The role of onset in the perception of sequentially presented vibrotactile patterns

JAMES C. CRAIG

Indiana University, Bloomington, Indiana

Interaction between sequentially presented vibrotactile patterns was measured both in a discrimination task and in a temporal masking paradigm. The vibrotactile patterns were generated on an array of stimulators, 6 columns $\times$ 24 rows, in contact with the subjects' fingertips. As the time between pairs of patterns presented to one fingertip was increased, performance in discriminating whether the two patterns were the same or different improved. When one member of the pair was presented to one finger and the other to a second finger, discrimination performance first declined slightly then improved as temporal separation increased. Performance on pattern recognition in the presence of either a forward or backward masker improved as the temporal separation between the target and masker increased. In both the discrimination and masking measurements, the time between the onsets of the two patterns (stimulus onset asynchrony) was found to be the best measure of interaction between the sequentially presented patterns. The implications of these findings for vibrotactile pattern processing are discussed.

The study of temporal interactions between sequentially presented vibrotactile patterns has paralleled similar studies of visual patterns. This is not surprising since both the skin and the eye are capable of perceiving spatially extended patterns, and there is continuing interest in the designing of cutaneous communication systems for replacing the visual system (Geldard, 1960, 1966, 1974; Schiff & Foulke, 1982; Sherrick, 1975; White, Saunders, Scadden, Bach-y-Rita, & Collins, 1970). Some studies using cutaneous stimuli have measured changes in performance as a function of the amount of temporal separation between patterns and have produced results that are in some instances both qualitatively and quantitatively similar to those produced by studies using visual stimuli. These include studies of apparent motion on the skin (Sherrick, 1968a, 1968b; Sherrick & Rogers, 1966), saltatory conduction (Geldard, 1975; Geldard & Sherrick, 1972), temporal integration (Craig, 1982a), metacontrast (Weisenberger & Craig, 1982), and temporal masking of patterns (Craig, 1978, 1980, 1982b).

An important question that has emerged in examining at least some of these changes in sequential interaction is how best to characterize these changes: Are they dependent upon the stimulus onset asynchrony (SOA), the interstimulus interval (ISI), amount of temporal overlap, or perhaps some other measure of temporal interaction? The answer to this general question has had major consequences for modeling the processing of visual patterns (e.g., Breitmeyer

& Ganz, 1976; Felsten & Wasserman, 1980; Massaro, 1975; Turvey, 1973).

In a recent study of visual patterns, Di Lollo (1980) found that the amount of temporal integration between two patterns was severely reduced if the duration of the first pattern was greater than about 100 msec. Additional results showed that the amount of forward masking (when the masker precedes the target) declined considerably as the duration of the masker was increased. These results suggested that iconic persistence was an inadequate explanation for the results and, more importantly for the present study, that SOA rather than ISI was the critical factor in these measures of temporal integration.

Recent work with vibrotactile patterns has also suggested the importance of SOA rather than ISI in measures of temporal integration. In one set of measurements, letters were divided in half, and the time between the presentation of the two halves was varied. As the time was increased, subjects had greater difficulty recognizing the letters. With several different durations tested, it was found that the decline in recognition appeared to be more directly related to the time between the onsets of the two patterns, SOA, than it was to ISI (Craig, 1982a).

A second measure of temporal integration took advantage of an earlier observation that a pattern masker produces more interference in letter recognition than does an energy masker (Craig, 1982b). A pattern masker is created by turning on randomly selected elements of letters to produce a letter-like pattern. An energy masker is created by turning on all the elements in the same area of the array as that occupied by the target letter. Figure 1 shows a representation of these patterns. We presented a target pattern immediately followed by an energy masker,

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Figure 1. A representation of a target letter, an energy masker, and a pattern masker and its complement. The time between the onset of the pattern masker and its complement could be varied (Craig, 1982a).

a backward masking paradigm, and then measured the increase in the amount of masking as we changed the energy masker into two pattern maskers. This was accomplished by gradually increasing the temporal interval between the pattern masker and its complement. As the temporal interval increased, the pattern masker "emerged," and the result was more interference in letter recognition. With the two durations of maskers tested, 13 and 26 msec, it was found that a single function could be fitted to the data if the results were plotted as a function of SOA (Craig, 1982a).

In addition to these measurements of temporal integration, studies of tactile apparent motion have demonstrated the importance of the time between onsets (Sherrick, 1968b; Sherrick & Rogers, 1966). Using pairs of stimuli with different durations, the critical variable in determining the emergence of good apparent motion was SOA.

These measures of tactile perception suggest that, in terms of interaction between two stimuli on the skin, the appropriate temporal dimension is SOA, and based on those measures involving pattern recog-

nition, there is the further suggestion that pattern onset is important for the generation of spatial contours. This paper will deal with the importance of onset in determining temporal interaction between successively presented vibrotactile patterns in a discrimination paradigm (Experiment 1) and in a masking paradigm (Experiment 2). This paper will also concern itself with discrimination performance when patterns are delivered to more than one site (Experiment 3) and examine the role masking plays in discrimination.

