information on both dimensions is required simultaneously, performance on either one dimension would be maintained only at the cost of chance performance on the other, given appropriate stimulus conditions such that S is not able to operate on

the dimensions sequentially within a trial ("single channel processing"). (4) "Parallel processing": As a result of distinct channels or analyzers associated with each of the separate input dimensions, the S is able to extract information on both dimensions simultaneously and independently.

Allport (1971) investigated the relationships between the encoding of three types of visual information in the stimulus: two dimensions defined on form, and the third on color. A paradigm was used in which a pattern of densely scattered fragments from the test stimuli (static visual noise) closely followed the presentation of the test stimulus. The visual noise served as a mask so that the effective exposure duration could be controlled as the interstimulus interval (ISI). It was found that the number of items reported from the test stimulus was a monotonic increasing function of ISI. Further, for a given ISI, discrimination performance for each dimension alone, i.e., when the S was required to report on a single, preselected dimension (1-D report), was compared with performance when S had to report on two dimensions (2-D report). A significant decrement of 2-D over 1-D performance was observed only for reports combining both stimulus dimensions of form and not for combinations of color with the form dimensions. The interpretation given to these results was that form and color information may be handled simultaneously, whereas, within the form dimensions, parallel processing is at least restricted.

Egeth and Pachella (1969) have shown, using much longer exposure durations, that 1-D judgments of ellipsoidal stimulus eccentricities are adversely affected by uncorrelated variations in stimulus size. However, 1-D judgments of color are not affected by variation in the stimulus form dimensions. In each case, the control was to obtain 1-D judgments

with the irrelevant dimensions held constant. This finding might also be related to parallel encoding of form and color dimensions, since that type of encoding might possibly allow closure by S of either of the channels if it was known to be irrelevant. This would be untrue if the same channel mediated both classes of information. Thus, the distracting or interacting effect of irrelevant dimensional information might have been avoided in the case of color-form but not of form-form dimensional combinations.

The present experiment was designed to determine whether such interpretations are limited to cases with a dimension defined on color or whether simultaneous encoding might be found for stimulus dimensions within the general category of "form." Specifically, the hypothesis examined was that stimulus components that vary on separate dimensions of form may be encoded in parallel, while those that fall within the same dimension must be encoded serially. The stimuli used were defined with spatial line frequency and two distinct orientation components over the same retinal region.

METHOD

Apparatus

The stimuli were presented binocularly with a Scientific Prototype Model GB three-channel tachistoscope, at a viewing distance of 4 ft.

Materials

Three physically distinct variables were used, each at three levels: (1) orientation of a spatial line grating; (2) orientation of a break in the lines of the grating; (3) spatial frequency of the lines in the grating (for constant width black lines). The gratings were cut with a circular boundary from Letratone paper.

On the basis of pilot data, the physical values chosen for the stimuli were as follows: The grating lines were 0.01 in. wide and the orientations of the grating to the vertical were 0, 30, and 60 deg. The break, of width 0.07 in., ran through the center of the circle and took orientations of 90, 120, or 150 deg to the vertical. All angles were measured in clockwise fashion. The spatial frequencies were 4, 8, or 16 lines/in.

Two sets of stimuli were prepared, each with all combinations of levels of two of the variables (i.e., there were nine distinct compound stimuli in each set). The two sets were: (1) "same" dimension—orientation of grating (O), with orientation of break in the grating (B) for line frequency held constant at the middle value; (2) "different" dimensions—spatial frequency of grating (F) with grating

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Fig. 1. (a) Test stimuli examples.

orientation (O'), break not defined. The stimuli, of 1.45-in. diam, were set in the center of 5 x 7 in. matte white cards (see Fig. 1a).

The masking field consisted of irregular segments of gratings, of all three spatial frequencies, arranged at random orientations and positions (with overlap permitted). The segments varied in both the number of complete cycles and the width. The area of the card covered by the segments formed a square approximately 2.50 x 2.50 in. in the center of the card. Four such cards were made, of similar overall appearance, having an average ratio of black line to total white area of the square of about 0.25 (see Fig. 1b). A white adapting field was used with a small fixation cross. Luminance of the white area of the adapting, test, and masking fields was 18.0 fL.

