Parallel processing in complex visual discrimination¹

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In a "same-different" reaction time (RT) task pairs of stimuli varying along one or more dimensions are presented and S is required to indicate, as rapidly as possible, whether the stimuli are physically identical or different. This task was employed in three experiments investigating the processes by which multidimensional stimuli are discriminated. The results indicated that stimulus dimensions are compared in parallel; that the time required to interrogate a dimension varies randomly across trials and is dependent upon the time required to interrogate other dimensions present in test stimuli, and that comparisons terminate upon the detection of information sufficient for a correct response.

This report describes three experiments designed to investigate the processes involved in complex visual discrimination. Ss were presented with pairs of geometric figures varying along one or more independent binary dimensions and were required to indicate, as rapidly as possible, whether the figures were physically the "same" or "different." The major dependent measure was "same-different" RT.

The experiments focus on a number of theoretical issues that have been raised by Egeth (1966) regarding the discrimination of multidimensional stimuli. These issues concern: (a) whether comparisons are made between overall

(unitary) stimulus representations, or between representations of the individual dimensions constituting each stimulus (analytic); (b) assuming the latter, whether comparisons are conducted simultaneously (in parallel) or serially; (c) whether comparisons terminate upon the detection of information sufficient for a correct response (self-terminating comparisons), or only after all relevant dimensions have been interrogated (exhaustive comparisons); (d) whether the time required to compare stimuli along a given dimension remains constant across trials (constant decision time), or fluctuates as a random variable (distributed decision times); and (e) assuming serial processing, whether the order in which dimensions are interrogated remains fixed (fixed order), or varies randomly (random order), across trials. Several models of the discrimination process can be distinguished based on different sets of the assumptions underlying these issues.

Table 1 summarizes the behavioral implications of these models for the "same-different" RT task. Predictions were made in reference to stimuli varying along one, two, or all three of the hypothetical two-valued dimensions, X, Y, and Z. The values selected for the three dimensions are such that $\overline{RT}_x < \overline{RT}_y < \overline{RT}_z$. By combining these dimensions in all permissible ways at each of the three levels of dimensionality, seven sets of stimulus pairs can be constructed: X, Y, Z; XY,

Table 1

Summary of Several Models of Multidimensional Stimulus Comparison and of their Behavioral Implications in the "Same-Different" RT task

			“SAME” RT ^{1,2}	“DIFFERENT” RT ^{1,3}			
			Relation between RT _z and RT _{xyz}	As a function of the number of dimensions of difference	Relation between RT _x and RT _{xyz} when all dimensions differ	Relation between RT _{x(yz)} and RT _{xyz}	
Assumptions							
Analytic Models	Parallel	Distributed times	$\overline{RT}_z < \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} > \overline{RT}_{xyz}$	$\overline{RT}_x > \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} > \overline{RT}_{xyz}$	
		Constant times	$\overline{RT}_z = \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} > \overline{RT}_{xyz}$	$\overline{RT}_x = \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} = \overline{RT}_{xyz}$	
	Exhaustive	Distributed times	$\overline{RT}_z < \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} = \overline{RT}_{xyz}$	$\overline{RT}_x < \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} = \overline{RT}_{xyz}$	
		Constant times	$\overline{RT}_z = \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} = \overline{RT}_{xyz}$	$\overline{RT}_x < \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} = \overline{RT}_{xyz}$	
	Serial	Self-terminating	Random order	$\overline{RT}_z < \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} > \overline{RT}_{xyz}$	$\overline{RT}_x < \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} > \overline{RT}_{xyz}$
		Fixed order	$\overline{RT}_z < \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} > \overline{RT}_{xyz}$	$\overline{RT}_x = \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} = \overline{RT}_{xyz}$	
Exhaustive		Random order	$\overline{RT}_z < \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} = \overline{RT}_{xyz}$	$\overline{RT}_x < \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} = \overline{RT}_{xyz}$	
	Fixed order	$\overline{RT}_z < \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} = \overline{RT}_{xyz}$	$\overline{RT}_x < \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} = \overline{RT}_{xyz}$		
Unitary Models (Template Matching)			$\overline{RT}_z = \overline{RT}_{xyz}$	$\frac{\overline{RT}_{x(yz)} + \overline{RT}_{y(xz)} + \overline{RT}_{z(xy)}}{3} = \overline{RT}_{xyz}$	$\overline{RT}_x < \overline{RT}_{xyz}$	$\overline{RT}_{x(yz)} = \overline{RT}_{xyz}$	

¹ Where $\overline{RT}_x < \overline{RT}_y < \overline{RT}_z$

² $\overline{RT}_{xyz}$ denotes $\overline{RT}$ for tridimensional stimuli identical along all dimensions

³ $\overline{RT}_{xyz}$ denotes $\overline{RT}$ for tridimensional stimuli differing along all dimensions

XZ, YZ; and XYZ. At the bidimensional level, stimulus pairs requiring the "different" response may differ along either or both dimensions. Similarly, "different" pairs at the tridimensional level may differ along any one, two, or all three dimensions. For instance, the $\overline{RT}$ for tridimensional stimuli differing only along X is denoted in the table by $\overline{RT}_{x(yz)}$. For a more detailed treatment of the models, the reader is referred to the Egeth paper.

In a study designed to assess the models, Egeth presented Ss with geometric figures varying along three binary dimensions. Stimulus complexity was varied instructionally: either one, two, or all three dimensions were designated as relevant prior to each trial block. Unexpectedly, Ss appeared unable to ignore irrelevant stimulus information present under uni- and bidimensional conditions. Because of this confounding, no attempt was made to evaluate the proposed models on the basis of the "same" response data. The results of comparisons made within the "different" response data (see Table 1), however, were interpreted as supporting only those models involving the assumptions that comparisons are enacted serially, are self-terminating, and are randomly ordered across trials.