EXPERIMENT 1

Several studies have examined perception of tactile spatial patterns using a discrimination task (Geldard & Sherrick, 1965, Note 1; Gilson, 1968). These studies have generally not manipulated the time between stimuli and therefore do not provide evidence on the role of temporal separation. Although not concerned directly with the role of SOA and ISI, one of these studies, involving patterns generated by stimulating different fingertips, found no difference in discrimination when performance was measured with 300-msec SOAs as compared with 1,000-msec SOAs (Geldard & Sherrick, Note 1).

In Experiment 1, subjects were required to discriminate pairs of patterns presented to their fingertips. To assess the role of SOA, the temporal interval between the patterns was varied, as was the duration of the patterns. Given current views of perceptual processing, we expected that subjects would store a copy of the first pattern presented, that the image of this pattern would begin to fade, either immediately after the offset of the pattern or immediately after onset of the pattern, and that subjects would compare the second pattern to this more or less imperfect copy. Thus, one might expect that discrimination performance would decline as the time between patterns increased. On the other hand, previous measures had shown that two patterns presented in temporal proximity may be integrated and form a single pattern (Craig, 1982a), making discrimination difficult. Also, measures of temporal masking, which are also thought to be dependent in part upon integration, show that performance in identifying target patterns improves as the time between target and mask increases. These considerations lead to the opposite prediction, that discrimination performance would improve with increasing temporal separation.

Method

Subjects. The subjects were college students who were paid employees of the laboratory. They had passed an initial screening test and received several days of testing without feedback prior to formal data collection. Three women and one man served as subjects.

Apparatus. The apparatus consisted of a tactile display similar to that used in the Optacon, a reading aid for the blind, interfaced

with a PDP-11/34 computer. The display is composed of 144 elements, which can be made to vibrate at 230 Hz. The elements are arranged in a rectangular matrix, 6 columns $\times$ 24 rows, measuring 1.1 $\times$ 2.7 cm. The array fits against the distal portion of the subject's fingerpad. A more complete description of the apparatus may be found in Craig (1980).

Stimuli. The stimuli were 10 patterns that previous measurements had determined were relatively easy to identify. Figure 2 shows representations of the patterns. When presented singly, the subjects were able to identify the patterns with better than 95% accuracy. The reason for using these easily identified patterns was that some preliminary work with more difficult patterns (uppercase letters) had produced relatively poor discrimination performance.

Procedure. The subject was seated with the left index finger resting on the tactile display. The subject wore earphones through which low-pass-filtered noise was presented to reduce auditory cues produced by the tactile array. To begin a trial, the subject pressed a key and received a tactile cue stimulus (the topmost left and right pins were turned on for 26 msec, a cue that also served to keep the subject's finger in the correct position on the display) followed 1 sec later by the first of the pair of stimuli separated by some temporal interval. On half the trials, the two patterns were the same, and on half, they were different; the subject was required to indicate whether the two patterns felt the same or different. The subject responded by pressing either "S" or "D" on the keyboard. Trial-by-trial feedback was provided by means of a CRT display in front of the subject. When the subject was correct, the word "correct" appeared; when the subject was incorrect, an "S" or a "D" appeared indicating whether the pair had been the same or different.

Two conditions were examined. In one condition, each member of the pair of patterns was presented for 4 msec. In a second condition, each was presented for 52 msec. The same series of SOAs was tested in both conditions: 9, 17, 26, 56, 100, and 300 msec. From these SOAs and pattern durations, one can calculate the corresponding ISIs. With the 4-msec patterns, these SOAs produced ISIs of 5, 13, 22, 52, 96, and 296 msec. With the 52-msec patterns, these SOAs led to some negative ISIs, that is, the onset of the second pattern occurring before the offset of the first pattern. The ISIs were -43, -35, -26, 4, 48, and 248 msec. Prior to the collection of the discrimination data, the 52-msec patterns were adjusted to be equal, in intensity, to the 4-msec patterns. This required setting the tactile array at a higher voltage level when the 4-msec patterns were presented than when the 52-msec patterns were presented.

Figure 2. A representation of the 10 patterns used in Experiments 1 and 2.

All SOAs were tested within a 40-trial block of trials, that is, the sessions were not blocked according to SOA. A testing session consisted of nine blocks of trials during which each SOA was presented for 60 trials. The subjects were tested for 2 consecutive days in the 4-msec condition, alternating with 2 days of testing in the 52-msec condition.

Results and Discussion

Each of the four subjects was tested for 240 trials at each of the six SOAs. The subjects showed a similar pattern of responding as a function of SOA so their data were combined. The standard errors of the means on the obtained "same" and the obtained "different" responses were approximately 3%, with one condition reaching 5%.

The subjects showed a large response bias in that they responded "same" more often than they did "different," a bias that was particularly evident at the briefer SOAs. To avoid some of the problems in comparing results across SOAs when response bias was changing, the data were analyzed in terms of signal detection theory measures. Specifically, trials on which subjects responded "different" when the patterns were different were considered "hits," and trials on which subjects responded "different" when the patterns were the same were considered "false alarms." Using the hit and false-alarm rates thus generated, d' was computed for each SOA (Swets, 1964). From each d' , a $P(C)$ max was computed, which is the proportion of correct responses the subject would have achieved had the subject shown no response bias (McFadden, 1970). It is this value that is plotted in Figure 3 as a function of SOA. The figure shows the best-fitting straight line with a slope of 12.7 and a Pearson r of .96.

