Reaction times and error rates for "same"-"different" judgments of multidimensional stimuli[1]

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Each S indicated whether two successively presented rows of letters were "same" or "different." Reaction times of the "different" response seemed to indicate that S examined the stimulus letters in a serial, self-terminating manner. However, the reaction times of the "same" response were not consistent with this model. Consequently, it was proposed that S employs simultaneously two distinct processes for comparing stimuli. One process would generate the "different" responses; the other process would generate the "same" responses. Most false "same" responses occurred when the two rows of letters differed minimally. Thus, the false "same" responses appear to result from a failure to detect the difference between the two stimuli. However, when S made a false "same" response, he was aware that he had done so. Therefore, it was suggested that only one of the two comparison processes failed to detect the stimulus difference.

Suppose S is presented, either simultaneously or successively, with two multidimensional stimuli and is asked to judge whether the two stimuli are "same" or "different." Egeth (1966) has outlined a number of plausible models showing how S might perform this task. The discussion that follows is similar to his analysis.

A stimulus dimension will be said to be either "same" or "different" depending on whether or not the two stimuli match each other along that dimension. The act of comparing two stimuli along a given dimension and, thus, deciding if that dimension is "same" or "different" may be termed *processing* that dimension.

Since the stimuli are multidimensional, S must process a number of dimensions in order to decide whether the stimuli are "same" or "different." Would S process these dimensions one at a time, one after another? Or might they all be processed simultaneously? Models of S's performance that assume the former may be called *serial* (process) models, while those that assume the latter may be called *parallel* (process) models. In the case of parallel models, even though the processing of each dimension is begun simultaneously with the other dimensions, it need not be finished simultaneously with the other dimensions.

When the two stimuli are "same," S must process all relevant dimensions in order to be sure that the stimuli are "same." What about the occasions when the two stimuli are "different"? As soon as S has finished processing any "different" dimension, he has enough information to decide that the stimuli are "different." Will he conclude at that point that the stimuli are "different," or will he wait until processing has been finished on all dimensions before making a decision? Models that assume the former may be called *self-terminating* (process) models, while those that assume the latter may be called *exhaustive* (process) models.

This analysis has generated four types of models. There are serial and parallel models and within each of these types there are both self-terminating and exhaustive models.

The reaction times (RT) of S's judgments provide a means of testing these models. Suppose that S is asked to make one of two responses depending on whether the two stimuli are "same" or "different." One question of interest is: How does the mean RT of the "same" response compare with the mean RT of the "different" response?

On a certain subset of trials, the two stimuli differ along exactly D stimulus dimensions. Suppose that the D dimensions that are to be "different" are chosen randomly on each trial. Another question of interest is: How does the mean RT of the "different" response vary as a function of D, the number of "different" dimensions?

The term *processing isochronality* will indicate that, for each stimulus dimension, the processing time for that dimension is independent of whether the dimension is "same" or "different." Similarly, the term *efferent isochronality* will indicate that the amount of time intervening between the decision to respond and the completion of the response is independent of whether the response is "same" or "different."

The self-terminating models, both serial and parallel, state that S will initiate the "different" response as soon as processing is completed in any "different" dimension. The more "different" dimensions there are, the earlier on the average will be the first completed processing of a "different" dimension. So, the mean RT of the "different" response will decrease as the number of "different" dimensions increases. When the two stimuli are "same," processing must be completed in *every* dimension before the "same" response can be initiated. So, if both processing and efferent isochronality hold, then the "same" responses should be slower than the "different" responses.

The exhaustive models, both serial and parallel, state that processing will be completed on every dimension before a response is initiated. So, if processing isochronality holds, the RT of the "different" response should not depend on the number of "different" dimensions. If efferent isochronality also holds, then the RTs of the "same" and "different" responses should be equal.

Egeth (1966) and Nickerson (1967) did experiments to test these predictions. Egeth presented Ss simultaneously with two stimuli that could vary along the dimensions of color, shape, and the tilt of an interior line. Nickerson presented two stimuli, sometimes simultaneously and sometimes successively, to the Ss. His stimuli varied along the dimensions of color, shape, and size. Both investigators found that the mean RT of the "different" response decreased as the number of "different" dimensions increased. This is consistent with a self-terminating model. In addition, Egeth found some evidence favoring a serial model.

