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SPACE, TIME, AND ATTENTION: PROCESSING OF STIMULI DELIVERED TO THE HANDS

BY

LINDA LA GRANGE CALHOON (C)

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ABSTRACT

Spatiotemporal patterns of four to six vibrotactile stimuli were delivered to fingertips (2-4 per hand) at SOAs ranging from 0-360 msec. Pattern delivery was varied by presenting single, triple, and redundant patterns. Subjects reported which loci were stimulated. Results indicated that response accuracy decreased as number of loci increased and SOAs decreased; accuracy increased with triple presentations and certain types of redundancy patterns. These results are discussed with regard to their relevance for the design of tactile visual substitution devices.

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INTRODUCTION

Historically, there has been general acceptance of Aristotle's division of the five major senses: vision, audition, feeling (touch), taste, and smell. Since Aristotle's time the list has been expanded to include kinesthesia and the vestibular sense. Of these seven senses, vision and audition are the two most likely to be identified as being crucial to so much of human behavior (Geldard, 1960). The impairment or loss of one or both of these senses can leave an individual in a state of sensory deprivation and emotional isolation. Informational compensation for the lost sensory system via one of the still functioning sensory systems can be defined as "sensory substitution". It is the goal of many of those involved in the development and design of sensory substitution devices to facilitate the subsequent reorganization of the remaining senses to the extent that the deaf and/or blind person is no longer forced to function under conditions of marginal sensory information.

In order to facilitate this sensory reorganization, it must be determined which of the remaining senses (or combination thereof) is best suited for the acquisition of the information normally transmitted by vision and audition. If the visual and auditory senses are not functional, of the five remaining senses, the two chemical senses (taste and smell) can be eliminated from consideration as substitute senses simply because of their prolonged adaptation effects and the slow and indirect process of transporting the stimuli from the source to the receptor sites. Similarly, the vestibular and kinesthetic systems can be dismissed as practical substitution "host" systems because of their requirements for unusual forms of stimulation and the subsequent undesirable residual side effects.

The cutaneous system is the remaining major sensory pathway that could be used to provide substitute channels for stimulus processing. Typically, the cutaneous system is considered to include the sense of pressure, pain, cold, and warmth. Cold and warm sensations are subject to the same limitations associated with the chemical senses, namely sluggish stimulus reception and transmission, prolonged adaptation effects, and poor spatial localization. Pain can be dismissed as a possible sensory pathway for sensory substitution due to obvious limitations. The remaining option is the sense of touch or pressure. Geldard (1977) writes that "...broadly speaking, there are two great discriminations made about things and events in the world;

they involve distinctions of space, on the one hand, and of time, on the other" (p. 214). According to Geldard, touch occupies a niche midway between vision and audition with respect to its spatiotemporal processing capabilities; it is superior to vision when making temporal discriminations, and superior to hearing when making spatial discriminations. The current study is an attempt to further define the relative capacity of the skin to process spatial and temporal information.

<u>Rationale</u>

The sense of touch seems to be the best choice of a sensory substitution "host" system for the reception and processing of stimulus information lost to a nonfunctioning visual and/or auditory system. Researchers and engineers have designed tactile and haptic-based displays, but have frequently had an insufficient understanding of the processing capabilities of the skin. Geldard (19[illegible]7) acknowledged this problem when he wrote, "Both here and abroad the same basic mistake was made. No one paused to ask the skin what language it could compass" (p.117). That statement, made over thirty years ago, fortunately is less salient today.

Basic spatiotemporal processing capabilities of the skin can best be understood by examining those spatiotemporal tasks routinely performed by the skin. Kirman (1973) said that "...whereas the eye excels in coding spatial patterns and the ear in coding temporal patterns, the skin is best suited for coding spatiotemporal patterns " (p.41). This is certainly logical when considering the type of information that is acquired via haptic exploration. When the hand slides over an object, the latter fingers encounter, only seconds, or even milliseconds, later the same stimuli as those encountered by the first fingers. As the temporal flow of spatial information continues across the individual fingers, spatiotemporal information is integrated, resulting in the perception of an object with a definite shape. Katz (1936) found that subjects were better able to identify a material when using five fingers as opposed to just one. Because of this spatiotemporal integration, subjects are able to fill in the gaps of sensation that are inherent in the usually fragmented process of haptic exploration. These observations are of interest within the context of the current study specifically because they suggest that haptic exploration is sustained by successive stimulus input that is encountered in a predictable fashion.