The main question Experiment 1 was meant to answer was whether SOA or ISI or some other measure best characterizes any changes that might be seen in discrimination performance. The fact that a single function can be fitted (Figure 3) to the two different duration conditions and account for 92% of the variance ($r^2 = .96^2 = .92$) suggests SOA is a good choice. To see how well ISI might account for the changes, the data from Figure 3 were replotted in Figure 4. There is clear separation between the two conditions, and a single function fitted to the data plotted in this way accounts for 76% of the variance. Another measure of temporal separation, the amount of temporal overlap, likewise does a poorer job than SOA in accounting for the changes in performance.

The data show that discrimination performance does, as predicted, change as a function of the temporal separation between the two patterns. The fact that performance improves as the time between the two patterns increases might be considered surprising, particularly when the sequence of patterns the subject was receiving is considered. For example, with the 52-msec patterns at the briefer SOAs, the subject was presented either a single pattern contin-

Figure 3. Percent correct responses, $P(C)$ max, in a discrimination task as a function of SOA. Both patterns presented to the index finger. Patterns were presented for either 4 or 52 msec. A line of best fit has been drawn through the data points.

uing on for some period of time (a "same" trial) or two patterns coming on sequentially and continuing together for some period of time before then going off sequentially (a "different" trial). Why should discrimination be so difficult at the briefer SOAs and improve with longer SOAs?

The fact that recognition performance is good with these patterns and discrimination is at first poor but improves with temporal separation suggests that masking may be responsible for the discrimination functions. The time course for the improvement of discrimination is consistent with previous measurements of temporal masking functions with vibrotactile patterns (Craig, 1976, 1978, 1980), and suggests that had the task in this experiment been changed slightly to make it a study of masking, similar results would have been obtained. Experiment 2 deals directly with the question of SOA and temporal masking functions, and Experiment 3 deals with the possible role of masking in pattern discrimination.

EXPERIMENT 2

Experiment 2 measured interaction between two sequentially presented patterns in a masking paradigm. Both forward and backward masking were examined, and, following the logic of Experiment 1, several durations of patterns were tested to separate the roles of SOA and ISI. In the forward-masking condition, the target patterns were presented for the same duration (26 msec), whereas the forward maskers were presented for either 9 or 52 msec. Thus, for an SOA of 56 msec, the ISIs with the 9- and 52-msec

maskers would be 47 and 4 msec. In the backward-masking condition, the maskers were presented for the same duration (26 msec) and the targets for either 9 or 52 msec, again permitting a separation of ISI from SOA. The results from Experiment 1 and the attempt to use masking to explain the discrimination functions also imply that measures of temporal masking would show SOA to predict performance better than other indices of temporal separation.

Method

Subjects. The subjects were selected as in Experiment 1. Two women and two men were tested in the forward-masking condition, and three women and one man were tested in the backward-masking condition. Two subjects served in both conditions. None of the subjects tested in Experiment 2 had been tested in Experiment 1.

Stimuli. The target patterns were the 26 uppercase letters of the alphabet. To avoid possible ceiling effects, letters were used as targets, rather than the 10 patterns from Experiment 1. Previous measures had determined that letters were more difficult to identify than the 10 patterns. The letters were generated on the top 18 rows and, with the exception of letters I and J, all six columns of the display. The masker was generated by turning on randomly selected segments of letters and generating what has been termed a "pattern masker." An example of one of the pattern maskers is shown in Figure 1. These pattern maskers share features with letters and generally produce more interference in letter recognition than does an energy masker (Craig, 1982b). There were 26 different pattern maskers.

Procedure. The apparatus used in Experiment 1 was used in Experiment 2. Masking was determined by measuring the percent correct recognition of the target letters in the absence of and in the presence of a pattern masker. In the backward-masking condition, the masker was always presented for 26 msec, whereas the target was presented for either 9 or 52 msec. In this condition, the subjects matched the intensity of a 52-msec target to that of a 9-msec target. The targets were matched in order to produce equal levels of performance in the absence of masking stimuli. Using the matching settings, preliminary measurements revealed an inequality in performance in the absence of a masker. The intensity of the 52-msec target was raised slightly, and the 9-msec target was lowered slightly, an adjustment that resulted in very similar levels of performance in the absence of a masker. Additional measurements would have been required to see if the original intensity match was slightly in error or if patterns unequal in intensity actually yield equal levels of performance. Other results suggest that the former is likely to have been the case (Craig, 1980).

Figure 4. The data from Figure 3 replotted as a function of ISI.

With the 9-msec targets, five SOAs were tested, 13, 26, 56, 104, and 300 msec. The corresponding ISIs were 4, 17, 47, 95, and 291 msec. With the 52-msec targets, the five SOAs tested were 56, 69, 104, 147, and 347 msec, and the corresponding ISIs were 4, 17, 52, 95, and 295 msec.

