Tactile pattern perception by two fingers: Temporal interference and response competition

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The identification of a spatial pattern (target) presented to one fingerpad may be interfered with by the presentation of a second pattern (nontarget) to either the same fingerpad or a second fingerpad. A portion of the interference appears to be due to masking and a portion to response competition. In the present study, vibrotactile spatial patterns were designed to extend over two fingerpads. Target and nontarget patterns were presented to the same two fingerpads with a temporal separation between the two patterns. The function relating target identification to the temporal separation between the target and nontarget was very similar to the functions obtained with one-finger patterns in temporal masking studies. Subsequent measurements showed that a substantial portion of the interference resulted from response competition. Pattern categorization was better when patterns were presented to two fingers on opposite hands than to two fingers on the same hand; however, there was more interference for patterns presented bilaterally than for patterns presented ipsilaterally. The results supported the conclusion that similar processes are involved in the perception of sequences of spatial patterns whether the patterns are presented to one or to two fingers.

In haptic exploration of objects, the objects are typically larger than the surface area of a single fingerpad. Hence, information is acquired in a serial fashion as the finger is moved over an object. By using two or more fingers or by gripping an object, one can bring a larger surface area into contact with the object. In this situation, information about the object may also be acquired serially or in parallel from several fingerpads. The question of whether or not bringing additional fingers in contact with tactile patterns improves information processing has received a mixed answer. For line drawings of relatively large objects, increasing the tactual field of view from one to two fingers produced virtually no improvement in performance (Loomis, Klatzky, & Lederman, 1991). Similarly in reading with the Optacon, no improvement was found when subjects shifted from using a single finger to using two fingers (Hill, 1974). However, there is some evidence that certain dimensions of tactile stimulation may be processed simultaneously across several fingers, and that other dimensions require serial processing. Lederman, Browse, and Klatzky (1988) presented various types of tactile stimuli to the fingerpads. The

subject's task was to search for the presence (or absence) of certain features. The number of locations (fingerpads) was varied from 1 to 6 in a search paradigm like that of Treisman and Gelade (1980). As the number of sites of stimulation to be monitored increased from 1 to 6, search times for complex stimuli showed large increases, whereas smaller increases were observed with simpler patterns (Lederman et al., 1988). The authors concluded that with more difficult and complex patterns, there was a shift toward serial, self-terminating processing. Using a detection paradigm and surface texture as the stimulus dimension, Sathian and Burton (1991) found that the role of spatially selective attention varied as a function of the nature of the task, but not necessarily the difficulty of the task.

With regard to spatial patterns, it has been observed that dividing a pattern in half and presenting the halves simultaneously to two fingerpads results in a drop in identification performance as compared with presenting the pattern to a single fingerpad. As the temporal separation between the two halves of the patterns increases, identification performance increases as well (Craig, 1982). Poorer performance in such a selective attention task, combining spatial pattern information from two fingerpads, has typically been attributed to a processing limitation, specifically, an inability to spread attention effectively across two spatial locations (Craig, 1983, 1985a).

In other studies, researchers have concluded that subjects have difficulty restricting their attention to a single location. In these studies, tactile spatial patterns were presented to two fingers; subjects were instructed to attend

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to one fingerpad—the designated target site—and to ignore the pattern presented to a second fingerpad—the nontarget site. The results indicated that subjects were often unable to restrict their attention to a single location and erred by responding with the nontarget pattern. The results from these studies of selective attention indicate that subjects automatically process spatial information from all fingerpads on the same hand (Evans & Craig, 1991, 1992; Evans, Craig, & Rinker, 1992; Rinker & Craig, 1994) and in some cases from the opposite hand as well (Evans et al., 1992).

It might seem to be a contradiction that subjects in one situation are unable to attend efficiently to two fingerpads and in another situation are unable to restrict their attention to a single fingerpad. The results are less contradictory than they might at first appear to be. In the divided-attention task, subjects' performance levels are better than chance, indicating that they are able to process some information from both fingers, although not as efficiently as from a single finger. Similarly, when asked to restrict their attention, subjects are not at chance levels in identifying the pattern presented to the target site. In terms of a visual analogy, attention to tactile spatial patterns appears to operate like a spotlight. Locations in the center of the spotlight are processed more effectively than locations at the edge of the spotlight. The spotlight can be widened to include additional sites but with some loss of processing effectiveness at each site.

Recent studies that have focused on the way in which target patterns are interfered with by the presentation of nontarget patterns have differentiated between what has been referred to as "response competition" and "masking." As the term will be used here, *response competition* refers to interference in the perception of a target pattern that results from subjects responding with a nontarget pattern. The assumption is that both the target and nontarget patterns are processed to the point of evoking a response and that the nontarget response "competes" with the target responses. In *masking*, the interference in the perception of the target is assumed to be the result of a physically different nontarget distorting or altering the representation of the target. The representation of the target pattern may no longer evoke a target ("correct") response. It should be noted that a correct response to a target pattern does not necessarily mean that the representation of the target is unaltered by the nontarget. It does indicate that the representation of the target has not been altered to the point that it is unrecognizable. One could have both response competition and an altered representation of the target, a possibility that will be considered in the discussion of the results of Experiments 2 and 3.

The researchers who have attempted to distinguish between masking and response competition have required subjects to categorize stimuli. For example, in what has been referred to as a "4-to-2 paradigm," as used by Eriksen and Hoffman (1973) with visual stimuli, there are four patterns—such as A, B, C, D—but only two responses—1 and 2. A and B are to be placed in Category 1, and C