The present experiments provide answers to two questions emerging from the Egeth study. The first concerns the effect of stimulus complexity on "same" RT. Egeth's results make it clear that an adequate description of this relationship can be obtained only when the confounding effects of irrelevant stimulus information have been adequately controlled. Consequently, "same" RT was investigated in the first two experiments with stimulus materials constructed so that irrelevant stimulus variability was absent across all levels of complexity. Under these conditions, "same" RT was found to increase little or not at all with increases in stimulus complexity (Experiment 2). The second question relates to Egeth's conclusion that the "different" response data, and specifically the finding that $\overline{RT}_x < \overline{RT}_{xyz}$, are consistent only with serial processing models. This interpretation rests on the implicit assumption that the time required to interrogate a given dimension is independent of the time required to interrogate other dimensions present in test stimuli. Fine grain analyses of the "different" response data of Experiments 1 and 3 indicated that this assumption is unwarranted. It was possible on this basis to interpret Egeth's results without recourse to the serial processing assumption.

While these experiments were concerned principally with the theoretical issues raised by Egeth, they also provide information relative to findings recently described by Nickerson (1967). Stimuli in the Nickerson study were geometric figures varying independently along three trinary dimensions. He found that "same" $\overline{RT}$ when stimuli were identical along all three dimensions is significantly faster than "different" $\overline{RT}$ when stimuli differed along a single dimension. This result was unpredicted because logically S should examine all three dimensions before deciding that stimuli are "same," but only two [i.e., $(N+1)/2$] dimensions on the average before deciding that stimuli are "different" when they differ only along a single dimension. Three alternative interpretations were considered: (1) A response bias may exist favoring the "same" response, corresponding perhaps to the verbal bias that induces the word combination "same-different" to seem more compatible than "different-same." (2) The processes underlying the "same" response for the particular dimensions used by Nickerson may require less time than those underlying the "different" response (Bindra, Dondori, & Nishisato, 1967). (3) "Same" RT may be faster for multidimensional stimuli because comparisons underlying the "same" response may not be exhaustive. Nickerson's data provided no evidence pertaining to the first two alternatives, and of the third he concluded that the false-"same" error rates obtained for

stimuli differing along a single dimension seemed too low to warrant such an interpretation. The present studies employ a modification of Donder's type-c reaction measure in which responses are made only on trials where a prespecified state ("same" or "different") obtains between test stimuli. This measure should eliminate the effects of response bias since the "same" and "different" response systems are not placed in direct competition, i.e., they do not vie for temporal priority. Thus, if the asymmetry of "same" and "different" RTs reported by Nickerson were replicated in these studies, it would not appear to be due to response bias. If asymmetry were obtained at all levels of dimensionality, this result would suggest that the "different" response requires more time than does the "same" response. (4) If asymmetry were obtained at multidimensional levels, but not at the unidimensional level, this result would imply that comparisons are carried out nonexhaustively under multidimensional conditions. The latter interpretation was found to be most appropriate under the conditions of the present experiments.

EXPERIMENT 1

This experiment investigated the effects of stimulus dimensionality on "same-different" RT. The method differed from Egeth's in two major respects. First, stimulus complexity was varied across levels of dimensionality by altering the number of physical attributes contained in test stimuli, rather than by instructing Ss to ignore one or more dimensions under some conditions. Second, the dependent measure was based on the type-c reaction rather than on the type-b reaction where both "same" and "different" responses are made within a single trial block.

Subjects

Four undergraduate women with normal uncorrected vision participated in the main experiment. Eight additional women with normal uncorrected or fully corrected vision served under three control conditions. All Ss were paid \$1.50 per hour for their services.

Incentive System

To encourage Ss to respond both quickly and accurately, a \$5.00 bonus was awarded to the S exhibiting the lowest average "error-corrected" $\overline{RT}$ across all conditions of the main experiment. The error correction consisted of adding 5 msec to the $\overline{RT}$ under each condition for every incorrect response. An equivalent system was used under the control conditions.

Apparatus

Stimuli were viewed through a Polymetric two-field mirror tachistoscope. On a desk situated directly before S was a set of response keys, one of which was used by all Ss throughout the experiment. Response latency was indicated by a Hunter Klockounter which is accurate to the nearest millisecond. During testing S wore earphones over which a low amplitude masking noise was channeled.

Stimuli

Stimulus figures were constructed of colored cardboard and mounted on white index cards. The horizontally arrayed stimulus pair appearing on each trial subtended a visual angle of 11 deg on the horizontal and 4 deg on the vertical plane.

Three 24-card decks were used under the unidimensional condition. The *color* (C) deck consisted of pairs of 16-mm square figures, either blue or green in hue. The two hues were equal in saturation and brightness. The *form* (F) deck consisted of pairs of neutral gray trapezoids, approximately equal in brightness to the hues used in C, that were 16 mm (height) x 15 mm (short base) x 17 mm (long base). The long base was either up or down. The *size* (S) deck consisted of

pairs of neutral gray 16 mm squares each containing an inked circle (No. 3 Rapidograph) either 7 or 9 mm in diam. Stimulus pairs were identical on half of the cards in each of these decks.

Three 24-card decks were also used under the bidimensional condition. Each deck contained 12 cards on which stimuli differed: on four of these differences appeared along one dimension, on four, differences appeared along the other, and on the remaining four, both dimensions differed. The three decks were *form-color* (FC), *form-size* (FS), and *size-color* (SC). Stimuli used in each of these decks contained the appropriate combination of features described for the unidimensional condition.

A single deck of 84 cards was used under the tridimensional condition (CFS). Prior to each administration, the entire deck was shuffled and only the first 72 cards from the deck were used. Forty-two of the cards contained stimuli identical along all three dimensions. The "different" cards consisted of seven equal-sized sets. In terms of the dimension(s) along which they differed, these were C, F, S, CS, CF, SF, and CFS.