The trials were presented in 30-trial blocks with a different SOA tested in each block. Performance was also measured in the absence of any masking stimulus for both the 9- and 52-msec targets. During the first half of the session, one of the two masking stimulus durations would be used, with the second half of the session devoted to the other duration. The order of testing of the masker durations was alternated daily.

In the forward-masking conditions, the subjects were presented a masker and then, after some temporal interval, the target letter. The target was always presented for 26 msec. The maskers were presented for either 9 or 52 msec. Prior to the collection of the masking data, the subjects matched the intensity of one of the 52-msec masking patterns to the intensity of the same pattern presented for 9 msec, and these intensity values were maintained throughout the experiment. Five SOAs were tested with the 9-msec masker, 13, 29, 56, 150, and 500 msec (corresponding to ISIs of 4, 20, 47, 141, and 491 msec), and five SOAs were tested with the 52-msec masker, 56, 72, 130, 250, and 500 msec (corresponding to ISIs of 4, 20, 78, 198, and 448 msec). The targets and maskers did not overlap one another temporally. There was also a single-letter condition in which no masking stimulus was presented. Trials were presented in 30-trial blocks with a different SOA tested in each block. The 11 blocks, five SOAs with each of the two maskers plus a single-letter condition, were presented in random order during a single testing session. Trial-by-trial feedback was provided in both the forward- and backward-masking conditions.

Results and Discussion

Recognition performance for the 9- and 52-msec patterns in the absence of masking stimuli was very similar, 64% and 66% correct and, as expected, poorer than that seen with the 10 patterns from Experiment 1. The amount of masking was calculated by subtracting the percent correct target recognition in the presence of the masking stimulus from the percent correct target recognition with no masking stimulus present. The standard errors of the means for both the forward and backward masking conditions were approximately 2%. The amount of masking in the backward-masking condition plotted as a function of SOA is shown in Figure 5. Each point represents the mean of 1,200 trials, 300 from each of four subjects. A line of best fit has been drawn through the data points with a slope of -37.5 and an $r = -.98$. Replotting the data in terms of ISI again shows that the functions separate when presented in this way. Consistent with the apparent difference between the two functions shown in Figure 6 is the fact that the r value for a line of best fit for these data is lower, $-.85$, than it is for the data plotted as a function of SOA.

A similar picture emerges from the forward-masking conditions, as shown in Figures 7 and 8. Each point represents 300 trials from each of four subjects. In the absence of any masking patterns, recognition performance for these 26-msec target patterns was 69% correct. The function drawn through the forward-masking data in Figure 7 has a slope, -21.6 , shallower than that seen with a backward masker and an r value

Figure 5. Amount of masking (decline in percentage correct from condition in which no masking stimulus was presented) as a function of the time between the onset of the target and the onset of a backward masker. Targets of two different durations, 9 and 52 msec, were presented. The line of best fit has been drawn through the data points.

of $-.98$. Plotting the results as a function of ISI again shows the separation of the two functions and, for a line of best fit, a reduced r value of $-.90$.

Comparing the temporal course of the backward- and forward-masking functions with the discrimination function (Figure 3) suggests that the improvement in discrimination reflects a recovery from masking. Consistent with that assertion is the fact that changes in both discrimination and masking are directly related to SOA rather than to ISI. The extent to which masking can predict discrimination performance in other situations and the implications that discrimination is dependent upon recognition will be considered in Experiment 3.

The role that onset apparently plays in a masking paradigm may also reflect on a distinction referred to earlier, the difference between energy and pattern

Figure 6. Data from Figure 5 replotted as a function of ISI.

Figure 7. Amount of masking (decline in percentage correct from condition in which no masking stimulus was presented) as a function of the time between the onset of a forward masker and the onset of the target. Maskers of two different durations, 9 and 52 msec, were presented. The line of best fit has been drawn through the data points.

Figure 8. Data from Figure 7 replotted as a function of ISI.

masking. It has been suggested that, when a masker and target patterns are presented in close temporal proximity, perception of the target is interfered with both because the signal-to-noise ratio is reduced by the energy component of the masker and because the features of the target are distorted in some way by the features in the masker. The present study used pattern maskers exclusively, maskers that, while they are thought to be effective primarily because they alter the features of the target, are thought to affect the signal-to-noise ratio as well. It might be expected that the energy component of the masker would be more sensitive to changes in ISI (or perhaps the time between the middle of the target and the middle of the masker) rather than to SOA. Future studies might include using energy maskers to see if this alters the role of SOA in temporal masking functions.

The present masking results also affect one of the conclusions of an earlier study on pattern and energy maskers (Craig, 1982b). In the earlier study, the intensity of brief maskers was increased by lengthening their duration. With backward maskers, changing

duration did not affect SOA—both SOA and ISI remained constant—but with forward maskers, as duration increased, SOA increased. One of the conclusions of the earlier study was that, unlike the results from studies of visual masking, increasing masker intensity has a greater effect on backward masking than on forward masking. What the present results suggest is that increasing the SOA as the duration of the forward masker was increased tended to reduce the amount of masking. Over the range of masker durations tested in the earlier study, 13 to 52 msec, and the corresponding range of SOAs, 17 to 56 msec, one could expect at least a 10% decline in performance (Figure 7), more than enough to offset the relative change in forward and backward masking produced by increasing the duration of the maskers, about 7%, and thus producing results more in line with visual studies.