and D in Category 2. When a nontarget is presented along with the target, it is selected from one of the four patterns. The random selection of target and nontarget stimuli from the same set of patterns produces three types of trials: stimulus compatible (SC), response compatible (RC), and response incompatible (RI). On SC trials, the target and nontarget patterns are identical. On RC trials, the target and nontarget are physically different but associated with the same (compatible) response. For example, Pattern A might be the target and Pattern B the nontarget. Both are associated with Response 1. On RI trials, the target and nontarget are physically different and associated with different responses. For example, Pattern A might be the target pattern and Pattern C the nontarget pattern. In this paradigm, which is more fully explained in Experiment 2, subjects might be asked to differentiate between the target and nontarget patterns on the basis of a difference between the two patterns due to spatial location (Craig & Evans, 1995; Evans & Craig, 1991, 1992) or due to temporal position when patterns are presented to the same location (Craig, 1995). The RC trials are included to test for the possibility that the nontarget "masks" the target. For example, by presenting Target Pattern A and Nontarget Pattern B, it is generally assumed that the interference seen is due to the physically different nontarget distorting or altering the representation of the target in some way (Craig, 1989; Evans, 1987; Evans & Craig, 1986). Subjects have difficulty identifying the target pattern because it no longer evokes the correct response. In response competition, on the other hand, both the target and nontarget still evoke their respective responses; the subject errs by responding with the nontarget. If masking is affecting target identification, it should be evidenced by lower performance on RC trials, when the subject is presented with two physically different stimuli that signal the same response; however, if response competition is a major source of interference, target identification performance should be affected very little by the presence of a physically different nontarget, as long as the nontarget signals the same response as the target.

The response competition paradigm was used in several studies of selective attention (Evans & Craig, 1991, 1992; Evans et al., 1992). In these studies, a target pattern was presented to one location on the skin (one fingerpad) and a nontarget pattern was presented to a second location (a nearby fingerpad). The subject's task was to identify the target and ignore the nontarget. As noted, the results showed that subjects often erred by reporting the nontarget rather than the target stimulus, and further, that there was little masking between adjacent fingerpads. Subsequently, the same paradigm was used to examine interaction between targets and nontargets presented to the same location. The type of interference that is seen with patterns presented in close temporal proximity to the same location is typically attributed to either forward or backward masking (Craig, 1976, 1985b; Craig & Evans, 1987; Evans, 1987; Evans & Craig, 1986). One of the results of these recent measurements was that nontargets

physically different from the targets but associated with the same response as the target (RC trials) produced some interference. A larger amount of interference was seen on trials in which the nontarget was physically different and associated with a response different from that of the target (RI trials). It appears that even when patterns are presented to the same location, an unexpectedly large proportion of the interference is due to response competition rather than masking (Craig, 1995; Craig & Evans, 1995).

The picture that emerges from these studies is that when pairs of patterns are presented in close temporal proximity to adjacent fingerpads, the identification of one of the members of the pair may be interfered with because of response competition. When pairs are presented to the same site, interference may be due to both masking and to response competition.

Although haptic exploration usually involves multiple fingers and multiple patterns, to our knowledge no previous studies have examined the ability of subjects to identify spatial patterns that extend over two fingerpads, and, specifically, how these patterns are identified in the presence of other temporally contiguous patterns. The main goal of the present study was to see the extent to which identification of spatially extended patterns is similar to the identification of patterns presented to one fingerpad. Although the present study is a logical extension of earlier studies, in which a target pattern is presented to a single fingerpad and a nontarget pattern is presented to either the same or to a different location, there are a number of interactions that might occur when the target and nontarget patterns extend over two fingers. The two halves of the target pattern may interfere with one another, either through response competition or masking or both. Similarly, the two halves of the nontarget pattern may interfere with target identification through response competition and masking.

The present study consisted of three experiments. In Experiment 1, a temporal-interference function was generated for spatial patterns extending over two fingers. In Experiment 2, a response competition paradigm was used to compare pattern identification for spatially extended patterns with patterns presented to a single fingerpad. In Experiment 3, pattern identification in a response competition paradigm was measured for two widely separated locations—fingerpads on opposite hands—and compared with identification for patterns presented to two fingerpads on the same hand.

EXPERIMENT 1

Temporal masking functions for spatial patterns presented to a single location have been obtained in a number of studies. The typical function relating target identification performance and the time between the onsets of the masker and target shows peak interference in target identification when the masker trails the target by 25–50 msec (backward masking). As the temporal separation between the target and backward masker is increased, performance improves until little interference is

seen at separations of 200–300 msec. For forward maskers, interference is seen over longer temporal intervals; in some cases, a masker presented as much as 1,200 msec before the target can produce significant interference (Craig & Evans, 1987). At close temporal separations, the amount of interference increases slightly but remains less than that produced at comparable temporal separations by a backward masker.

We know of no studies that have generated temporal masking functions for target patterns that extend over two fingers. The aim of Experiment 1 was to generate a temporal interference function for target patterns that extend across two fingers. The target patterns were created so that the information from both fingerpads was necessary to correctly identify the target. The nontarget patterns also extended across two fingers: When several fingers are used in haptic exploration, both target and nontarget patterns will extend across the two fingerpads. Also, in the design of cutaneous communication systems, if spatial patterns are presented to two fingers (Hill, 1974), the patterns will at one moment in time be a target and then become a nontarget as the next pattern is presented. The range of temporal separations between the target and nontarget patterns, $\pm 1,000$ msec, was selected so that the results could be compared with those of earlier studies in which patterns were presented to a single fingerpad.

Method

Subjects. All subjects were students at Indiana University who were experienced in identifying tactile patterns. They received an hourly wage for their participation. Six subjects were tested, 4 women and 2 men. All subjects in these experiments were right-handed.

Apparatus. The apparatus consisted of two tactile displays interfaced to a computer. Each tactile display consisted of a 6-row $\times$ 24-column array of pins that could be made to vibrate at 230 pulses per second. Each array measured 1.1×2.7 cm and fit against the distal portion of the subject's fingerpad. A computer controlled the tactile displays and the duration and sequencing of the tactile patterns, as well as a visual monitor that was used to give instructions and feedback to the subjects. It was also used to collect the responses. More details about the apparatus may be found in Craig (1980) and Evans and Craig (1992).

Stimuli. In all three experiments the same six patterns that extended across two fingers were used. Representations of these patterns are shown in Figure 1. As can be seen in Figure 1, the patterns were created out of horizontal and vertical line segments. The patterns were designed so that the spatial information from both fingers (both tactile displays) was required to identify the pattern. We wanted to avoid the situation in which subjects could identify a pattern on the basis of spatial information from a single finger.