Procedure

All Ss in the main experiment participated for 1 h on each of seven consecutive days. On the first day, they were instructed as to procedure and the incentive system and then given training trials on all conditions. Beginning on Day 2, Ss were given 25 warm-up trials using letters ("A" and "B") as stimuli, and were then tested on all seven stimulus decks. Two Ss were run on Days 2, 3, and 4 under the instruction to respond *only* when stimulus pairs were "same." During the last three days, these Ss were instructed to respond only when stimuli were "different." The order of response conditions was reversed for the other two Ss.

Each S received a different presentation sequence of the seven stimulus decks on each day under each response condition. In each sequence, the three uni- and the three bidimensional decks followed one another in a block, and the order of the uni-, bi-, and tridimensional conditions formed a Latin-square over the three days of practice within each response condition. Within the uni- and bidimensional conditions the order of decks formed a Latin-square over the three days within each response condition.

Five-min rest intervals were provided between each condition and 2-min rests were given between each deck within the uni- and bidimensional conditions, and every 24 trials during the tridimensional condition.

Within decks, the intertrial interval was 6 sec. Prior to the onset of a stimulus pair, the masking noise channeled over S's earphones was interrupted and replaced by a high frequency warning tone of 1 sec duration. Onset of stimulus pairs coincided with the offset of this tone.

On trials where S made no response, E manually terminated the trial at approximately 1.5 sec, automatically initiating the next trial cycle.

Control Conditions

Three control conditions were run following the main experiment. These controls were used to assess whether the time required to discriminate the state of a given dimension was influenced by variations in the character of the other attributes present in test stimuli.

Four Ss were tested on two 24-card stimulus decks under *Control S(C)*. Stimuli contained in the first of these decks, S, were identical to those of Deck S of the main experiment. Stimuli in the second deck, S(C), were identical to those of S except that they were constructed of the blue cardboard used in some of the decks in the main experiment. Ss were instructed to respond only when stimuli were "same."

Two additional Ss were tested on two 24-card stimulus decks under *Control S(F)*. The two decks, S and S(F), were based on Decks S and SF in the main experiment. In both decks, Ss were instructed to respond only when stimuli were identical along the S dimension.

Two more Ss were tested on two 24 card decks under *Control C(F;S)*. Stimuli in Deck C(S) were identical to those used in Deck CS, and those in Deck C(F) were identical to those used in Deck CF in the main experiment. Ss' task was to respond "different" whenever stimuli differed along C and to ignore S or F, which varied independently of C. Following 25 warm-up trials with letter stimuli, half of the Ss were run in ABBA order and half in BAAB order under all control conditions.

RESULTS AND DISCUSSION

The results for both "same" and "different" response conditions are summarized in Table 2. The dependent measure was arithmetic RT. Excluded from analysis were individual RTs greater than four standard deviations above the mean of a given S's distribution of times for each stimulus deck.

"Same" Reaction Time

An analysis of variance for the "same" response data was performed using a one-factor repeated measurements design. The results of this analysis indicated that the seven stimulus decks differed significantly, $F(6,16) = 18.23$; $p < .001$. Of principle interest in these data was the relationship between stimulus complexity and "same" RT. This relationship can best be expressed with comparisons between each multidimensional deck and the unidimensional deck containing the slowest of the dimensions comprising that multidimensional deck. The present data permitted four such comparisons:

Table 2
Mean RT and Per Cent Errors (in parentheses) Under "Same" and "Different" Response Conditions in Experiment 1

	Unidimensional decks			Bidimensional decks			Tridimensional deck
	C	F	S	CF	CS	FS	CSF
"SAME" RT	357 (.059)	455 (.020)	517 (.065)	421 (.071)	468 (.065)	505 (.020)	481 (.058)
"DIFFERENT" RT	361 (.049)	496 (.097)	474 (.083)	C(F):383 F(C):507 CF:376 (.063)	C(S):427 S(C):532 SC:393 (.076)	F(S):531 S(F):564 FS:461 (.083)	C(FS):404 F(CS):511 S(CF):657 CF(S):394 CS(F):387 FS(C):510 CFS:386 (.059)

S-SF, S-SC, S-SFC, and F-FC. Differences within each of these pairs of decks were analyzed by means of Fisher's Least Significant Difference (LSD) test. Differences obtaining for pairs S-SC, S-SFC, and F-FC were statistically reliable, $LSD = 33.0$; $p < .05$.

The finding that $\overline{RT}$ declined with increases in stimulus complexity was not predicted by any of the models outlined in the introduction. All of these models imply that "same" $\overline{RT}$ should either remain constant or increase with stimulus complexity. Two possible interpretations of this outcome were considered. First, since the set of attributes defining the stimulus context in which dimensions were interrogated was not constant across stimulus decks, it is feasible that the discriminability of the values of the dimensions increased with stimulus complexity. Second, comparisons may not have been carried out exhaustively under the multidimensional conditions. The first interpretation was tested with data obtained under Controls *S(C)* and *S(F)*. If the values of the size dimension were more discriminable at the multidimensional levels of the main experiment, it follows that "same" $\overline{RT}$ to size should decrease between Control Decks S and *S(C)* and between S and *S(F)*. The results of neither control were consistent with this interpretation. In fact, $\overline{RT}$ increased somewhat, though not significantly, both between S and *S(C)* and between S and *S(F)*. The nonexhaustive comparisons interpretation implies that false-"same" error rates for stimulus pairs differing along a single dimension should increase with stimulus complexity. That is, if some dimensions are not examined, or are examined only incompletely in the multidimensional decks, then errors for stimuli differing only along these dimensions should increase between the uni- and multidimensional conditions. Figure 1 shows the false-"same" error rates across levels of stimulus complexity for each dimension when it alone differentiated test stimuli. To interpret this figure, consider the function labeled "size." At the unidimensional level the value on this function indicates the percentage of trials containing stimuli differing in size

where Ss incorrectly responded "same." The values at the bi- and tridimensional levels represent the percentage of those trials containing stimuli differing *only* in size where Ss incorrectly responded "same." The systematic increases in error rates for S and F suggest the Ss increasingly tended to either neglect the less discriminable dimensions, or to process these incompletely, as stimulus complexity increased. It is possible for Ss to operate in this manner under the conditions of the present experiment (as in Egeth, 1966; Nickerson, 1967), and at the same time to maintain stable *overall* error rates across conditions (see Table 2), because the states of dimensions under the multidimensional conditions were correlated. These correlations, or contingent probabilities, resulted from the constraint that stimuli requiring the "same" and "different" responses appear with equal frequency within each deck. In Deck CS, for example, when stimuli are "same" along C, the probability that they are also "same" along S is .750. If stimuli are "same" along both C and F in Deck CFS, they will be "same" along S with a probability of .875. In either case, S, the most difficult dimension, can be at least partially ignored with little or no resultant increase in overall error rate.