Nickerson found that responses to "same" stimuli were faster than responses to "different" stimuli with only one "different" dimension. Now, all the above predictions concerning the relative speeds of "same" and "different" responses depend upon the assumptions of processing and efferent isochronality. Since Egeth considered the latter assumption to be questionable, he did not compare the speeds of "same" and "different" responses. However, an examination of the graphs in his article shows that he obtained results that were similar to Nickerson's.

These results raise the question of why the "same" responses were so fast. If both processing and efferent isochronality are assumed, these results are inconsistent with all the models discussed above. Could it be that either of the isochronality assumptions is incorrect?

It has not been a uniform finding that "same" responses are faster than "different" responses. At present it is not entirely clear what determines whether "same" responses are faster or slower than "different" responses (Bindra, Williams, & Wise, 1965; Bindra, Donderi, & Nishisato, 1968; Sekuler & Abrams, 1968; Nickerson, 1965; Posner & Mitchell, 1967).

A PROPOSED EXPERIMENT

In the experiment reported here, Ss judged whether or not two successively presented horizontal rows of letters, which contained equal numbers of letters, were identical (i.e., contained the same letters arranged in the same order). The stimulus presented first will be called the *criterion* stimulus, while the stimulus presented second will be called the *test* stimulus. A test stimulus will be termed either "same" (as) or "different" (from the criterion stimulus). Similarly, each letter in the test stimulus will be said to be either "same" (as) or "different" (from the letter occupying the corresponding position in the criterion stimulus). A letter in the test stimulus will be said to have been processed when S has decided whether it is "same" or "different."

A stimulus is completely described by specifying, for each letter position, the letter occupying that position. Consequently, each letter position may be regarded as a stimulus dimension. Thus, the models discussed above may be applied to the present experiment.

Of these models, the serial, self-terminating model will be given the most attention. Some of Egeth's (1966) and Nickerson's (1967) findings suggest a self-terminating model. Sternberg (1967) found that digits presented in a tachistoscopic display were examined in a serial, self-terminating manner.

Some quantitative predictions can be derived from the serial, self-terminating model. This model states that S will decide that a test stimulus is "different" as soon as he processes any "different" letter. Therefore, S will process exactly one "different" letter before deciding that the test stimulus is "different." Suppose that, on a certain subset of trials, the test stimulus contains L letters, D of which are "different." The positions of the D "different" letters are randomly chosen on each trial. It has been shown elsewhere (Bamber, 1969) that the mean number of "same" letters processed prior to the first "different" letter being processed will be $(L - D)/(D + 1)$. Let b_s and b_d represent the processing times of a "same" and "different" letter, respectively. Then the mean amount of time spent processing the stimulus before deciding that it is "different" will be $[(L - D)/(D + 1)]\, b_s + b_d$. Of course, stimulus-processing time is only a portion of a total RT. Time is required for the transmission of information from the retina to the brain and the transmission of motor commands from the brain to the musculature, etc. Let h_s and h_d represent the mean amount of time for these delays when a "same" or a "different" response is involved, respectively. Then the mean RT of the "different" response will be given by

$$RT_d = h_d + \left(\frac{L - D}{D + 1}\right) b_s + b_d \qquad (1)$$

Suppose the test stimulus is "same" and contains L letters. The S must examine every letter before deciding that the stimulus is "same." Then, the mean RT of the "same" response will be given by

$$RT_s = h_s + Lb_s \qquad (2)$$

Let

$$a = h_d + b_d$$

$$e = (h_s - h_d) + (b_s - b_d)$$

Then Eqs. 1 and 2 become

$$RT_d = a + \left(\frac{L - D}{D + 1}\right) b_s \qquad (3)$$

$$RT_s = a + (L - 1)b_s + e \qquad (4)$$

When the above predictions are fitted to experimental data, there will be no way to estimate b_d, the processing time for a "different" letter, since this parameter is confounded with h_d. On the other hand, there will be two ways to estimate b_s, the processing time for a "same" letter. It can be estimated from both the "same" and the "different" response RTs.