Procedure. Subjects were seated with the left hand and arm resting on the table in front of them. The subject's left index fingerpad contacted one tactile array, and the left middle fingerpad contacted the other tactile array. The subjects responded with their right hands, using a keyboard. Each subject was tested individually.

On each trial, a target and a nontarget were selected at random and presented sequentially to the subjects. The random pairing of target and nontarget patterns meant that on approximately one sixth of the trials the target and nontarget were identical and on five sixths of the trials they were different. Random pairing was necessary to ensure that the nontarget pattern provided no information about the identity of the target pattern. Twelve stimulus onset asynchronies (SOAs) were tested: $-1,000$, -500 , -300 , -100 , -52 , -26 , $+26$, $+52$, $+100$,

Figure 1. Representations of the six two-finger patterns.

+300, +500, and +1,000 msec. Negative SOAs refer to conditions in which the nontarget preceded the target. Each session consisted of seven blocks of 50 trials, including one block in which the target was presented by itself. During each block of trials, the same SOA was tested, and subjects were instructed to identify either the first pattern presented (on those blocks in which the nontarget trailed the target, positive SOAs), or the second pattern presented (on those blocks in which the nontarget led the target, negative SOAs). The order of testing each block (that is, each SOA) was determined randomly. Half of the SOAs were selected at random for testing in one session, with the remaining SOAs tested in the following session. Subjects were tested for 12 sessions or 6 sessions for each SOA.

For all experiments, the patterns were presented for 26 msec with the intensity of the vibration on the tactile array set at a comfortable level (36 V), a level that remained the same for all subjects. At the beginning of each block of trials, a message was presented on the CRT telling subjects to identify the first pattern (on blocks of trials in which the target led the nontarget) or the second pattern (on blocks of trials in which the target followed the nontarget). The subject started each trial by pressing a button on the keyboard. The target stimulus was presented 1.25 sec later. Following the presentation of the stimuli, subjects responded and received feedback via the visual display. Subjects were instructed to respond as accurately as possible. A correct response was followed by the word "correct" on the visual display. Subjects were not allowed to respond until both the target and nontarget had been presented. An incorrect response was followed by the number of the pattern that had been presented. Subjects then initiated the next trial by pressing the space bar. Throughout the testing sessions, the subjects wore earplugs and earphones through which white noise was presented to eliminate auditory cues produced by the tactile displays.

Results and Discussion

The results presented in Figure 2 show the percentage correct as a function of SOA for trials on which the non-

target was identical to the target (one sixth of the trials) and trials on which the nontarget was different from the target. The standard errors of the mean ranged from 1% to 10% with an average of 7.2%. The results show when the nontarget is identical to the target, there is little interference; however, when the nontarget differs from the target, there is considerable interference. The amount of interference also depends on the temporal separation of the target and nontarget, with briefer separations leading to greater interference. The large drop in performance with a trailing nontarget at brief SOAs (+25 and +52 msec) is characteristic of temporal interference functions for patterns presented to a single fingerpad (Craig & Evans, 1987). An analysis of variance (ANOVA) supported these observations. There was a significant effect of the type of nontarget [$F(1,5) = 44.26, p < .01$], a significant effect of SOA [$F(11,55) = 10.77, p < .0001$], and a significant interaction between type of nontarget and SOA [$F(11,55) = 9.69, p < .0001$].

A comparison of the function obtained when the target was different from the nontarget with previous functions obtained with patterns presented to a single finger (Craig, 1982; Craig & Evans, 1987) shows some obvious similarities. At brief SOAs a trailing nontarget interferes in target identification more than a leading nontarget; there is more backward than forward masking. There continues to be interference at long SOAs, and this interference is particularly evident with temporally leading nontargets.

To examine more closely the factors that might produce interference, a confusion matrix was generated for

Figure 2. Percent correct pattern identification as a function of the time between the onset of the target and the onset of the nontarget (SOA). Negative SOAs refer to conditions in which the nontarget precedes the target. Positive SOAs refer to conditions in which the nontarget follows the target. One function represents the results in which target and nontarget were the same patterns; the other, the results in which the target and nontarget were different patterns.

the condition in which the target and nontarget were the same. In addition, six other confusion matrices were generated, one for each of the six nontargets. Using these matrices, we could examine how subjects distributed their responses when the nontarget was the same as the target and when the nontarget was Pattern 1, 2, and so on. If a physically different nontarget were altering the representation of the target in such a way that the target no longer evoked a correct response, the number of incorrect responses should increase in the presence of a nontarget pattern such as Pattern 1; however, the distribution of responses should not change; that is, the proportion of responses corresponding to Pattern 1 ought not to increase. The results showed that the percentage of responses corresponding to the nontarget did increase. The increase was significant (chi-square, $p < .0001$) and ranged from 7% to 18% with a mean of 11.6%. This result is very similar to the results that have been obtained when target and nontarget patterns are presented to a single finger (Craig, 1995). For patterns extending across two fingers, it appears that a portion of the interference effect is due to subjects' attempting to respond with the nontarget, possibly because of response competition. For the results shown in Figure 2, when the nontarget was not identical to the target, it was both physically different from the target and associated with a different response. Thus it was not possible to separate the contributions of masking and response competition. In Experiments 2 and 3, we used a response competition paradigm to permit separate examination of these factors.

EXPERIMENT 2

The results of Experiment 1 showed that the temporal course of interference in identifying spatial patterns that extended across two fingers was similar to that seen with one-finger patterns. In Experiment 2, we examined the nature of the interference between target and nontarget patterns when these patterns extended across two fingers. To do this we used a variation of the 4-to-2 paradigm described earlier. Specifically, a 6-to-3 paradigm was used—six patterns to be categorized into three responses. The reason for increasing the number of patterns from four to six and the number of categories from two to three was to permit an analysis of the kind of errors that subjects make. With only two categories, it is difficult to know whether subjects err by choosing the wrong category or simply guess between the two available responses. With three categories, the errors on RI trials (nontarget is associated with a category different from that of the target) can be analyzed to see if subjects are selecting the nontarget category or simply guessing between the two incorrect categories. Two sets of six patterns were tested, a set of two-finger patterns and, for purposes of comparison, a set of one-finger patterns.