Procedure

On each trial, S fixated the cross on

the adapting field and initiated the onset of the test field with a handheld microswitch. A trial comprised the following sequence of events: (1) test field of fixed (threshold) duration for a given S with one of the two stimulus sets; (2) masking field of 1 sec duration; (3) return of the adapting field.

In any block of trials, the S's task was to report the value of the stimulus on either one or both dimensions according to prior instructions from the E. S said his response aloud and then wrote it on a prepared sheet. After making his response, he was told the correct answer for the dimension(s). When instructed to report on two dimensions, it was emphasized that S should try to maximize the number of trials in which he was correct on both dimensions. S was informed of the number of such "double hits" at the end of each block of trials. For the two-dimensional conditions, the order of report was specified in advance and remained constant for any S.

Stimulus cards were presented in pseudorandom order with single repetitions permitted, each card being selected with roughly equal frequency in any block of trials. The masks were interchanged at random every two trials.

Design

Each of eight Ss took part in one practice and two experimental sessions of about 50 min on consecutive days. In the first session, the Ss were first familiarized with reporting on each dimension singly, then on two dimensions together. The rest of the session was used to determine, for each S, an approximate 70% correct threshold on 1-D report by reducing the exposure duration. The other dimension was then given for 1-D report to ensure that performance was approximately at the same level. The procedure was repeated for the other set of stimuli.

In the second session, after some warm-up trials, six blocks of 20 trials were run. The first block required S to report one of the two dimensions (1-D) and the second block was devoted to reporting on the other dimension. Two-dimensional reports (2-D) were collected in the third block, order of report being counterbalanced across Ss. The procedure was repeated for the second set of stimuli. In the third session, Ss were given the 2-D report condition, followed by the two 1-D report conditions for both of the sets of three blocks.

Subjects

Eight members of the Psychology

Fig. 1. (b) Masking stimulus example [half scale with respect to (a)].

Department at Reading University served as Ss. All had corrected vision and wore their glasses for the experiment.

RESULTS

Each item was scored correct or incorrect on each relevant dimension. Percent correct responses obtained for each of the dimensions under both 1-D and 2-D conditions of report are shown in Table 1.

The 70% correct thresholds for each of the two sets of stimuli were only approximate, and, as might be expected, there is a main effect of conditions of report [$F(7,49) = 8.15$, $p < .01$]. However, from a priori considerations, the important comparison is between the effects of 2-D vs 1-D report, respectively, in the two different combinations of dimensions. Summing each S's score over both dimensions under 2-D report and comparing this with the summed scores for the same two dimensions under 1-D report, the "different" dimensions' combination of orientation and spatial frequency (O'-F) yielded virtually identical results in both cases: mean 73.6% correct in the 1-D condition and 72.7% correct in the 2-D condition. On the other hand, in the "same" dimensions' combination of grating orientation with break orientation (O-B), the accuracy of report decreased sharply when both dimensions were to be abstracted together: mean 69.5% correct in the 1-D condition vs 55.2% correct in the

Table 1
Mean Percent Correct Responses Averaged Over Ss as a Function of Dimension Reported, for 1-D and 2-D Report (N = 8)

Condition of Report	"Same" Dimensions		"Different" Dimensions	
	O	B	O'	F
1-D	75.3	63.8	69.1	78.1
SD	8.2	7.2	9.6	14.2
2-D	62.5	47.8	66.0	79.4
SD	8.7	11.4	12.1	13.8

Table 2
Observed vs Predicted 2-D Report Scores
Combined Over Both Dimensions as Percent
Correct as a Function of "Same" vs
"Different" Stimulus Sets

S	"Same" Dimensions O with B		"Different" Dimensions O' with F	
	Predicted	Observed	Predicted	Observed
1	50.75	48.75	62.00	82.50
2	55.75	55.00	52.00	62.50
3	59.50	57.50	52.00	80.00
4	52.00	50.00	58.25	77.50
5	54.50	60.00	55.75	83.75
6	55.75	60.00	55.75	66.25
7	58.25	63.75	63.25	75.00
8	47.00	46.25	58.25	53.75

2-D condition ($t = 13.28$, $p < .005$, one-tailed). All eight Ss gave results in the same direction ($p < .005$, one-tailed sign test). The difference in the effects of 2-D over 1-D report between the two combinations of dimensions is, of course, also significant ($t = 3.38$, $p < .01$). Under 2-D report, chi-square tests did not reject the hypothesis of independence of correct and error responses in the two 2 by 2 data matrices based on the summed response frequencies of all eight Ss, either for the "same" ($\chi^2 = 0.08$, $df = 1$, $p > .75$) or for the "different" ($\chi^2 = 2.21$, $df = 1$, $p > .13$) dimension combinations. In the latter combination, the data of one S (No. 2) exhibited an excessively large number of double correct and double error responses; exclusion of his data gave, for the "different" combination, an overall $\chi^2 = 0.40$ ($df = 1$, $p > .50$) and no change for the "same" combination of dimensions.