When the targets and maskers are equated for intensity, the amplitude of vibration at the onset of the longer patterns is less than the amplitude at the onset of the briefer patterns; yet, the amount of masking is the same. With the apparent importance of SOA, it may seem to be a paradox that the amplitude of vibration at the onset of a pattern is not critical, as long as the overall intensity of the two patterns is equal. The result may not be paradoxical, in light of the fact that the duration of these patterns, less than approximately 50 msec, is within the limits of temporal integration for vibrotactile patterns (Craig, 1982a), and that the distribution of energy across temporal intervals as brief as these may not be critical. According to this view, the onset of the pattern is a sharp discontinuity to which the rest of the pattern is somehow "funneled," in the manner that von Békésy has hypothesized (von Békésy, 1960).

EXPERIMENT 3

The results from Experiments 1 and 2 suggested that masking might account for the obtained functions. At brief temporal separations, masking between two patterns would be considerable, declining as the separation increases. If masking were responsible for the results, then testing under conditions that minimize masking should improve discrimination performance and change the form of the function relating discrimination to temporal separation, perhaps seeing a decline in performance with SOA. Experiment 3 measured discrimination performance with one of the pair of patterns presented to the index finger and the other to the middle finger, a separation that, based on previous measures of detection masking (Sherrick, 1964), would be expected to reduce the amount of masking between the two patterns.

Method

Subjects. The same subjects tested in Experiment 1 were tested in Experiment 3.

Procedure. Prior to the measurements of discrimination, it was necessary to measure the amount of masking at a single site and between two sites to be certain that masking between two sites of stimulation was less than masking at a single site. The target and masking patterns were selected at random from among the 10 patterns used in Experiment 1. The target patterns were presented for 26 msec to the subject's left index fingertip. The masking pattern was presented for 26 msec to either the index fingertip, using the same tactile array on which the targets were presented, or to the left, middle fingertip, using a second tactile array. In the separate-site condition, four SOAs were tested. The onset of the masker preceded the onset of the target by 56 msec, was simultaneous with it, or followed it by either 56 or 104 msec. In the same site condition, three SOAs were tested. The onset of the masker either preceded the target's onset by 56 msec or followed it by 56 or 104 msec.

Trials were grouped in blocks of 40, with each block testing a particular SOA, including one block per session in which no masker was used. A daily testing session consisted of eight 40-trial blocks, with the conditions presented in random order. Trial-by-trial feedback was provided.

For the discrimination measurements, the only difference between the procedure used in Experiment 1 and the procedure used in Experiment 3 was the presentation of one of the two patterns to the middle fingertip. The first pattern was always presented to the middle finger, followed by the second pattern to the index fingertip. The same pattern durations, 4 and 52 msec, and the same SOAs were tested.

Results and Discussion

The masking data are presented in Figure 9. Each point represents the mean of 1,120 trials, 280 trials

Figure 9. Amount of masking (decline in percentage correct when compared with a condition in which no masking stimulus was presented) as a function of the SOA between the target and the masker. In the same-site condition, both the target and masker were presented to the index finger. In the separate-site condition, the masker was presented to the middle finger, and the target to the index finger.

from each of four subjects. The standard errors of the means for these data ranged from 1% to 3%. Performance in the absence of a masking stimulus was 98% correct, with the amount of masking indicated by the decline in performance from this level. As a number of previous studies have shown, there is more backward than forward masking (Craig, 1976, 1978, 1980, 1982b). Also, there does appear to be slight interference in recognizing a pattern presented to the index finger in the presence of a second pattern presented to the middle finger. Some preliminary measurements of the amount of masking resulting from presentation of the target to the middle finger and the masker to the index finger showed more masking than the reverse situation; however, separate-site masking was still considerably less than same-site masking. Finding more same-site than separate-site masking is not surprising in light of previous detection-masking results (Sherrick, 1964), and leads to the prediction that if masking were responsible for the relatively poor performance in Experiment 1 and for the improvement in discrimination with SOA, then overall the two-finger discrimination performance should be considerably better and the shape of the function relating SOA to performance might be altered from that of same site performance.

The discrimination data are shown in Figures 10 and 11. The standard errors of the means averaged less than 3%, with the highest value being 4%. The obtained data were transformed as in Experiment 1, calculating hit and false-alarm rates and d' , and from d' computing $P(C)$ max, which is plotted as a function of SOA. The results are complicated in that performance is not a monotonic function of SOA; however, when the data are plotted as a function of SOA, the 4- and 52-msec functions are similar. Both sets of data show a slight decline in performance, about 6% to 7%, from the briefest SOAs out to the middle SOA values. This slight decline in performance may be more significant when the results are compared with those in Figure 3, where, over the same range of SOAs, performance improves by 7% or 8%. Thus, the total change in performance at the briefer SOAs produced by moving to a separate site is more than may at first be apparent. The 52-msec data do show a definite minimum at an SOA of 56 msec, whereas the 4-msec data show a broader trough in performance, extending from 26 to 100 msec.