These measurements addressed whether response competition, which has been shown to contribute to the interference observed between patterns presented on a single fingerpad, is a major factor in the interference observed for patterns extending across two fingers (Figure 2). Response competition requires that both the target and nontarget be processed to the point of evoking a

response. For this to happen with two-finger patterns implies that the information from both fingers is combined and evokes a response. Evidence for response competition also implies that subjects are unable to prevent themselves from combining the spatial information from the two fingerpads, even for nontarget patterns.

Method

Subjects. Six subjects were tested in Experiment 2, 5 women and 1 man. Three of these subjects also served as subjects in Experiment 1.

Apparatus. The apparatus was the same as that used in Experiment 1.

Procedure. Two sets of patterns were tested, six two-finger patterns and 6 one-finger patterns. The same set of two-finger patterns as that used in Experiment 1 (Figure 1) was used in Experiment 2. Subjects were trained to categorize the six two-finger patterns into three categories: Patterns 2 and 6 were associated with Response 1; Patterns 3 and 4, Response 2; and Patterns 1 and 5, Response 3. Preliminary training with the six two-finger patterns was used to establish a level of identification performance in the absence of nontarget patterns. A set of six alphabetic characters was selected for the one-finger patterns. These letters were selected so that performance levels would be similar to those achieved with the two-finger patterns, at least when presented in the absence of a nontarget (Craig, 1979). The six letters—*B*, *C*, *H*, *O*, *P*, and *R*—were categorized into three responses: *B* and *C* were categorized as Response 1; *H* and *O* as Response 2; and *P* and *R* as Response 3. Subjects also received some training with the one-finger patterns.

The one-finger patterns and two-finger patterns were tested on alternate days. One half of the subjects began testing with one-finger patterns, and the other half of the subjects began testing with two-finger patterns. Six SOAs were tested: -300 , -100 , -52 , $+52$, $+100$, and $+300$ msec. As noted above, a 6-to-3 paradigm was used. Subjects were tested for 20 sessions: 10 sessions for one-finger patterns and 10 sessions for two-finger patterns. Each session consisted of seven blocks of 50 trials: one block testing each SOA and one block in which the target was presented by itself.

As in Experiment 1, trials were self-paced. The first stimulus, either target or nontarget, was presented 750 msec after the subject pressed a key on the keyboard. The same SOA was tested throughout a block of trials. A message remained on the screen throughout the block, reminding the subject to categorize the first stimulus (on blocks in which the target led the nontarget) or to categorize the second stimulus (on blocks in which the nontarget led the target). In both training and formal sessions, subjects received trial-by-trial feedback. The rest of the procedure was similar to that used in Experiment 1. Although accuracy was stressed, subjects were encouraged to respond quickly, and reaction times (RTs) were recorded.

Results and Discussion

The results, presented in Figure 3, show the percentage correct for the three types of trials—SC, RC, and RI—as a function of SOA. Also shown is the percentage correct in the absence of a nontarget. The top panel represents performance for the one-finger patterns; the bottom panel that for the two-finger patterns. The standard errors of the means ranged from 2% to 7% with a mean of 4%.

Experiment 2 was designed to examine the nature of the interference that occurs between patterns presented successively to two different fingers and to compare the results with those obtained from patterns presented to a single finger. For both the one- and two-finger patterns,

performance on RI trials—that is, trials on which the nontarget is associated with a response that is different from that of the target—is generally poorer than on RC trials, where the target and nontarget are associated with the same response. Overall, the one- and two-finger functions appear to be similar. A three-way ANOVA supported this observation in that there was no significant effect of pattern type (one finger vs. two) [$F(1,5) = .80$, $p > .05$]. There was a significant effect of trial type [$F(2,10) = 124.42$, $p < .00001$] and a significant effect of SOA [$F(5,25) = 6.34$, $p < .001$]. There was also a significant interaction between trial type and SOA [$F(10,50) = 6.97$, $p < .00001$], but no significant interaction between pattern type and SOA [$F(5,25) = 1.64$, $p > .05$] or between pattern type and trial type [$F(2,10) = 1.02$, $p > .05$]. There was no significant three-way interaction, pattern type $\times$ SOA $\times$ trial type [$F(10,50) = 1.69$, $p > .05$].

The RT data were analyzed to determine if there was any speed-accuracy tradeoff between the RC and RI functions. No such relationship was observed. If anything, the opposite trend was evident with greater accuracy on SC trials associated with RTs briefer than those obtained on RI trials. The average RT (correct trials only) on SC trials was 858 msec; on RC trials, 896 msec; and on RI trials, 930 msec. The ANOVA showed a significant effect of trial type [$F(2,10) = 19.53$, $p < .001$]. Unlike previous results (Craig, 1985a), the RT for correct identification of two-finger patterns (997 msec) was not significantly longer than the RT for one-finger patterns (791 msec) [$F(1,5) = 6.05$, $p = .057$]. None of the two-way interactions was significant, nor were any of the three-way interactions significant. With the relatively high error rates, the RT data should not be weighted too heavily.

Further analysis of the results supported the conclusion that for both one- and two-finger patterns, response competition can be a major part of the interference between temporally contiguous patterns. As noted, response competition is revealed by the difference between performance on RC and RI trials. To see whether RC and RI trials differed from each other, the data were analyzed excluding the SC trials. For the one-finger patterns, there was a significant effect of trial type [$F(1,5) = 117.39$, $p < .001$], a significant effect of SOA [$F(5,25) = 6.34$, $p < .001$], and a significant interaction between trial type and SOA [$F(5,25) = 6.73$, $p < .001$]. Similarly, for the two-finger patterns there was a significant effect of trial type [$F(1,5) = 40.30$, $p < .01$], a significant effect of SOA [$F(5,25) = 4.22$, $p < .01$], and a significant interaction between trial type and SOA [$F(5,25) = 7.45$, $p < .001$]. For these patterns, the data indicated that response competition contributes to the amount of interference for both one- and two-finger patterns.