Processing this spatiotemporal information requires varying degrees of attention. Two aspects of attention are important in the design of tactile visual sensory substitution devices: divided attention and selective attention. Specifically, how much tactile information can be successfully attended to and processed within a given amount of time, and how efficiently can a person focus upon relevant features of the tactile stimuli? Kahneman (1973) commenting on divided attention states that "... if the effort that man can exert at any time is limited, then any two tasks whose joint demands exceed that limit must be mutually interfering. Thus, the main prediction from an effort theory is that the ability to respond to simultaneous inputs should depend primarily on the demands of the activities among which attention is to be divided" (p.148). Regarding selective attention, he says that "... focusing attention on one message does not completely prevent the processing of stimuli on irrelevant channels" (p.119). Given these two statements, it was felt that within the current study it would be appropriate to explore the limits of attention as well as the extent of the significance of providing irrelevant stimuli in tasks examining focused attention.

In addition to questions addressing tactile processing and attentional factors, the current series of experiments will attempt to answer questions similar to those posed by the earlier studies of Hill and Bliss (1968a & b). Because of some commonalties between the previous and the present studies, it is hoped that a comparison of the results will allow further inferences to be drawn with regard to the inherent processing capabilities of the skin, i.e. the sense of touch. These inferences regarding tactile spatiotemporal discrimination are vital within the context of designing a maximally functional tactile-visual substitution system.

Sherrick (1970) commented on the complex situation facing anyone attempting to develop a tactile-visual substitution system, "Increasing information-handling capacity by compressing events in time and at the same time reducing the size of the haptic display not only multiplies the problems of the equipment design, but also tests the inner limits of the skin's capability for resolving temporal and spatial events" (p. 25).

Overview of the Current Research

The general area reexamined is that of tactile processing of multiple point stimuli. Although there has been a substantial amount of experimental work done associated with experimental protocols similar to those to be used in the current study, the body of work, taken collectively lacks closure, and as well, the current study includes a few unique areas not sufficiently examined. However, two sets of particularly noteworthy experiments serve to focus the current research: The first set (Bliss, Crane, Link, & Townsend, 1966a; Bliss, Crane, Mansfield, & Townsend, 1966b; Hill & Bliss, 1968a, 1968b; Hill, 1971), will be more extensively reviewed in a subsequent chapter. Briefly, in these studies the subjects were asked to respond with the location and temporal order of from two to six successive stimuli that could be delivered to any of 24 sites on the fingers (thumbs were not included). The stimuli were generated by an airjet array and were delivered at stimulus onset asynchronies (SOAs) ranging from 0-200 msec. The other set of experiments was conducted by Geldard and Sherrick (1972) and Sherrick (1972). As with the first set of experiments, subjects were to report location and temporal order of the stimuli. A second task required the subjects to detect whether two sequence patterns, presented one second apart, were the same or different. For both tasks SOAs varied from 20 to 500 msec. Stimuli were delivered to either one hand or both hands, via two to five activated vibrators.

For the most part, both sets of experiments yielded similar results. For example, when the number of stimuli was increased, longer SOA values were required for correct localization and temporal order judgments. Bilateral versus ipsilateral delivery of stimuli did not have an affect on response accuracy except for the same/different task in the Sherrick study, where there was a bilateral advantage. Mislocalization responses were generally for sites closest to the correct location. Tactile short term memory appeared to have a storage duration of approximately 1.5 seconds, and a capacity limited by spatial factors. A final observation, made by Sherrick (1972), and one that will be considered in the present study, is that there is "... evidence that when stimulus onset interval (SOI) lengthens, the slopes of the function decrease in proportion to the number of stimuli involved" (p.12). This function can be defined as the rate at which response accuracy improves as the temporal separation between stimuli is increased.

The current study is intended to expand upon these two sets of experiments, as well as investigate the effects of attentional factors on tactile stimulus processing. Specific conditions to be examined include: a) the delivery of four to six vibrotactile stimuli to the distal phalanges (2 - 4 per hand), b) SOAs ranging from 0 msec (simultaneous) to 360 msec (successive), and c) the requirement that subjects report spatial position of stimuli as well as the order in which they were delivered.

After examining the functional relationship between number of loci stimulated versus SOA, Sherrick (1972, p.233) queries "...what factors of the stimulation can we vary to increase the slope of the function?", and provides two possible answers by noting that increased dissimilarity of pairs (in the same/different task) and increased distance between loci seemed to increase the rate of improvement as SOA is lengthened. To explore this question further, I will introduce two additional conditions, repetition and redundancy, and assess their effect upon the slope of the function of number of loci versus SOA. The repetition factor will be tested by comparing response accuracy to a triple delivery of the sequence pattern versus a single delivery. Redundancy will be introduced via the presentation of either an identical or similar pattern to both hands and the subsequent measurement of the response accuracy of a single "attended" hand. Although almost every facet of these experiments requires at least some degree of attention from the subjects, the redundancy condition will be referred to as an attentional task because the subjects are asked to focus their attention exclusively on and respond to the stimuli delivered to a designated hand, and ignore any stimuli delivered to the nondesignated hand.