These results imply that an adequate statement of the relationship between stimulus complexity and "same" $\overline{RT}$ must be obtained under conditions in which the effects of the contingent probabilities described above have been controlled. Experiment 2, described later in this report, was designed for this purpose.

A Comparison of "Same" and "Different" Reaction Time

Table 1 (bottom) gives arithmetic $\overline{RT}$ s for each of the seven stimulus decks under the "different" response condition. For the multidimensional decks separate means were calculated for each of the possible sets of stimulus cards requiring the "different" response in each deck. For instance, F(SC) in the tridimensional deck denotes the set differing only in form.

Under the conditions of the present experiment no difference was obtained between pooled "same" (443 msec) and "different" (444 msec) $\overline{RT}$ s at the unidimensional level. However, in agreement with the findings of Egeth and of Nickerson, "same" $\overline{RT}$ at the tridimensional level was significantly below that for "different" $\overline{RT}$ for tridimensional stimuli differing only along S, *t*, paired observations, (3) = 11.79, $p < .001$. The equality of pooled times at the unidimensional level suggests that a response bias favoring the "same" response was not a factor in these data. Supporting this view, a comparison of false-response rates for the "same" and "different" response conditions at the unidimensional level suggested, if anything, the possibility of a bias favoring the "different" response, i.e., false-"different" error rate was slightly higher than false-"same" error rate.

The results also indicate that for the dimensions used in this experiment there is little difference on the average between the "same" and the "different" decision processes with respect to the time required by each. The most plausible view of the difference at the tridimensional level was suggested earlier, viz., not all dimensions are completely interrogated under the "same" response condition. An additional factor, the counterpart of this, was evidenced by the fact that stimuli differing only along S in Decks CS, FS, and CFS, evoked a disproportionately large percentage of slow (> 900 msec) $\overline{RT}$ s, as though Ss had initially decided that these stimuli were "same," but following a reinspection, had amended this decision. Some support for this view appeared in subjective reports elicited from Ss following the experiment.

"Different" Reaction Time

"Different" $\overline{RT}$ as a function of the number of differing dimensions. Within the tridimensional deck the pooled $\overline{RT}$ s for

Fig. 1. Per cent false-"same" errors across levels of dimensionality on trials where each dimension provided the only source differentiating between test stimuli.

stimuli differing along one, two, and all three dimensions were 524, 430, and 386 msec, respectively. This result, also obtained by Egeth, implies that comparisons are self-terminating, or at least that they are not carried out exhaustively.

Two sets of "different" RTs were extracted from the bidimensional decks for each S. One set consisted of RTs from trials on which stimuli differed along both dimensions, and the other, from trials on which stimuli differed only along the most discriminable (fastest) single dimension present in each deck. $\overline{RT}$ was significantly faster when stimuli differed along both dimensions, t , paired observations, $(3) = 4.18$, $p < .05$. This finding is consistent only with serial/self-terminating models assuming random testing order and with parallel/self-terminating models assuming distributed decision times. The serial models predict this relationship based on the assumption that the order of comparisons is random. Thus, on some trials, S will initially interrogate not the dimension with the fastest average time, but the other, slower, dimension. On such trials two comparisons are made before a difference will be detected. However, when both dimensions differ, a difference will always be detected on the initial comparison. The parallel models predict the obtained relationship on the basis of the assumption that decision times are distributed as a random variable. Following Rapoport (1959), it can be shown that when the distributions of decision times for the separate dimensions overlap, the time required to detect a difference along the dimension with the fastest decision time on a given trial decreases with the number of dimensions that are different.

Stimulus context as a determinant of "different" RT. Two further comparisons offered a possible basis for distinguishing between these two models. First, the serial models imply that "different" $\overline{RT}$ for the most discriminable unidimensional deck, C, should be faster than in the tridimensional deck for stimuli differing along all three dimensions. This prediction follows the assumption that comparison order is random which implies that, while the first dimension interrogated in the tridimensional deck will always yield a difference, this dimension will not always be the fastest one. Therefore, the set of times for these stimuli should be longer, on the average, than for those within C. The parallel models imply the opposite relationship based on the assumption of distributed decision times (Rapoport, 1959). Consistent with the serial models, $\overline{RT}$ increased between C and CFS, t , paired observations, $(3) = 4.03$, $p < .05$. Second, within the bidimensional decks the serial models imply that $\overline{RT}$ for a given dimension, when critical (i.e., provides the only difference between stimuli), should vary as a function of the "difficulty"

of the other dimension contained within the deck. The "difficulty" of a dimension was defined in terms of the overall $\overline{RT}$ associated with that dimension across the conditions of this experiment. The above prediction follows the assumption that the order of comparisons is random. The effect on $\overline{RT}$ produced by the noncritical paired dimension presumably derives from trials on which this dimension is examined prior to the critical one. Since interrogation times for noncritical and critical dimensions add together on these trials, increases in the former should produce increases in RT for the critical dimension. The parallel models predict that differences in the difficulty of the noncritical dimension will have no effect on response time. A two-factor repeated measurements design was used to assess the effects of the difficulty of the noncritical dimension. Critical dimension (C, F, S) and difficulty of noncritical dimension (High, Low) were the two factors. As predicted by the serial models, $\overline{RT}$ increased with the difficulty of the noncritical dimension, $F(1,3) = 10.21$, $p < .05$.