In several earlier studies, when subjects were presented target and nontarget patterns to the same fingerpad, they often responded with a pattern corresponding to the composite of the target and nontarget patterns (Evans, 1987; Evans & Craig, 1986). This tendency to respond with nontarget patterns was particularly evident at brief SOAs (within approximately 65 msec) and was taken as evi-

Figure 3. Results from 6-to-3 paradigm. Percent correct for three trial types—stimulus compatible (SC), response compatible (RC), and response incompatible (RI)—as a function of stimulus onset asynchrony (SOA). The top panel presents the results from the one-finger patterns. The bottom panel presents the results from the two-finger patterns.

dence of temporal integration. Might temporal integration be operating in the present experiments, and might it, rather than response competition, account for the results in the present experiments? With regard to the first question, the nature of the stimulus conditions in the present experiments suggests that at brief SOAs, the target and nontarget are likely to be integrated to some extent. Because the particular set of patterns used (Figure 1) did not contain possible composite patterns, the results can provide no direct evidence of temporal integration. If the parts of the patterns presented to the same fingerpad are being integrated into a single pattern, the question becomes whether the integrated pattern has sufficiently altered the representations of the target and nontarget in such a way that they are no longer identifiable. If the two

patterns are no longer identifiable, the performance on RC and RI trials should be very similar. The fact that on RC trials the same response label is associated with both the target and nontarget should not produce any improvement over the performance on RI trials if the representations of the target and nontarget patterns have been greatly altered. Yet, if the target and nontarget are being integrated, how is it that RC performance is better than RI performance? It is possible that temporal integration is taking place, but that information about separate patterns is not being lost. In fact both the present results and earlier results (Craig, 1995) strongly support the position that there is sufficient information in these integrated patterns to evoke both a target response and a nontarget response. Recent results in our laboratory have also sup-

ported this conclusion. Pattern sets were created in such a way that certain pairs of patterns would, if integrated, form a composite that was a possible response. With a paradigm similar to that used in Experiment 2, the results showed that subjects responded on some trials with composites and on some trials with the nontarget or with the target. In other words, temporal integration is likely to be present at brief SOAs (<100 msec), but information about the target and nontarget patterns is still sufficient to evoke appropriate responses—and, on RI trials, conflicting responses. In addition, at longer SOAs, such as –300 msec, temporal integration is very unlikely to be playing any part in the results, yet there remain large differences between the performance on RC and on RI trials.

Further support for the role of response competition comes from an analysis of subjects' responses on RI trials. On all trials, subjects had available three responses—the target response (correct response), the nontarget response, and a response corresponding to the third category, that is, neither the target nor the nontarget. We refer to this third category as an "other" response. How do subjects respond when incorrect on RI trials? Do they simply guess between the nontarget and other response (both incorrect), or do they select the nontarget response more often than chance? The results from Experiment 1 indicated that with an identification task subjects were more likely to respond with the nontarget than with one of the remaining patterns. Previous results with the categorization task and one-finger patterns showed that when incorrect on RI trials, subjects chose the nontarget response significantly more often than the third available response (i.e., the "other" response, Craig, 1995). A similar analysis for the present data is shown in Table 1. A chi-square test showed that for both one-finger patterns ($p < .0001$) and two-finger patterns ($p < .0001$), subjects responded more frequently, when incorrect, with the nontarget response rather than with the remaining (other) response. This result is consistent with the results from Experiment 1 and the view that subjects had representations of both the target and nontarget available in tactile short-term memory when they responded.

On the basis of previous selective attention studies, one might expect that regardless of whether subjects are instructed to attend to one fingerpad or to two fingerpads, information from both fingerpads is processed. The present results support an additional conclusion, suggesting that the information from the two fingerpads is more or less automatically combined under conditions in which target stimuli extend across two fingers. Subjects do not appear able to prevent the combining of in-

formation from the two fingerpads even when that information is generated by a nontarget pattern.

Masking also appears to contribute to the overall interference between successively presented patterns. This is revealed by comparing performance levels on SC trials with performance levels on RC trials. The question with regard to masking is, Do physically different stimuli associated with the same response result in lower levels of performance? The ANOVA for the SC and RC trials for both one- and two-finger patterns indicates that performance is significantly lower on RC trials. For the one-finger patterns, there was a significant effect of trial type [$F(1,5) = 8.41, p < .05$], no significant effect of SOA [$F(5,25) = 0.56, p > .05$], and no significant interaction between trial type and SOA [$F(5,25) = 0.87, p > .05$]. The same pattern of results held for the two-finger patterns. There was a significant effect of trial type [$F(1,5) = 10.89, p < .05$], no significant effect of SOA [$F(5,25) = 1.37, p > .05$], and no significant interaction between trial type and SOA [$F(5,25) = 2.05, p > .05$]. Whether patterns are presented to a single finger or to two fingers, subjects appear to have difficulty in identifying a target pattern in part because the nontarget differs physically from the target and alters the representation of the target (that is, masks it), as revealed by the difference between SC and RC trials, and in part because subjects attempt to respond with the nontarget (response competition). The function shown in Figure 2 (nontarget different from target) suggests that the interference is produced by two factors, masking and response competition.

Two aspects of the functions shown in Figure 3 are somewhat surprising. First, performance on RC trials changed very little over the range of SOAs tested. On the basis of the results shown in Figure 2 and previous results with patterns presented to one finger, it might be expected that performance on RC trials would drop considerably at brief SOAs. However, the briefest SOAs tested were 52 msec, and changes in performance at briefer SOAs would not have been seen. A second surprising aspect of the functions shown in Figure 3 is that considerable interference was seen at SOAs of –300 msec. Although the results from Experiment 1 did show considerable interference at long negative SOAs, previous results with patterns that produced higher levels of performance showed that RI performance returned to levels almost equal to SC and RC performance at –300 msec (Craig, 1995). To examine these two aspects, we repeated the one- and two-finger measurements with both briefer and longer SOAs. Specifically, six SOAs were tested: –500, –52, –26, +26, +52, and +500 msec. Seven subjects were tested for six sessions on the two-finger patterns, and 6 subjects were tested for six sessions on the one-finger patterns.