Presenting the data as in Figure 11 shows how the two functions separate when plotted as a function of ISI. Thus, one conclusion from Experiment 3 is that interaction between successively presented patterns appears to be related to the SOA, even when the patterns are presented to separate sites on the skin.

Experiment 3 was also undertaken to clarify why performance in discriminating between these patterns is poor and what role masking plays. A comparison of Figures 10 and 3 shows that for most SOAs, per-

Figure 10. Percent correct responses, $P(C)$ max, in a discrimination task, as a function of SOA. One member of the pair of patterns was presented to the middle finger, and the other to the index finger. Patterns were presented for either 4 or 52 msec.

formance was poorer in the separate-site condition than in the same-site condition. It is only at the briefer SOAs that performance is better in the separate-site condition. It is tempting to attribute the small advantage in the separate-site condition at these brief SOAs to the fact that the two patterns mask each other very little. Yet, even if masking were contributing to the differences between the two conditions at briefer SOAs, there are problems with interpreting all the results, particularly the separate-site results, in terms of masking. The large difference in the amount of masking between the same- and separate-site conditions would lead one to predict a large advantage in discrimination for the separate-site condition, one that is simply not seen.

Perhaps it is not surprising that discrimination performance is poor in the separate-site condition, given that subjects may have difficulties in attending to two sites at the same, or very nearly the same, time. If the skin is subject to some attentional limitation when presented complex patterns, then the dividing or the switching of attention required in the separate-site condition would be expected to reduce performance. At longer SOAs, the subject could presumably switch attention from the first site to the second site and performance should improve, as indeed it does beyond 100 msec.

Several studies directly concerned with attention and vibrotactile stimuli have measured the detection of weak vibrotactile stimuli presented to one site, two sites, or three sites and have produced conflicting results. One study (Franzen, Markowitz, & Swets, 1970) found no evidence that subjects could attend to more than one channel of stimulation at a time, whereas another study (Craig, 1968) found that subjects could detect two stimuli presented simultaneously to two different fingers more readily than they

could detect a single stimulus. A third study (Shiffrin, Craig, & Cohen, 1973) found evidence supporting this latter result and proposed an unlimited-capacity, nonattention model for detection of weak vibrotactile stimuli. These results and models were concerned with detection of vibratory stimuli but did not deal directly with how patterned stimuli might be combined from several loci.

In several studies, the subjects' task was to discriminate pairs of patterns that stimulated a number of sites on the skin simultaneously (Geldard & Sherrick, 1965; Gilson, 1968). The fact that subjects were able to discriminate between such patterns shows that they used the information resulting from stimulation of spatially distinct loci. However, using two Optacon displays, Hill (1974) found no improvement in reading when the material was scanned across two fingers rather than a single finger, even though the two-finger display provided a wider field of view. Although such a result might suggest that subjects have difficulty in combining information from spatial patterns presented to two fingers, Hill also found no improvement when the display was widened to permit two letters to be presented to a single finger. It might be expected, with regard to this latter result, that subjects could combine patterns presented to a single finger. Their failure to do so suggests that there may have been considerable interference due to masking or that reading, because it involves considerably more than simply recognizing patterns, may not be a good measure of the skin's ability to combine spatial patterns. A simpler task, such as discrimination, may provide a more accurate indication of this ability. Before the possible role of attention and processes related to masking can be considered in greater detail, two additional items need to be discussed. One is the similarity of the separate-site function to earlier studies, and the second is a closer analysis of the subjects' responses in Experiments 1 and 3.

The shape of the function relating performance to SOA is reminiscent of the functions obtained in an earlier study in which recognition performance in a masking paradigm was measured as a function of SOA, when the target and masking stimuli were presented to different areas on the same fingertip

Figure 11. The data from Figure 10 replotted as a function of ISI.

(Weisenberger & Craig, 1982). In this metacontrast-like paradigm, the masking stimuli flanked the target stimuli and produced maximum interference, not when the target and masker were presented simultaneously, but when the onset of the masker followed the onset of the target by 25 to 50 msec. The change, as a function of SOA, in the amount of separate-site masking shown in Figure 9 is too small to assert that a metacontrast function is responsible for the separate-site discrimination function. It is possible that the masking function generated with a target on the middle finger and a masker on the index finger might show a greater change in masking as a function of SOA; however, as already noted, the overall amount of masking in the separate-site condition is too small to make a direct appeal to masking *per se* convincing. Still, the similarity of metacontrast and discrimination functions suggests that they might be related to mechanisms such as integration and interruption, which have been used to explain these functions, but that the ways in which these mechanisms operate may differ in the separate-site and the same-site conditions.