It is of interest to compare the obtained results with predicted values for an optimum "single-channel" model. To predict performance for 2-D report, it is assumed that S selectively processes that dimension which gives greater probability of correct performance, as estimated by the number correct under 1-D report. The predicted values expressed as percent correct are shown in Table 2 for each S, along with the obtained percent correct (averaged over both dimensions).

Clearly, in the O'-F condition, the obtained results exceed the maximum possible for optimum performance under the model in all but one S (No. 8) ($p < .01$, one-tailed Wilcoxon test). By contrast, in the O-B condition, predictions from the model approximate the observed data much more closely. Differences between the observed and predicted values in this condition were not significant.

DISCUSSION

In the introduction, four

contrasting types of possible functional interrelation between dimensions of a stimulus were put forward. As Garner and Morton's (1969) analysis indicates, the obtained result of independence in the overall correct-error frequencies in the 2 by 2 matrices rules out the form of process dependence between two input dimensions, which they call error correlation, i.e., integrality, between either pair of dimensions. In addition, the fact that Ss were able to perform at about 70% correct for each dimension under 1-D report allows us to reject the possibility that, when reporting, say, Dimension A, there was serial dependence of encoding Dimension A on irrelevant Dimension B, or vice versa. While the present analysis does not rule out the possibility of joint response bias, the lack of correlation and, in the O'-F condition, complete performance parity strongly supports the hypothesis of parallel encoding.

On the other hand, in the combination of two orientations, O-B, the decrement in performance from 1-D to 2-D report coupled with the absence of dependence in the 2 by 2 correct-error matrix is consistent with an optimum single-channel model for selective encoding of dimensional information of multidimensional stimuli. In this connection, it is interesting to note that several Ss occasionally reported an impression of apparent movement with regard to the stimuli defined on two orientations. As they described it, one apparent orientation began to emerge, only to "flip" part way through the exposure to a different one, an experience they found curiously frustrating.

To the extent that the O' and F components of the stimulus were separable and could be simultaneously encoded, the Es' decision to choose O' and F as "different" dimensions was justified. Suppose, for a given stimulus location in physical space, there is a finite set of analyzers in the organism available for encoding information on the various stimulus dimensions and that the extraction of information from any given dimension requires at least one analyzer. Then it is reasonable to expect simultaneous encoding of different aspects of the stimulus only if the information necessary for correct report can be encoded through separate analyzers (i.e., if the dimensions are "different"). When the E selects two aspects of a stimulus which have to be encoded via an identical analyzer (i.e., if the dimensions are "same"), serial encoding might be expected. From this theoretical viewpoint, a prediction of performance approaching parity with 1-D report follows for the 2-D

combination of frequency and orientation of break (F-B). If the basis for parity loss in the 2-D combination of two orientations is a commonality of analyzers for encoding information from O and B (in contrast to performance parity resulting from no commonality of analyzers for O' and F), the greatest commonality for F and B will be less than for O and B. Thus, the lower bound for 2-D performance for F-B should be above 2-D performance for the O-B condition. This experiment has not yet been run.

Shiffrin and Gardner (1972) concluded, from a visual letter discrimination task in which performance on simultaneous vs sequential presentation was not significantly different, that encoding of several spatially distinct stimuli is conducted simultaneously. However, such a conclusion does not necessarily imply that simultaneous encoding of two stimulus components differing in value on the same primary dimension (e.g., orientation) should be possible if the two components fall on different retinal regions. It may be sufficient to postulate that, in Shiffrin and Gardner's study, letters are discriminated on the basis of any one of several alternative dimensions (Allport, 1971), each of which is utilized at a different spatial position containing an item to be discriminated. However, it is certainly an interesting question to ask whether the processing limitation found in the present study for distinct components within the same primary dimension falling on the same retinal region would also be found if these same components were spatially separated.

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