The above results support only the serial/self-terminating/random comparisons models. However, two further sets of comparisons suggest that even these models are inadequate. First, the serial models imply that $\overline{RT}$ for any critical dimension should increase between the bi- and tridimensional conditions because as the number of stimulus dimensions increases, the likelihood that any one dimension will, by chance, be interrogated first should decrease. In several instances, however [$F(C) - F(SC)$; $C(S) - C(FS)$; $F(S) - F(SC)$], the prediction did not hold. In fact, small decreases occurred within the last two comparisons. Second, according to the serial models, the difference in $\overline{RT}$ to C, when critical, between Decks CF and CS is produced on trials where the noncritical dimension, F or S, is interrogated first. Further, on those trials where C is examined first, no latency differences should occur between C(S) and C(F), and these trials should provide the bulk of the times constituting the lower portions of the C(F) and C(S) RT distributions. The two distributions, therefore, should be distinguished by the densities of times comprising their upper portions, these times reflecting trials on which the noncritical dimension was examined before C. The same argument holds for F, when critical, between Decks CF and FS. The general form of the relationship between the cumulative distributions of times for C(F) and C(S) and for F(C) and F(S), as predicted on the basis of the serial models, is given in Fig. 2a. The observed distributions are given in Figs. 2b and 2c. Contrary to the prediction, much of the difference between the members of each pair of distributions can be described as a constant displacement along the

Fig. 2. Expected relationship between distributions for hypothetical dimension, X, in decks X(Y) and X(Z), where $\overline{RT}_Y < \overline{RT}_Z$, based on the assumptions that dimensions are tested serially and in random order across trials (Fig. 2a), together with obtained distributions for color (Fig. 2b) and for form (Fig. 2c) at the bidimensional level.

horizontal axis equal to the difference between the means of the distributions.

In their present form, none of the models described by Egeth finds consistent support in the "different" RT data presented in this section. These data tentatively suggest that the time required to determine the state of a given dimension was dependent on the time required to determine the state of other dimensions present in test stimuli. The data suggest further that this dependency did not result from the sequencing of comparisons along the individual dimensions.

Experiment 3 was specifically designed to test the notion that comparison times for a dimension are dependent upon the context in which the comparison must be made.

EXPERIMENT 2

This experiment served as a further study of the relationship between "same" RT and stimulus complexity. Stimulus decks were constructed to eliminate the contingent probabilities apparent in the stimulus decks of Experiment 1. One-fourth of the cards under unidimensional conditions contained stimuli that were "same." This was also true of bidimensional conditions: one-fourth of the cards were identical along both dimensions, one-fourth differed along both dimensions, one-fourth differed along one, and one-fourth differed along the other. Thus, within the bidimensional decks, one dimension, Y, was "same" on only half of the cards containing stimuli that were also "same" along the other dimension, X. Accordingly, the state of Y was unpredictable based on knowledge of the state of X.

In order to equate dimensions in discriminability across levels of dimensionality, stimuli used in the unidimensional decks, X and Y, contained the features defining the irrelevant dimension (Y or X, respectively), but these features did not vary in value either between the stimulus figures appearing on a given trial, or across trials within a given day of practice.

Four Ss were tested on stimuli varying along one or both of the Dimensions S and F. As a partial replication, four additional Ss were similarly tested with the Dimensions S and C.

As characterized by Egeth (1966), the parallel/distributed/self-terminating and the serial/self-terminating/random models both imply that "same" $\overline{RT}$ should increase as a function of stimulus complexity. More precisely, both models predict that RT to XY should be longer than to the slowest of the unidimensional conditions, Y. To sharpen the differences between these two models, a formal method was generated for estimating limits to the increase in "same" RT between Y and XY implied by each model. The limit derived for the serial model is a lower bound, while that derived for the parallel model is an upper bound. The procedures used to generate these bounds and the assumptions underlying them are provided in the Appendix.

METHOD

Subjects

Nine undergraduates, seven women and two men, with normal or normal-corrected vision were employed at \$1.50 per hour. The incentive system was comparable to that used in Experiment 1. The data of one S were not used because of procedural irregularities.

Stimuli

Stimulus decks used in Part 1 of this experiment contained the Dimensions S and F as in Deck SF in Experiment 1. The bidimensional deck, SF, contained 32 cards. On eight of these, stimuli were identical along both dimensions. The remaining 24 cards consisted of three equal-sized sets: stimuli in one differed along S, in the second, along F, and in the third, along both S and F. Four decks, each containing 32 cards, were used

under the unidimensional condition in Part 1. Two of the decks contained stimuli varying along S. These two decks differed only with respect to the value of F, the irrelevant dimension, which remained constant within and across the cards of a given deck. Eight of the 32 cards in each deck were identical along S. The remaining two decks contained stimuli varying along F. These differed with respect to the value of the irrelevant dimension, S. Eight of the cards in each deck were identical along F.

Stimulus decks used in Part 2 contained the Dimensions S and C, as these appeared in Deck SC of Experiment 1. These decks were constructed as above.

An additional deck, denoted A, was used as part of the serial lower-bound estimating procedure (see Appendix). Each card contained a pair of inked circles, 15 mm in diam. A circle was either filled (black) or unfilled (white). As before, eight of the 32 cards contained stimuli that were identical.

Procedure

Each S participated during two 1½-h sessions held on consecutive days. Thirty-two practice trials with letter stimuli ("A," "B") were given at the beginning of each session. In addition, a familiarization period was provided prior to the presentation of each of the stimulus decks on both days. During this period the entire deck was presented "out of hand" to S who was instructed to indicate orally whether each stimulus pair was "same" or "different." Sixty-four trials were run on each deck on each day. Presentation order was reversed within Ss across sessions, and counterbalanced across Ss within sessions.