Relevant to the question of integration of the two patterns and to the conclusion that masking might help explain the same-site results but not the separate-site results is a closer analysis of the pattern of subjects' responses in both Experiment 1 and Experiment 3. As noted before, there is a considerable response bias in Experiment 1, and the bias changed as a function of SOA. For this change to be seen, the subjects' responses from the 4- and 52-msec conditions in Experiment 1 were combined and are presented in Figure 12, in which the percentage of correct "same" responses and correct "different" responses as well as the percentage of the total responses that were "same" and that were "different" are plotted as a function of SOA.

The large bias towards responding "same" at briefer SOAs shown in Figure 12 may reflect temporal integration of the two patterns. That is, the two patterns separated by a brief temporal interval are integrated into a single pattern that the subject reports as "same." Previous results have shown that temporal integration may be found over intervals of up to approximately 50 msec (Craig, 1982a), and, as noted before, temporal integration is dependent upon the SOA of the patterns being integrated. As the temporal separation increases, the subject can differentiate the two patterns more readily, and at longer SOAs, correct responses on both "same" and "different" trials may rise as the subject can perceive both members of the pair.

The same sort of bias towards responding "same" exists with the separate-site data, as shown in Figure 13. Figure 13 displays the data for the separate-site functions in the same way as Figure 12 displays the data for the same-site functions. The bias at the briefer durations is as large as that seen with the same-

Figure 12. Results from Experiment 1 showing the percent correct achieved on "same" trials and on "different" trials as well as the total percentage of the responses that were "same" and that were "different" as a function of SOA. The data from the 4- and 52-msec conditions have been combined.

site data, a result that again poses a problem for a masking interpretation of the separate-site condition. It has been suggested that temporal masking functions for vibrotactile patterns result from two processes, temporal integration and interruption (Craig, 1980, 1982a, 1982b). If temporal integration is a major component of temporal-masking functions, then one might expect to see little or no integration under conditions in which there was little masking (Kirman, 1973). However, the separate-site data suggest the possibility that integration and masking need not be as closely related as originally hypothesized. At brief SOAs, there is a large bias towards responding "same," which, following the above reasoning for the same-site data, suggests considerable temporal integration, but under conditions in which little masking is seen (Figure 9).

In attempting to formulate a general framework to account for the same- and separate-site discrimination performance, it is necessary to accommodate the observations on integration, the masking results (Figure 9) and metacontrast effects, and possible attentional effects. It may be that the processes of integration and interruption operate in somewhat different ways, depending upon whether two patterns are delivered to the same (or nearly the same) site or to different sites. In the same-site masking paradigm, integration and interruption may be unavoidable because the spatial-temporal proximity of the two patterns results in the two affecting one another. In the dual-site masking paradigm, the subject may be able to attend to one finger and have the processing of the pattern at that finger only slightly perturbed by

Figure 13. Results from the discrimination measurements in Experiment 3 plotted as in Figure 12.

a pattern presented to the adjacent finger. When required to, as they are in the discrimination task, subjects can attend to both fingers with some loss of information about the pattern presented to each finger. At briefer times, the subjects may be able to form a single impression, that is, they can integrate the patterns from the two fingers. At slightly longer SOAs, those that exceed the tactile temporal integration time (Craig, 1982a), a single impression of the two patterns can no longer be formed and attention must be switched from one finger to the other. In that sense, the subjects' processing of the first pattern is interrupted when attention is switched to the second pattern. As SOA increases, additional time is provided to switch attention, and performance improves. More work will clearly be necessary to determine how useful this distinction is between "automatic" processing of two patterns at a single site and the perception of patterns presented to two sites, which is related much more to attentional processes.

There is an implication in this framework that discrimination performance is based on recognition; that is, if conditions are such that subjects can recognize the two patterns, then they can discriminate between them. Can recognition performance be used to predict discrimination? The masking results shown in Figure 9, which used the 10 patterns from the discrimination task, provide an estimate of recognition performance when two patterns are presented in close temporal proximity. From the same-site masking data, one can calculate that pattern recognition performance at -54 msec is 75.5% correct (98% correct in the absence of a masker minus the amount of masking shown, 22.5%) and at $+54$ msec is 42% (98% minus 56%). Based on these recognition estimates,

discrimination performance at an SOA of 54 msec should be 66% correct by the following logic: Subjects can recognize both patterns on 32% of the trials ($.755 \times .42$), and thus could discriminate between the two patterns. On the remaining trials, $1 - .32$, or $.68$, subjects should be correct half the time by chance, $.68/2$, or $.34$. Total discrimination performance should be $.32$ plus $.34$, or 66% correct, assuming no deficit due to processing two patterns in a brief period of time, that is, having to give two different responses to the two patterns. Measured discrimination performance was better than predicted by the recognition data, 76% and 78% correct (Figure 3), suggesting that additional factors might be operating to raise discrimination performance. At briefer SOAs, such phenomena as apparent motion and saltatory conduction might provide cues as to whether two patterns occupied the same location or not and thus whether the two were the same or different.