If efferent isochronality holds, h_s will equal h_d. Similarly, if processing isochronality holds, then b_s will equal b_d. So, if both hold, the quantity e will be zero.

METHOD

Subjects

All Ss were given a screening test to ensure that they could perform the experimental task with a low error rate. Four prospective Ss were screened and all passed. All four Ss were right-handed undergraduate females at Stanford University. They were paid volunteers.

Stimuli

Stimuli were constructed as follows: A master letter sheet was made by placing black transfer-sheet letters (Trans-artype T1528) upon a sheet of white paper. Copies of this sheet were reproduced by photo-offset printing. These sheets were cut into small rectangles with one letter on each rectangle. The rectangles were then cemented upon white 6 x 9 in. cards.

Each stimulus card contained from one to four letters. The letters were arranged in a horizontal row that was centered on the vertical midline of the card. The center-to-center distance between adjacent letters was 2.0, 1.5, and 1.0 in. for cards containing two, three, and four letters, respectively. Each letter was approximately 0.7 in. in height.

The letters on each stimulus card were drawn from the set of 12 capital consonants: B, C, D, F, J, K, L, N, S, T, V, Z. All these letters occurred with equal frequency in both the criterion and test stimuli. No letter ever appeared twice within a single stimulus. The criterion stimulus and the test stimulus always contained an equal number of letters. Whenever any letter appeared in both the criterion stimulus and the test stimulus, it occupied the same position in both stimuli. On half the trials, the two stimuli were identical.

So, in this experiment, a test stimulus was "different" if and only if it contained one or more letters that were contained nowhere in the criterion stimulus. Thus, it would have been possible for Ss to compare stimuli simply as collections of letters without regard to the order of the letters. However, evidence has been presented elsewhere (Bamber, 1969, Chap. 9) that Ss in fact did take letter order into account when deciding whether a test stimulus was "same" or "different."

Apparatus

The S sat in front of an Iconix 6134 tachistoscope. One of the tachistoscope's fields was used as a fixation field. A second field was used to expose the test stimulus. The criterion stimulus was mounted outside the tachistoscope, beside the viewing window. The criterion stimulus was much closer to S than was the test stimulus. Consequently, even when the criterion and test stimuli were physically identical, their retinal images were quite different.

The fixation field was exposed continuously except when the test stimulus was exposed. Two hundred milliseconds after S depressed a footswitch on the floor, the fixation field went off for 100 msec while the test stimulus came on for 100 msec. This brief exposure was used to prevent S from moving his eyes from one letter of the test stimulus to another.

In front of S were two finger-operated response keys, one for each hand. The S indicated whether the test stimulus was "same" or "different" by depressing one of the keys. The RT was defined as the interval, which was measured to the nearest millisecond, between the onset of the test stimulus and the depression of either key. The force required to depress either key was approximately 100 g.

The fixation and test-stimulus fields were viewed binocularly. Both fields covered an area of approximately 4 in. square at an apparent distance of approximately 40 in. A piece of Color-aid Black paper filled the fixation field. At the center of the fixation field, there was a fixation mark which was an X about ¼ in. square drawn with a No. 2 graphite pencil. The fixation mark coincided with the apparent location of the center of the test stimulus. The luminance of the fixation field was roughly ½ ft-L. With a white card in the test-stimulus field, that field's luminance was roughly 20 ft-L.

Procedure

The Ss were instructed to try to make *no* errors in responding. Within that constraint, they were told to respond as quickly as possible. No system of payoffs for correct or incorrect, fast or slow responses was used. For two Ss (S2 and S3), pressing the right- or left-hand response key indicated that the test stimulus was "same" or "different," respectively. For the other two Ss, the assignment was reversed.

At the start of each trial, a new criterion stimulus was exposed. The S inspected this for as long as he wanted. The E placed a new test stimulus in the tachistoscope and signaled "ready" to S. The S rested his fingers on the response keys and fixated the fixation mark. The S then initiated the exposure sequence by depressing the footswitch. After viewing the test stimulus, S pressed one of the response keys. Then S reported verbally whether he believed his response had been correct or incorrect. The S was given feedback concerning the accuracy but not concerning the speed of his response.