Four Ss were tested in each part of the experiment. Under all conditions Ss were instructed to respond only when stimulus pairs were "same." Unless indicated above, the procedure was identical to that in Experiment 1.

RESULTS AND DISCUSSION

Table 3 gives arithmetic "same" $\overline{RT}$ and false-"same" error rate broken down by Ss and stimulus decks for both parts of the experiment. The two error values associated with RTs for the bidimensional decks denote the relative frequencies of incorrect responses when stimuli differed only along the indicated dimension. The two columns to the right contain the upper-bound parallel and the lower-bound serial estimates of $\overline{RT}$ for the bidimensional deck for each S.

False-"same" error rates for stimuli differing along S, the most difficult dimension, exhibited little or no measurable increase between Decks S and SF (Part 1) or between S and SC (Part 2). This finding verifies that the nonexhaustive comparisons strategy used by Ss in Experiment 1 did not apply in the present results.

The increases in $\overline{RT}$ between Decks S and SF and between Decks S and SC obtained for all Ss fall below both serial and parallel bound estimates. The conclusion that Ss can interrogate at least two dimensions in parallel when comparing identical stimuli seems unavoidable on the basis of these results. While both bound estimates are grounded on several untested assumptions, the fact that virtually no increases in $\overline{RT}$ occurred between S and SC in Part 2 of the present experiment could be made compatible with serial processing models only by means of the highly implausible supposition that the interrogation of color requires *no* processing time.

EXPERIMENT 3

This experiment provided a further test of the hypothesis suggested by the "different" RT data of Experiment 1 that decision times for the separate dimensions appearing within a stimulus deck are correlated. One-half of the stimulus cards in each of three decks contained unidimensional stimulus pairs varying in color (C). The remaining cards in each deck

Table 3
"Same" RT for the Four Stimulus Conditions During Both Parts of Experiment 2, Together with Predictions of Bidimensional $\overline{RT}$ Based on the Serial and Parallel/Distributed Models. Values in Parentheses Represent Error Percentages. A is a Baseline Condition used to Generate the Serial Estimate

Part 1: Form-Size											
A			F		S		SF			Lower Serial Bound	Upper Parallel Bound
SNo.	RT	% Err	RT	% Err	RT	% Err	RT	% Err			
								S	F		
1	362	(.021)	516	(.021)	592	(.031)	606	(.031)	(.000)	762	623
2	374	(.000)	507	(.010)	532	(.010)	542	(.015)	(.015)	655	546
3	363	(.010)	490	(.031)	488	(.042)	516	(.062)	(.015)	614	520
4	304	(.052)	347	(.052)	400	(.073)	402	(.078)	(.000)	443	409
$\bar{x}$	351	(.021)	465	(.028)	503	(.039)	503	(.047)	(.008)	619	525

Part 2: Color-Size											
A			C		S		SC			Lower Serial Bound	Upper Parallel Bound
SNo.	RT	% Err	RT	% Err	RT	% Err	RT	% Err			
								S	F		
1	329	(.010)	360	(.010)	467	(.031)	464	(.031)	(.000)	498	475
2	363	(.042)	381	(.031)	515	(.083)	514	(.047)	(.015)	533	519
3	431	(.000)	444	(.000)	562	(.031)	567	(.031)	(.000)	574	575
4	365	(.010)	373	(.000)	479	(.010)	478	(.031)	(.000)	487	483
$\bar{x}$	372	(.013)	390	(.010)	506	(.044)	506	(.035)	(.004)	523	513

constituted a set containing unidimensional pairs varying in either orientation (O) or size (S). The values chosen for the last two dimensions were such that $\overline{RT}_O < \overline{RT}_S$. By varying the relative frequencies of cards containing O or S, it was possible to systematically manipulate the overall $\overline{RT}$ associated with this set across stimulus decks. If decision times for the separate dimensions appearing within a deck are correlated, this manipulation should produce corresponding changes across decks in $\overline{RT}$ for the set of stimuli varying along C.

The present approach differed from that of Experiment 1 and of Egeth (1966) in that the data were based on a set of stimuli, C, which were both unidimensional and structurally invariant across decks. This approach should obviate a serial processing interpretation of any systematic changes in $\overline{RT}_C$ that might be obtained across stimulus decks.

METHOD

Subjects

Six women were recruited from introductory psychology courses and paid \$1.50 per hour. The incentive system was equivalent to that described previously.

Stimuli

Three stimulus decks, each containing 32 cards, were constructed. One-half of the cards in the three decks contained figures identical to those used in the color deck in Experiment 1. The remaining cards in Deck A contained a pair of square figures, identical in color, that were bisected either vertically or horizontally by a black inked line. In Deck B, three-fourths of the remaining cards contained figures that varied with respect to the orientation of a bisecting line, and one-fourth contained figures varying with respect to the size of an inscribed circle (as in S stimuli of Experiment 1). In Deck C, one-fourth of the remaining cards varied with respect to the orientation of the bisecting line, and three-fourths, with respect to the size of the inscribed circle. One-half of each of the stimulus types in the three decks required the "different" response.

Procedure

Except as indicated below, the procedure was identical to that used in Experiment 1. Following 32 warm-up trials with letter stimuli, Ss were tested on all three decks on each of three consecutive days. Prior to each deck, Ss were familiarized with the coming stimuli as in Experiment 2. The order in which the decks were presented was counterbalanced in the Latin-square manner across Ss and days. During each 32-trial condition, Ss responded only when stimuli differed.

RESULTS AND DISCUSSION

In the introduction, it was assumed that the time required to judge the S dimension would be longer than for the O dimension. This assumption was confirmed by a comparison of $\overline{RT}$ s obtained for S in Deck C and for O in Deck B, t , paired observations, $(5) = 8.71 < .001$.