At longer SOAs such phenomena break down and discrimination performance could be closer to that predicted by recognition. Unfortunately, there are not comparable masking data on 10 patterns used in the discrimination task at long SOAs. However, if one uses the masking data obtained with letters, Figures 5 and 7, the estimate of the masking at an SOA of 300 msec would be approximately 10%, averaging across the forward- and backward-masking conditions. Using this estimate of masking, discrimination performance at an SOA of 300 msec would be about 89% correct, $(.98 - .10)(.98 - .10) + [1 - (.98 - .10)(.98 - .10)]/2$. This predicted value is close to the obtained values, .85 and .87 from Figure 3, and suggests that for longer SOAs subjects are not picking up additional cues in the discrimination task to improve their performance.

Finally, with the separate-site condition, the recognition data are likely to overestimate discrimination performance. With the small amount of masking between separate sites, Figure 9, discrimination should be considerably better than we found, suggesting, as noted before, that limitations produced by such factors as attention are contributing to the lowered performance.

GENERAL DISCUSSION

One of the major questions this study investigated was: What is the appropriate temporal dimension for determining the interaction between sequential patterns? The results have been discussed primarily in terms of distinguishing between SOA and ISI; however, the results can also be used to examine other measures of temporal separation. Specifically, could other measures, such as amount of temporal overlap, the time between offsets of two patterns, or the time between the middle of the first pattern to the middle of the second, do as well as SOA in accounting for

the results? The answer appears to be no. The discrimination results show that pattern overlap fails to predict the changes in performance. In Experiment 1, for example, the shortest three SOAs for the 52-msec patterns produced temporal overlap, whereas the same SOAs for the 4-msec patterns did not, yet the two sets of data showed the same changes in performance.

To separate SOA from such measures as time between offsets or the time from the middle of the first to the middle of the second pattern requires that the two patterns whose interaction is being studied be of unequal duration. The conditions of Experiment 2 satisfy this requirement. For example, in the backward-masking condition with an SOA of 56 msec, which produced about the same amount of masking for both the 9- and 52-msec targets, the temporal separation measured from offset of target to offset of masker was 73 msec for the 9-msec target and 30 msec for the 52-msec target. If offset-to-offset were the critical interval, unequal amounts of masking would be expected under those conditions. A similar picture emerges if one thought that the cutaneous system was averaging across the presentation time for a masker and for a target and thus the temporal center of the pattern should be used to measure interactions between patterns. Using the backward-masking conditions and a 56-msec SOA, the center-to-center times were 64 and 91 msec, increasing the separation between the 9- and 52-msec functions shown in Figure 5. Calculating other temporal separations for both the backward- and forward-masking conditions leads to the same conclusion; that is, SOA is the best way to characterize the changes in performance.

The fact that SOA is apparently the critical variable in temporal masking functions is relevant both to theoretical issues relating to pattern recognition and discrimination and to applied problems such as reading through the skin. When previous studies demonstrated that reasonably good letter recognition was possible with the Optacon at exposure times as brief as 4 msec, it was speculated that reading performance might be improved by presenting letters for very brief times and increasing the amount of "off" time between letters, that is, letting SOA remain constant while ISI is increased, and thereby increase reading comprehension by reducing masking. The present results indicate that even if ISIs were increased, but SOA remained constant, there would be no improvement in reading. Support for this conclusion comes from some measurements of word recognition. Subjects were trained to recognize three-letter words that were generated in 300 msec. In one condition, the exposure time for the letters was fairly brief with relatively long ISIs; in a second condition, the exposure time for each letter was relatively long with relatively brief ISIs. The resulting SOAs were

fairly similar, and word recognition performance was identical in the two conditions (Craig, 1983).

The same conclusion, that is, that the time between onsets is the critical variable, not the "off" time between letters, was reached in a study of visual word reading by Haber and Nathanson (1969). In that study, letters were presented rapidly at the same retinal locus, very much as is the case with the tactile display. The result was that reading was a direct function of SOA; increasing the "off" time had no effect on performance.

The results of these experiments also suggest that the masking produced by presenting patterns in close temporal contiguity can be overcome if the patterns are delivered to separate fingers. Thus, in palpating objects, one should expect that if attention is directed to a single finger, little interference will be produced by stimulation at adjacent fingers; however, the discrimination performance suggests that there may be difficulties in combining the information from separate fingers, at least at brief SOAs. By moving the hand over an object to be identified, a person may be both producing the onsets necessary for clear pattern recognition and keeping those onsets temporally discrete, and thus permitting attention to be shifted from one site to another and the information from the separate fingers to be combined. That this is probably not the whole story is suggested by people's abilities to use Tadoma, a system of speech reception used by some deaf-blind individuals. In using Tadoma, the receiver places his or her hand on the face of the talker, typically with the thumb placed on the lips and the fingers spread fan-wise along the cheek, jaw, and throat. Deaf-blind users of this method can understand speech, and, it is thought, must be combining information from different fingers at fairly high rates (Reed, Durlach, & Braida, 1982; Reed, Durlach, Braida, & Schultz, 1982). This is a situation in which users have little control over the rate of pattern presentation, and the time between onsets of successive patterns is brief. Additional work on multiple sites might well concentrate both on giving subjects much more extensive training on multiple finger tasks and on developing patterns that might be combined across several fingers and that are similar to those encountered naturally in the cutaneous environment.

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