After the screening test, each S participated in a practice session followed by 10 test sessions. Consecutive sessions usually occurred on consecutive weekdays. Each session lasted nearly 2 h. Within each session, there were 20 practice trials followed by 276 test trials. The S was permitted rest breaks if he wanted them.

Experimental Design

A single set of 276 criterion stimuli was used for the entire experiment aside from practice trials. Each criterion stimulus was presented once in every session. The order of presentation was chosen randomly and, thereafter, remained the same in every session. During the 10 test sessions, each criterion stimulus was paired with a "same" test stimulus in exactly five sessions. All four Ss were given an identical sequence of trials.

Table 1
Number of Trials per Session Belonging to each Category

	"Same"	"Different"			
		D = 1	D = 2	D = 3	D = 4
L = 4	54	12	18	12	12
L = 3	36	12	12	12	
L = 2	24	12	12		
L = 1	24	24			

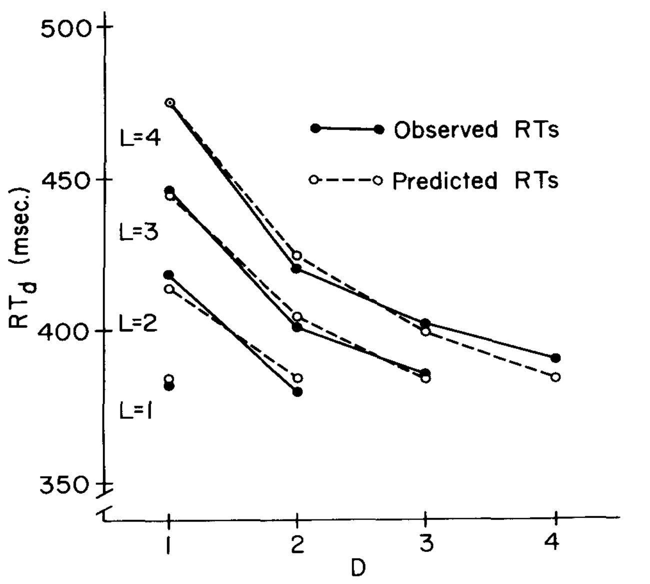

Fig. 1. Predicted and observed mean RTs of the "different" response.

Trials may be classified according to the number (L) of letters in the test stimulus, according to whether the test stimulus is "same" or "different," and according to the number (D) of "different" letters in the test stimulus. Table 1 presents the number of trials per session that belonged to each of the resulting categories. For each category of "different" test stimuli, the D "different" letters occurred in all possible positions in the test stimulus with equal frequency. In order of presentation, trials of all categories were randomly mixed together.

Data Analysis

Before analyzing the RT data, a total of 1.5% of the responses were discarded: 1.1% because S pressed the wrong response key, 0.1% because S pressed both the correct and the incorrect key, and 0.3% because the response was slow. The definition of a slow response has been given elsewhere (Bamber, 1969). Various models were fitted to the RT data by means of a least-squares technique that has been described elsewhere (Bamber, 1969). Using this technique, estimates of model parameters and their standard errors were calculated. To test a parameter estimate for statistical significance, a z test was employed.

RESULTS AND DISCUSSION

Reaction Times: "Different" Response

The "different"-response RTs predicted from the serial, self-terminating model are given by Eq. 3. This equation was fitted to the data of all Ss and of each S individually. Figure 1 presents, for the group, the observed mean RTs and the mean RTs predicted from Eq. 3. Ten RTs were predicted while estimating only two parameters from the data. The largest discrepancy, for the group data, between an observed RT and a predicted RT was only 7 msec. For data from an individual S, the largest discrepancy was 20 msec. Thus, the serial, self-terminating model predicted the "different"-response RTs fairly well.