Given this relation, the hypothesis that decision times are correlated implies that "different" $\overline{RT}$ to color stimuli should increase across Decks A, B, and C. Consistent with this prediction, $\overline{RT}$ s obtained for the three decks were 381, 410, and 431 msec, respectively. The differences between A and B, and between B and C were reflected in the data of all six Ss ($p < .05$). While $\overline{RT}$ for the color dimension increased across decks, the false-"different" error rates for trials containing this dimension showed moderate decreases. These values were .062, .034, and .015 for Decks A, B, and C.

Since unidimensional stimuli were used under all conditions of this experiment, a serial processing interpretation of the results would not seem to be applicable. Rather, it appears that as the average discriminability of dimensions contained in a stimulus deck decreased, Ss became progressively more circumspect regarding the time allocated for the interrogation of *all* dimensions, including the one (color) remaining constant in discriminability across decks. In the language of statistical decision theory (Swets, Tanner, & Birdsall, 1961), Ss adopted more stringent criteria for "same" and "different" decisions when the average difficulty of the discriminations required by test stimuli increased. Accordingly, the data imply that the

criteria ("same" and "different") established for each of the dimensions that are potentially critical on a given trial are not independent.

GENERAL DISCUSSION

The present findings were totally consistent with none of the models investigated by Eggh (1966) since these models share the implicit assumption that decision time for a given dimension is uninfluenced by the stimulus context. However, the results *are* adequately described by models incorporating the following assumptions: (1) stimulus dimensions are interrogated simultaneously (parallel processing), (2) the time taken to reach a decision regarding the state of a given dimension fluctuates from trial to trial (decision time is distributed as a random variable), (3) comparisons terminate when a single source of dissimilarity is detected (self-terminating comparisons), and (4) the time required to determine the state of a particular dimension covaries with the average time required to determine the states of other dimensions present within a stimulus deck (correlated criteria).

Support for the first two assumptions was provided in Experiment 2 where increases in "same" $\overline{RT}$ between the slowest of two unidimensional decks, Y, and a corresponding bidimensional deck, XY, either were not obtained, or if obtained, were well below formal lower-bound estimates based on the assumption that dimensions are interrogated serially. Consistent with the assumption that decision times are randomly distributed across trials, the magnitude of the increase between a unidimensional deck, Y, and a bidimensional deck, XY, varied with the degree of overlap obtaining between the distributions of X and Y (see Rapoport, 1959). This assumption gained additional support from the "different" response data of Experiment 1 where it was found that the time required to detect a difference when stimuli differed along all dimensions was consistently less than required when the stimuli differed only along the fastest single dimension.

The third assumption, of self-terminating comparisons, has been suggested by the results of Eggh (1966) and of Nickerson (1967), and was confirmed in Experiment 1 where "different" $\overline{RT}$ was shown to vary as the inverse of the number of dimensions differing between test stimuli.

The fourth assumption, of correlated criteria, was implied by the results of Experiment 3 where "different" $\overline{RT}$ for unidimensional color stimuli was found to vary as a function of the average $\overline{RT}$ recorded for the other dimensions appearing within a given stimulus deck. Further evidence for this assumption appeared in the "different" response data of Experiment 1 with the findings that (1) $\overline{RT}_{c(f)} < \overline{RT}_{c(s)}$, where $\overline{RT}_f < \overline{RT}_s$, (2) $\overline{RT}_{f(c)} < \overline{RT}_{f(s)}$, where $\overline{RT}_c < \overline{RT}_s$, (3) $\overline{RT}_{c(fs)} < \overline{RT}_{c(s)}$, where $\overline{RT}_f + \overline{RT}_s/2 < \overline{RT}_s$, and (4) $\overline{RT}_{f(cs)} < \overline{RT}_{f(s)}$, where $\overline{RT}_c + \overline{RT}_s/2 < \overline{RT}_s$.

Eggh's finding that "different" RT for the fastest of the unidimensional decks, color, was shorter than for the tridimensional deck on trials where all dimensions differed can also be interpreted on the basis of the assumption of correlated criteria. Since the difficulty of the discriminations demanded on some trials under the tridimensional condition was greater than that obtaining across trials for the color deck, the criteria associated with the color dimension accordingly should be more stringent in the former instance. As a result, longer latencies would be expected under the tridimensional condition, even on trials where all dimensions differed.

While the model outlined above adequately characterizes performance in the experiments reported here, its applicability may be limited to tasks requiring the comparison of simultaneously presented stimuli. If S must match an immediate stimulus against a set of stimuli represented in memory (e.g., Neisser, 1963; Sternberg, 1966), the encoding

operations necessary for a direct comparison of the two sources of information may be so complex that parallel processing is impossible, or possible only with extended practice (e.g., Neisser, Lazar, & Novick, 1963; Wattenbarger, 1968). These considerations suggest that future research will most profitably concern itself with the task of specifying the conditions under which parallel and serial processing can occur, rather than with seeking to resolve the more categorical issue of whether information is processed sequentially or in parallel.

APPENDIX

Underlying both serial and parallel bound estimates are five general assumptions regarding the components of the RT interval:

(1) The total reaction time, T_X , may be divided into two component latencies: (a) a discrimination, or decision, latency, t_X , defined as the time required to determine the state of X, and (b) a base latency, t_b , consisting of neural lag time, both sensory and motor, plus the time required to select a response system appropriate to a particular state decision.

(2) The latencies, t_X and t_b , are additive (nonoverlapping).

(3) The means of the distributions of t_X and t_b are independent.