The upper panel of Figure 4 shows the one-finger results, and the lower panel shows the two-finger results. The standard errors of the means for the one-finger results ranged from 1% to 7% with a mean of 4.0%. The standard errors of the means for the two-finger results ranged from 2% to 10% with a mean of 6.4%. This pattern of results is similar to that presented in Figure 3. The

Table 1
Percentage of Nontarget Responses on Incorrect
Response-Incompatible Trials

Pattern	Stimulus Onset Asynchrony					
	–300	–100	–52	52	100	300
One finger	66	66	64	67	66	54
Two fingers	58	56	56	63	61	54

Figure 4. Percent correct for three trial types as a function of stimulus onset asynchrony (SOA). The top panel presents results from the one-finger patterns. The bottom panel presents results from the two-finger patterns. (Figure 4 is similar to Figure 3, except that different SOAs were tested.)

results presented in Figure 4 indicate that even at brief SOAs the majority of the interference seen is due to response competition rather than masking. The results show a relatively modest drop in performance on RC trials from -26 to $+26$ msec and a more substantial drop on RI trials across the same two SOAs. The ANOVA for the one-finger patterns showed a significant effect of trial type [$F(2,10) = 29.05, p < .0001$], a significant effect of SOA [$F(5,25) = 5.63, p < .01$], and a significant interaction between trial type and SOA [$F(10,50) = 4.70, p < .0001$]. The ANOVA for the two-finger patterns also showed a significant effect of trial type [$F(2,12) = 13.32, p < .001$], a significant effect of SOA [$F(5,30) = 12.69, p < .0001$], and a significant interaction between trial type and SOA [$F(10,60) = 2.20, p < .05$]. The implication

is that with these patterns, response competition is responsible for a substantial proportion of the interference even at very brief SOAs. At the longer SOAs, performance on RI trials is still well below SC and RC performance. A nontarget pattern associated with a response that is different from that of the target continues to interfere with the target at long temporal separations. That this effect appears to be due to response competition suggests that even though the nontarget conveys no information about the target, it primes subjects to respond to it.

EXPERIMENT 3

In Experiment 3, we compared temporal interference functions for patterns presented ipsilaterally and bilaterally.

ally. In one condition, patterns were presented to the two fingers on the same hand, and in a second condition, patterns were presented to two fingers on opposite hands. In previous studies of pattern identification using two fingers, it has been reported that bilateral performance was generally superior to ipsilateral performance. In a discrimination task, subjects were better able to discriminate between members of a pair of spatial patterns when the sites of stimulation were bilateral rather than ipsilateral (Craig, 1985a). This advantage is particularly evident at brief SOAs and may disappear at longer SOAs (Horner, 1995). In an identification task, patterns were divided so that half of the pattern was presented to one fingerpad and half to another fingerpad. Performance was better when the patterns were presented bilaterally rather than ipsilaterally (Craig, 1985a; Craig, Green, & Rhodes, 1985; Weisenberger, Craig, & Abbott, 1991). In another task, subjects attempted to identify a spatial pattern presented to one of the two fingerpads. Because the target location was not specified until after the stimuli had been presented, subjects were required to attend to two fingerpads. Once again, identification performance was better when the two patterns were presented bilaterally rather than ipsilaterally (Craig, 1985a). Recent studies using the 4-to-2 paradigm have shown that when a nontarget is presented to a fingerpad on the same hand as the target, there is considerable interference on RI trials; that is, subjects respond with the pattern presented to the nontarget location. When the nontarget is moved to the opposite hand, there is much less interference (Evans et al., 1992). Taken together, these results indicate that subjects are better able to process spatial information bilaterally for two reasons. First, relative to two fingers on the same hand, subjects can selectively attend to one hand and ignore stimulation on the other hand. Second, subjects can attend to locations on both hands and process spatial patterns.

In the context of the present study, the question becomes, How readily can subjects identify bilateral target patterns in the presence of bilateral nontargets? And, if there is interference, is the interference the result primarily of masking or of response competition? In light of the fact that pattern identification may be easier bilaterally than ipsilaterally, one might predict that overall performance would be better in the bilateral condition. By the same token, response competition might be expected to produce even more interference given that the nontarget would be more clearly perceived in the bilateral condition than in the ipsilateral condition and thus be readily available as an incorrect response.

Method

Subjects. Six subjects were tested, 4 women and 2 men. Of these subjects, 4 had participated in Experiment 1 or 2.

Apparatus. The apparatus was the same as that used in Experiment 1.

Procedure. The procedure was similar to that used in Experiment 2. Trials were blocked by SOA. A message remained on the screen throughout the session, reminding the subject to categorize either the first stimulus or the second stimulus. The first stimulus of the pair of stimuli was presented 750 msec after the subject

pressed a key on the keyboard. The same six patterns were used (Figure 1), but the way in which the patterns were to be categorized was changed: Patterns 1 and 2 were associated with Response 1; 3 and 4 with Response 2; and 5 and 6 with Response 3. In the ipsilateral condition, subjects placed their left middle and left index fingerpads on the arrays. Spatial acuity is likely to differ as a function of which fingers are used. To ensure that the ipsilateral and bilateral conditions were as comparable as possible, the left middle and right index fingerpads were used in the bilateral conditions. The distance between the two arrays was increased from approximately 2.5 cm in the ipsilateral condition to more than 6 cm in the bilateral condition. Subjects responded by means of foot pedals. The same six SOAs as those initially tested in Experiment 2 (−300, −100, −52, +52, +100, and +300 msec) were tested. Sessions alternated between ipsilateral and bilateral placement of the tactile displays. Subjects were tested for six sessions with ipsilateral patterns and six sessions with bilateral patterns.

Results and Discussion

The top panel of Figure 5 shows the results from the ipsilateral measurements. The bottom panel shows the results from the bilateral measurements. The standard errors of the means ranged from 2% to 10% with a mean of 4.9%. The ordering of the functions, SC superior to RC superior to RI, is similar for the ipsilateral and bilateral placements and similar to results from Experiment 2. Overall, performance seems to be slightly better with a bilateral placement. An overall ANOVA showed that there was a significant effect of ipsilateral versus bilateral placement [$F(1,5) = 7.23, p < .05$]. This difference, favoring bilateral placement, appears to be due primarily to superior performance on SC trials for bilateral patterns. This result is consistent with earlier findings of bilateral superiority (Craig, 1985a; Lappin & Foulke, 1973). There was also a significant effect of trial type [$F(2,10) = 15.92, p < .001$] and a significant effect of SOA [$F(5,25) = 9.83, p < .0001$]. Both of these results are similar to the results of Experiment 2. There was a significant interaction between trial type and SOA [$F(10,50) = 6.68, p < .0001$] and a significant interaction between placement and trial type [$F(2,10) = 5.32, p < .05$]. There was also a significant three-way interaction, placement $\times$ trial type $\times$ SOA [$F(10,50) = 2.43, p < .05$].