Values of the parameters a and b_s of the serial, self-terminating model were estimated using Eq. 3. These estimates, together with their standard errors,[3] are presented in Table 2. The parameter estimates in this table are average values computed over the 10

Table 2
Estimates of a and b_s in Milliseconds

	a	b_s
All Ss	384.3 ± 0.9	60.2 ± 2.1
S1	406.5 ± 2.0	73.8 ± 4.7
S2	344.4 ± 1.5	36.0 ± 3.1
S3	415.3 ± 1.8	68.6 ± 4.7
S4	370.9 ± 1.5	62.3 ± 3.9

Table 3
Estimates of A, B, and C in Milliseconds

	A	B	C
All Ss	317.1 ± 2.2	25.4 ± 1.0	20.8 ± 2.7
S1	359.4 ± 4.9	30.0 ± 2.2	19.0 ± 6.2
S2	300.2 ± 3.9	13.7 ± 1.7	12.0 ± 5.0
S3	323.4 ± 4.1	27.1 ± 1.8	15.8 ± 5.0
S4	285.4 ± 4.5	30.9 ± 1.9	36.5 ± 5.6

test sessions. The parameter b_s, which represents the processing time of a "same" letter, decreased significantly, for each S, over the course of the experiment (Bamber, 1969). The group estimate of b_s was about 85 msec in the first test session and about 50 msec in the last session. An examination of error rates showed that this increase in speed did not result from the readjustment of a speed-accuracy tradeoff.

The "different"-response RTs were examined to see how they varied as a function of the position of the "different" letters in the test stimulus. On the basis of this analysis, it appeared that the order in which each S processed the letters in the test stimulus was fairly variable, but that he did have a tendency to process from left to right (Bamber, 1969).

Reaction Times: "Same" Response

Equation 4 gives the "same"-response RTs predicted from the serial, self-terminating model. If both processing and efferent isochronality hold, then the quantity e in Eq. 4 must be zero. Using the estimates of a and b_s given in Table 2 and taking e to be zero, the predicted "same"-response RTs were calculated for the group. These are plotted vs L in Fig. 2. Also plotted in the figure are the observed RTs. The observed RTs are considerably faster than the predicted RTs and, furthermore, the slopes of the two RT curves are rather different. Thus, although the stimuli in this experiment were rather different from Egeth's (1966) and Nickerson's (1967) stimuli, the results of this experiment agree well with their findings.

To further investigate the discrepancy between the predicted and observed RTs, the following equation was fitted to the observed RTs of each S:

$$RT_s = A + (L - 1)B + \delta_L C \qquad (5)$$

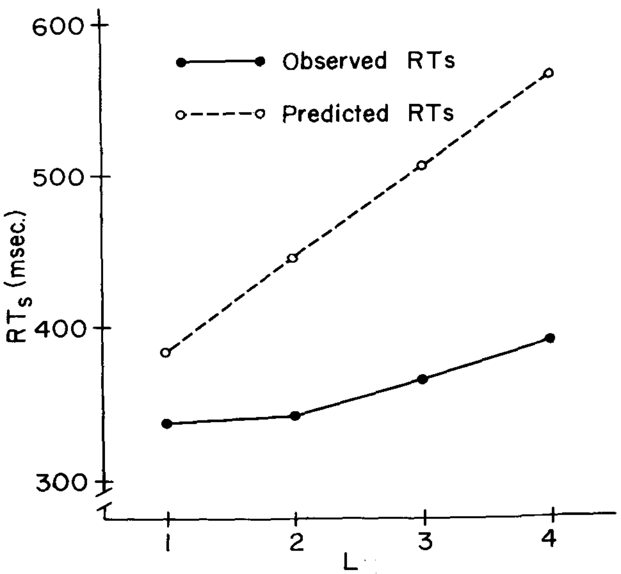

Fig. 2. Predicted and observed mean RTs of the "same" response.

The quantity δ_L is one when L is one, but zero otherwise. The term $\delta_L C$ was inserted in Eq. 5 because the graph of observed RTs in Fig. 2 appears to be somewhat concave upward. The parameters A, B, and C were estimated for each S and for the group. These estimates, together with their standard errors, are presented in Table 3. The estimates in Table 3 are average values computed over the 10 test sessions. For three of the four Ss (all except S3), the parameter B decreased significantly over the course of the experiment (Bamber, 1969). The group estimate of B was about 35 msec at the beginning of the experiment and about 20 msec at the end.