(4) Provided contingent probabilities (of the form discussed in connection with the "same" RT data of Experiment 1) do not exist, the mean of the distribution of t_X is independent of the means of decision latencies for other dimensions contained in stimuli.³

(5) Under a multidimensional condition, XY, the "same" response is initiated only after "same" decisions have been reached for both X and Y.⁴

Lower-Bound Serial Estimate

Let $\overline{T}_X$, $\overline{T}_Y$, and $\overline{T}_{XY}$ denote the mean "same" RTs for Conditions X, Y, and XY. Let $\overline{t}_b$ denote the mean base time common to all conditions. Let $\overline{t}_X$ and $\overline{t}_Y$ denote the average decision times associated with conditions X and Y. According to the assumption that dimensions are compared sequentially, if judged stimuli vary independently along X and Y, then $\overline{T}_{XY}$ should include $\overline{t}_b$ plus $\overline{t}_X$ plus $\overline{t}_Y$. That is,

$$\overline{T}_{XY} = \overline{t}_Y + \overline{t}_X + \overline{t}_b; \text{ or equivalently,} \quad (1)$$

$$\overline{T}_{XY} = \overline{T}_Y + \overline{T}_X - \overline{t}_b. \quad (2)$$

Unfortunately, a direct estimate of $\overline{t}_b$ is impossible to obtain. However, it is possible to obtain a value, $\overline{T}_b'$, which includes $\overline{t}_b$ plus $\overline{t}_a$, where $\overline{t}_a$ is some unknown, but presumably minimal, decision latency associated with a dimension, A, whose values are highly discriminable. Thus $\overline{T}_b'$ overestimates $\overline{t}_b$ by some unknown quantity, $\overline{t}_a$, and since the value, $\overline{T}_b'$ is used as the subtraction term in Equation 2 above, this equation underestimates $\overline{T}_{XY}$ by the quantity $\overline{t}_a$. Thus,

$$\overline{T}_{XY} \geq \overline{T}_X + \overline{T}_Y - \overline{T}_b'.$$

$\overline{T}_X$, $\overline{T}_Y$, and $\overline{T}_b'$ are calculated from the data of each S on each day of practice. Pooled across days, these terms are used to generate a lower-bound estimate of the increase between $\overline{T}_Y$ and $\overline{T}_{XY}$ for a given S.

Upper-Bound Parallel Estimates

The procedure described below would develop a direct estimate of the increase in RT between Y and XY based on the parallel/distributed model if the following special assumption held:

(6) $\text{Var}_{t_b} = 0$. That is, $\text{Var}_{T_X} = \text{Var}_{t_X}$, for any dimension X.

To the extent that this assumption is violated, the following calculations result in an overestimate. A word of explanation is required concerning the effects of such a violation. The estimate of $\overline{T}_{XY}$ is based on a particular sample of scores (RTs) selected from Conditions X and Y. More precisely, the only scores from the distribution of X that will enter directly into the calculation of the estimate are those contained in the region of overlap between the distributions of X and Y. If Assumption (6) does not hold, and thus if t_b is randomly distributed (which seems highly probable), then the estimated $\overline{t}_b$ for the sample of scores selected from X will be greater in value than the true $\overline{t}_b$. In other words, the estimate would be based in part on a biased sample of scores which will

tend to inflate the estimated $\bar{T}_{xy}$ above what would be expected following the assumption that comparisons are carried out in parallel. For this reason, the estimate will be treated as an upper bound.

The following definitions are established with respect to the data of a particular S on a given day of practice. Let $X = x_1, x_2, \dots, x_i, \dots, x_n$ denote the set of N_{x_i} response times from the unidimensional condition containing the lower mean, and $Y = (y_1, y_2, \dots, y_j, \dots, y_m)$ denote the set of N_{y_j} response times from the unidimensional condition containing the higher mean. Let $x_{i_{\max j}}$ denote a response time on Trial i under Condition X that is greater in value than the response time on some trial, y_j , under Condition Y. Let $N_{X_{\max j}}$ denote the number of response times under X whose values are greater than that on some y_j . Finally, let $N_{X_{\max j}}/N_{x_i}$ denote the proportion of trials under X containing values greater than that obtained on some y_j . This proportion provides an estimate of the probability that t_x will be greater than t_y on some hypothetical trial under the bidimensional condition, XY. If the average increase between y_j and all $x_{i_{\max j}}$ is weighted by this proportion, we are left with an estimate of the expected increase in response time between some Trial y_j and some hypothetical Trial xy_j' . That is,

$$\text{est. } d(y_j, xy_j') = \frac{N_{X_{\max j}}}{N_{x_i}} \left(\frac{\sum_{i=1}^{N_{X_{\max j}}} (x_{i_{\max j}} - y_j)}{N_{X_{\max j}}} \right) \quad (3)$$

Summing (1) across y_j , and dividing by N_{y_j} , we have,

$$\text{est. } d(\bar{T}_y, \bar{T}_{xy}) = \frac{\sum_{j=1}^m \left[\frac{N_{X_{\max j}}}{N_{x_i}} \left(\frac{\sum_{i=1}^{N_{X_{\max j}}} (x_{i_{\max j}} - y_j)}{N_{X_{\max j}}} \right) \right]}{N_{y_j}} \quad (4)$$

which is the expected increase between $\bar{T}_y$ and $\bar{T}_{xy}$ for a particular S on a given day of practice. Cancelling, (4) becomes,

$$\text{est. } d(\bar{T}_y, \bar{T}_{xy}) = \frac{\sum_{j=1}^m \sum_{i=1}^{N_{X_{\max j}}} (x_{i_{\max j}} - y_j)}{N_{x_i}^2} \quad (5)$$

since $N_{x_i} = N_{y_j}$. The results of (5) are averaged across days to provide an upper-bound estimate of the expected increase in response time between Y and XY for a given S.

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NOTES

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3. Violations of this assumption should be reflected by changes in the frequency of false-"same" errors for dimensions across stimulus decks. While the results of Experiment 3 indicate that the assumption may not be correct, an examination of the error data from Experiment 2 showed that the extent of the violation in this instance was at most quite small. The direction of the potential violation was such that both bound estimates may be set too low.

4. Violations of this assumption should be similarly reflected in the error data. Such violations were not indicated under the conditions of Experiment 2.

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