The ipsilateral and bilateral data were analyzed separately to see the extent to which pattern identification performance was affected in a similar way by nontargets in the two conditions. For the ipsilateral condition, there was a significant effect of trial type [$F(2,10) = 11.16, p < .01$], a significant effect of SOA [$F(5,25) = 3.21, p < .05$], and a significant interaction between trial type and SOA [$F(10,50) = 3.11, p < .01$]. The bilateral results were similar to the ipsilateral results. There was a significant effect of trial type [$F(2,10) = 15.25, p < .001$], a significant effect of SOA [$F(5,25) = 10.33, p < .0001$], and a significant interaction between trial type and SOA [$F(10,50) = 6.38, p < .00001$].

Although the pattern of results was similar in the two conditions, there were some differences. Specifically, single-pattern performance, and indeed SC performance in general, appears to have been higher for bilateral than for ipsilateral patterns; yet the overall difference between

Figure 5. Results from 6-to-3 paradigm. Percent correct for three trial types as a function of stimulus onset asynchrony (SOA). The top panel represents the condition in which the two-finger patterns were presented ipsilaterally. The bottom panel represents the condition in which the two-finger patterns were presented bilaterally.

the two RI functions is small. What this suggests is that nontargets interfere more in identification of bilateral patterns than in identification of ipsilateral patterns. To see this effect more clearly, the RI data from Figure 5 were replotted in terms of the amount of interference; that is, the difference between the single-pattern percentage correct and the percentage correct at each SOA. These results, shown in Figure 6, indicate that bilateral patterns are indeed subject to more interference than are ipsilateral patterns. There was a significant effect of placement [$F(1,5) = 11.31, p < .05$], a significant effect of SOA [$F(5,25) = 13.97, p < .0001$], and a significant interaction between placement and SOA [$F(5,25) = 5.74,$

$p < .01$]. Although less pronounced, a similar effect was seen with the RC data.

As in Experiment 2, the RI trials were analyzed to see the way in which subjects distributed their responses. When incorrect, do they select the nontarget more often than the third (other) response? The results of this analysis were similar to the results from Experiment 2 and are presented in Table 2. A chi-square test indicated that for both the ipsilateral ($p < .0001$) and bilateral ($p < .0001$) patterns, subjects were more likely to select the nontarget than to select the "other" response, indicating the importance of the role of response competition. The largest percentages of nontarget responses are seen in the bilat-

Figure 6. The results from the response-incompatible conditions (Figure 5) replotted to show the amount of interference as measured by the difference in percentage correct levels obtained in the absence of a nontarget and in the presence of a nontarget. The results from patterns presented ipsilaterally and bilaterally are shown.

eral condition at 52- and 100-msec SOAs. As Figure 5 shows, it is at these two SOAs that bilateral performance dropped below ipsilateral performance. This decline in performance appears to have resulted from an increase in nontarget responses. If, as the single-pattern and SC data indicate, it is easier to identify bilateral patterns than ipsilateral patterns, it is not surprising that nontargets may also be more readily perceived and thus interfere with target identification.

Bilateral RI performance levels (at 52 and 100 msec) not only fall below ipsilateral levels but also below the level that would be expected by chance (33%; chi-square test, $p < .0001$). Below-chance levels of performance like these would be surprising if the target were being masked, and subjects were simply guessing among alternatives. The results suggest that at certain SOAs, subjects are actively choosing the nontarget over the target. Some additional bilateral measurements were made at three SOAs with a reduced number of categories. By reducing the number of categories from three to two, chance performance rises to 50% and the possibility increases of observing performance levels below chance. A 4-to-2 paradigm was used. The results based on a total of 2,000 trials per SOA from 5 subjects are shown in Table 3. Single-pattern performance was 89% correct. The results are very similar to those seen with the 6-to-3 paradigm. Performance on RI trials at 52 and 100 msec was signifi-

cantly below chance (chi-square test, $p < .0001$). Again, it seems that subjects were choosing to respond with the nontarget when it trailed the target at brief SOAs.

The latter findings alter the view of response competition for tactile, spatial patterns. We have generally viewed the process of response competition as one in which subjects have available representations of both the target and nontarget patterns, and err on occasion by responding with the nontarget. The present results suggest that at certain SOAs, subjects are not simply guessing between the target and nontarget; they are selecting the nontarget in preference to the target. This result is perhaps more surprising in view of the fact that the subjects are receiving trial-by-trial feedback, and the trials are blocked by SOA. Paradoxically, if subjects were tested on only RI trials at 52- or 100-msec SOAs, they would improve their percentage correct by responding with the pattern they believed to be incorrect.

GENERAL DISCUSSION

The results of the present study demonstrate a considerable degree of similarity between the processing of spatial patterns presented to one finger and to two fingers. The temporal interference functions are very similar to one another, as are the relative effects of masking and response competition on the perception of one- and two-finger patterns. These results simplify the view of processing of temporal sequences of spatial patterns on the fingerpads in that it appears to be unnecessary to postulate different mechanisms for one- and two-finger patterns. In view of earlier findings that there can be complex interactions between spatial patterns presented to two fingers, the similarity between the one- and two-finger results may be surprising. In the earlier studies, pattern

Table 2
Percentage of Nontarget Responses on Incorrect
Response-Incompatible Trials

Placement	Stimulus Onset Asynchrony					
	-300	-100	-52	52	100	300
Ipsilateral	58	55	56	64	57	56
Bilateral	54	56	60	73	69	60

Table 3
Percentage Correct on Bilateral Patterns, 4-to-2 Paradigm

Stimulus Onset Asynchrony	Trial Type		
	Stimulus Compatible	Response Compatible	Response Incompatible
-52	86	66	71
52	78	55	36
100	85	58	38

perception in the absence of any nontarget patterns was examined and differences in levels of performance between patterns presented to one and two fingers were found. It may be that once performance levels on the one- and two-finger patterns are equated in the absence of nontargets, differences due to the presence of nontargets are minimized. Although earlier results suggest that dividing attention between two fingers reduces pattern identification performance, the present results indicate that requiring subjects to process patterns presented to two fingers does not alter temporal interference functions.