A comparison of Eqs. 4 and 5 shows that the serial, self-terminating model predicts the following: Provided processing and efferent isochronality hold, the parameters a and A should be equal. The parameter C should equal zero. The parameters b_s and B should be equal. A comparison of Tables 2 and 3 shows that the following actually occurred: First, A is significantly less than a for each S. This finding is ambiguous since it could be caused by a failure of either the model or the supplementary isochronality assumptions. Second, C is significantly greater than zero for each S. Third, B is significantly less than b_s for each S.

Clearly, the serial, self-terminating model has failed. The most important evidence of its failure is that it produced two highly discrepant estimates of the processing time for a "same" letter. The estimate (b_s) based upon the "different"-response data was 60 msec, whereas the estimate (B) based upon the "same"-response data was 25 msec. While failure of the isochronality assumptions could account for the discrepancy between a and A, it cannot account for the discrepancy between b_s and B.

One possible explanation of the above results is a two-process model. A flow diagram for this model is presented in Fig. 3. It is assumed that, on every trial, S employs simultaneously two distinct stimulus-comparison processes. One of these comparison processes, the *serial processor,* is simply the serial, self-terminating process discussed above. The serial processor emits

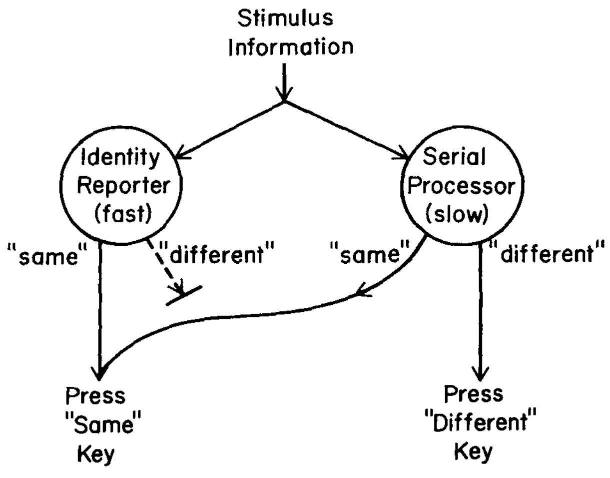

Fig. 3. A flow diagram for the two-process model.

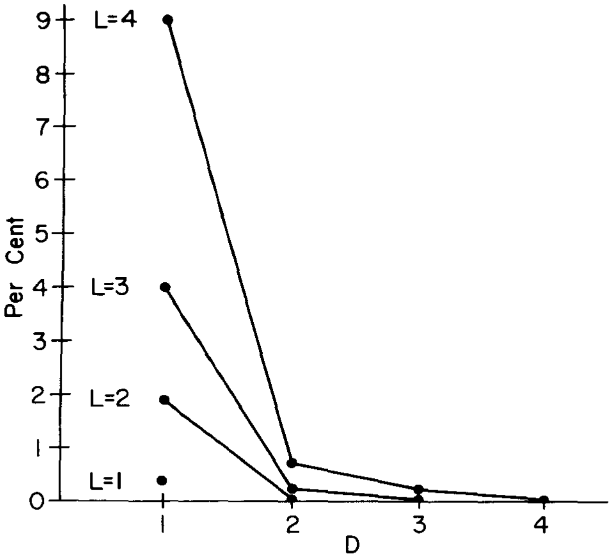

Fig. 4. Percentages of false "same" responses.

one of two signals depending on whether the test stimulus is "same" or "different." The other comparison process, the *identity reporter*, has only one signal. It emits this signal if the test stimulus is "same"; otherwise, no signal is emitted. The "different" signal from the serial processor initiates the "different" responses. When the test stimulus is "same," both comparison processes emit "same" signals. The identity reporter is assumed to be considerably faster than the serial processor. Consequently, the identity reporter's "same" signal has already initiated the "same" response by the time the serial processor emits its "same" signal. Thus, the "same" responses would be faster than would be predicted by the serial, self-terminating model.

It might be doubted whether Ss can do two things at once as required by this model. However, Posner and Mitchell (1967) have already provided good evidence that Ss can employ two distinct stimulus-comparison processes either simultaneously or in very rapid succession.

Another objection to the model might be that the nonemission of a "same" signal by the identity reporter would be equivalent to the emission of a "different" signal. Thus, the fast identity reporter could initiate the "different" response before the slow serial processor could do so. However, S must wait for the "same" signal before deciding that there is none. Three hundred milliseconds is too short a time to wait; S would make many false "different" responses. Five hundred milliseconds is too long; the serial processor would have already initiated the "different" response. It is by no means obvious that Ss could adjust their waiting times to these tolerances.

Errors

Barely over 1% of all responses were errors. There were a total of 121 errors. Excluded from this total are 11 trials where an S pressed both the correct and the incorrect key. The percentages of false "same" responses for each value of L and D are plotted in Fig. 4. The vast majority of false "same" responses occurred when there was only one "different" letter in the test stimulus. Nickerson (1967) obtained a similar result. Also, when there was only one "different" letter, the probability of a false "same" response tended to increase as the position of this letter was moved from left to right across the test stimulus. As the total number of letters in the test stimulus increased, the probability of a false "same" response increased.

The following is a model for the above findings: Images of the test-stimulus letters are stored in short-term visual memory (STVM) (Sperling, 1960; Averbach & Coriell, 1961). Either prior to or in the course of comparing the test and criterion stimuli, the test-stimulus letters must be transferred out of STVM. The transfer proceeds serially and tends to go from left to right across the test stimulus. The S will always classify a test-stimulus letter as "same" unless he finds evidence to the contrary. However, the clarity of images in STVM deteriorates rapidly. Thus, the later in time a "different" letter is transferred out of STVM, the more likely S will misclassify it as "same." It is assumed that, for M not equal to N, the classifications given the Mth and Nth letters transferred out of STVM are independent. The S will decide that a "different" test stimulus is "same" if and only if he misclassifies every "different" letter in the test stimulus.

It follows from the model that having redundant "different" letters in the test stimulus should decrease the likelihood of a false "same" response. Also, the more letters there are in the test stimulus, the longer it should take to transfer all of them out of STVM. Consequently, the probability of a false "same" response should be greater the more letters there are in the test stimulus. Since the transfer tends to go from left to right, a solitary "different" letter on the right side of the test stimulus would be more likely to be misclassified "same" than would a solitary "different" letter on the left. Thus, this model provides an explanation of the above data on false "same" response. Moreover, the model has been shown to be quantitatively accurate (Bamber, 1969).

It can be seen in Fig. 3 that the false "same" responses have two possible sources: the identity reporter and the serial processor. If the false "same" responses are generated by the identity reporter, they should have the same RTs as correct "same" responses (i.e., the lower curve in Fig. 2). If they are generated by the serial processor, their RTs should be given by Eq. 4 (i.e., the upper curve in Fig. 2). It turns out that the false "same" responses were about as fast as the correct "same" responses (Bamber, 1969). This result agrees with an incidental observation made by Nickerson (1967, p. 550). So, it appears that the false "same" responses are generated by the identity reporter. Thus, the identity reporter is sometimes fooled and responds to similarity as well as to identity.

The probability of a false "different" response was 1.0, 0.6, 0.6, and 0.6% for test stimuli containing one, two, three, and four letters, respectively. These incorrect responses to "same" stimuli were about as fast as correct "same" responses. These errors may result from S accidentally pressing the wrong response key after correctly deciding that the test stimulus was "same."

At the end of each trial, S was required to report whether or not he believed that he had just pressed the correct response key. These verbal reports were inaccurate on only four trials out of approximately 11,000 trials. Thus, whenever S pressed the wrong key, he almost always knew that he had done so. How is it that S knew this? In the case of false "different" responses, it seems likely that S noticed that his decision that the stimulus was "same" did not agree with his response. However, in the case of false "same" responses, supposedly S's response agrees with the output of the identity reporter. The reason S knows that he has made a false "same" response may be that, after the identity reporter has incorrectly generated a "same" response, the slower serial processor correctly indicates that the test stimulus was "different."

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NOTES

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3. When an estimate is stated in the form m ± s, m is the estimate and s is its standard error.

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