Previous results indicated that RTs for identifying spatial patterns presented to two fingers were longer than they were for identifying one-finger patterns (Craig, 1985a). Although not the focus of this study, RTs were measured in Experiment 2. RTs to two-finger patterns averaged 206 msec longer than to one-finger patterns, a difference that was not significant. The substantial variability associated with these RT data and the relatively high error rates may have obscured possible differences between the processing time of one- and two-finger patterns. On the other hand, if one supposes that pattern identification did take significantly longer for two-finger patterns, what effect would this have on the temporal interference function? On the portion of the function due to response competition, one might expect very little effect. If it takes longer for both the target and the nontarget to be processed, the point of maximum interference—the nontarget trailing by 25 or 50 msec—should change very little. If additional time is required to process two-finger patterns, the effect might be seen in a broadening of the peak in the interference function. An increase of 20% or 30% on RTs might well increase the overall variability of the temporal interference function and tend to spread out the peak of the interference function. The data from Experiment 2 (Figure 3) offer the best comparison between one- and two-finger patterns. There is little evidence that the nature of the peak differs between the two functions.

The present results offer support for the contention that response competition takes place relatively late in processing. Previous results (Evans et al., 1992) showed that a nontarget presented to the contralateral hand could exert a modest interference effect. The effect was presumably due to the information from the two hands being processed to the point of evoking a response—and the responses must interact with each other fairly late in processing. In the bilateral condition in the present study, the two halves of the pattern must be combined before they can evoke a response. Neurophysiological data indi-

cate that bilateral representations are generally found only beyond the level of SI in the cortex (Iwamura, Iriki, & Tanaka, 1994; Robinson & Burton, 1980). It would presumably be beyond the level of SI that information from the two hands could be combined, and at that level or later that interference due to response competition would take place.

In Experiment 3, performance on RI trials dropped below chance levels. One mechanism that might account for such low levels of performance is replacement (Evans, 1987). It may be that at least at brief SOAs, the nontarget replaces the target, and subjects have available only one representation, that of the nontarget. The present experiments were not designed to examine this issue, but earlier results favor the conclusion that at least for one-finger patterns, the nontarget does not replace the targets and that subjects have available representations in tactile short-term memory of both the target and nontarget (Craig, 1995). This conclusion was based on the results from an identification paradigm in which subjects responded twice on every trial, with their best guess as to the target and their second best guess. When correct on the first response, subjects were most likely to give the nontarget as their second response. Similarly, when subjects were incorrect, their most likely responses were the nontarget followed by the target. With the overall similarity of the interference functions for the one- and two-finger patterns, it is probably best, at present, to assume that subjects do have available representations of both the target and nontarget. The question then becomes, Why do subjects select the nontarget in preference to the target at brief SOAs? One hypothesis is that subjects select the stronger of the two representations and that the stronger pattern is the trailing pattern. In an earlier study, raising the intensity of the nontarget (masker) resulted in an increase in the number of nontarget responses (Evans, 1987). A similar intensity manipulation of the two-finger patterns would be needed to see the extent to which performance could be altered on RI as compared with RC trials. As noted in Experiment 2, the present results do not rule out the possibility that the target and nontarget patterns are integrated at the brief SOAs. The results do indicate that if such integration is taking place, the elements corresponding to the target and nontarget patterns are sufficiently identifiable to evoke corresponding responses.

There are some implications of the present results for haptic exploration. As the hand is moved over an object and one attempts to identify a particular spatial feature, the feature may be misidentified because its representation is distorted by a nearby feature (masked) or because the nearby feature is confused with the target feature (response competition). Because considerable portions of both types of interference are seen when spatial patterns are presented within 100 msec of one another, if the rate of hand movement is slowed, the temporal spacing between nearby features is increased and both types of interference will be reduced. However, significant interference is still observed at long temporal separations, out to 1,000 msec. The long temporal separation over which

interference is seen and relatively close spacing of features on many haptic objects may produce a general attenuation of spatial pattern identification, at least as the fingers are being normally scanned across an object. It is unlikely that subjects could slow their exploration so that adjacent spatial patterns would maintain a temporal separation greater than 1,000 msec. The fingers might be moved over an object so that spatial features (patterns) are encountered on average every 200–300 msec. This rate would avoid maximizing the interference seen at very brief SOAs without being so slow as to be impractical. Upon contacting a spatial pattern that might be the target pattern, subjects could stop and move their fingers back and forth across the pattern. This type of exploratory procedure has been observed in certain tasks (Lederman & Klatzky, 1987). By moving the fingers back and forth across the spatial pattern, subjects would enhance identification performance by increasing the time in contact with the pattern, by excluding contact with other spatial patterns, and by means of the initial, brief contact with the pattern, excluding a large number of possible patterns (responses). The latter two factors would improve performance by reducing both masking and response competition.

These results also have implications for the design of tactile displays. Earlier studies suggested that the use of two hands might improve pattern recognition. In a study of speech recognition using a tactile vocoder, it was found that the identification of single words was better when the two tactile displays were in contact with fingers on opposite hands rather than on the same hand (Craig et al., 1985; Weisenberger et al., 1991). The present results would lead one to expect a bilateral advantage when a pattern to be identified was presented by itself or with a considerable temporal gap (>100 msec) between it and other patterns. The bilateral advantage should disappear when nontarget patterns closely follow target patterns, and these patterns are associated with responses that are different from the target pattern. There is an implication here, although it has not been tested, that if a nontarget pattern were not associated with any response it would interfere very little in target identification, and the bilateral advantage would still be evident.

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