HISTORICAL REVIEW

The historical review will be divided into five sections: a) a description of studies that have investigated touch and its capacity for temporal discrimination; b) an overview of some measures of spatial acuity and spatial localization; c) a review of experiments that have dealt with both the spatial and temporal functions of the skin, d) a discussion of the series of experiments on tactile spatiotemporal interactions conducted Hill and Bliss; and e) an overview of the studies that have addressed attentional factors in tactile stimulus information processing.

Touch and Temporal Discrimination

Realizing that it is impossible to completely separate the temporal from spatial factors of tactile perception, I will reference those studies that have focused primarily upon assessing temporal discriminatory capabilities of the skin.

Geldard (1970) provided a convenient delineation of the temporal discrimination functions in vision, audition, and touch. Table 1 has been extracted from Geldard (1970) and modified to include a few additional measures that have been used to determine tactile temporal acuity. Of the functions listed, the three dealing with temporal order (single locus, dual locus, and multiple locus) will be the focus of this review.

Although one of the functions to be examined in this study is that of temporal order involving stimuli delivery to multiple loci, it is important to reflect upon the landmark studies that have determined levels of tactile temporal acuity using a variety of other approaches. Perhaps equally important is to acknowledge the relevance of studies designed specifically to assess the ability of human subjects to combine bottom-up cutaneous physiological capacity with top-down cognitive information processing to extract temporal information from tactile point stimuli delivered to multiple loci.

A basic measure of tactile temporal acuity is that of successiveness. Delivering two tactile pulses of approximately one msec each to a single locus on the fingertip, Gescheider (1974) found that the minimum separation between the two stimuli required for the

Table 1 *

<u>Temporal Discrimination Functions in Touch</u>

Function	Situation
1. Perception of duration	Single pulse of instantaneous duration; instantaneous or durative?
2. Delta t	Two successive durative stimuli; which longer?
3. Successiveness	Two pulses in train; one or two?
4. Numerosity	Train of pulses; how many can be counted?
5. Gap detection	Two or more identical pulses in train; gap detectable?
6. Temporal order: single locus	Two successive stimuli of different dimensions; which first?
7. Temporal order: dual locus	Two identical stimuli spatially separated; which first ?
8. Temporal order: multiple locus	More than two identical stimuli spatially separated; order of presentation?
9. Precedence effect	Two stimuli spatially separated; where localized when fused?
10. Lateralization	Two successive or intensively unbalanced stimuli; where localized?
11. Flutter fusion	Train of equally spaced pulses; fusion?
12. Synthetic movement	Spatially and temporally separate pulses; best movement?
13. Time estimation	Two temporal gaps; which are longer?

* Adapted from Geldard (1970).

perception of two distinct events was 5.5 msec. When compared with measures of successiveness for other modalities, this placed the tactile modality between audition (10 μsec) and vision (25 msec).

An acuity measure that requires not only the perception of two distinct events, but also the determination of which of the two events occurred first, is that of temporal order. Hirsh and Sherrick (1961), using vibratory stimuli delivered to the index fingertip of the right and left hands, found that for subjects to correctly identify, 75% of the time, which of two tactile stimuli preceded the other, there must be a 20-msec interval between stimuli. For them, this interval began when the first stimulus was turned off and the second stimulus was turned on, and was referred to as the interstimulus interval (ISI). In more recent studies the length of this interval has been determined by the temporal distance between the onset of the first stimulus and the onset of the second stimulus, and is called stimulus onset asynchrony (SOA). Unlike measures of successiveness which vary according to the modality being investigated, the 20-msec interval required for correct judgment of temporal order was reported to remain relatively constant for audition and vision, as well as for conditions involving intramodal stimulation. Since temporal order judgment thresholds were essentially similar for inter- and intramodal conditions, Hirsh and Sherrick speculated that this similarity in the ordering of temporal events reflected the existence of a central mechanism.

Subsequently, Sherrick (1970) investigated temporal order judgments in situations where tactile stimuli were delivered ipsilaterally (same side of the body) and bilaterally (opposite sides of the body) to dual loci. In one condition the stimuli were delivered to two loci on the same thigh, and in the second condition the stimuli were delivered to two locations on opposite thighs. The previously established temporal order threshold of 20 msec did not change for the bilateral condition, however for the ipsilateral condition, as spatial separation decreased, the order threshold increased.

Finally, Craig and Baihua (1988) determined levels of performance for temporal order judgments in three conditions: separate-site (bilateral), separate-site (ipsilateral), and same-site. Instead of reporting which location was stimulated first, subjects were required to report which of two patterns was presented first. This methodological difference may account for the somewhat higher temporal order judgment thresholds observed in this study. Seventy five per cent accuracy for the two separate-site conditions was achieved at 35-msec temporal intervals whereas Hirsh and Sherrick (1961) reported values that ranged from 20 to 33 msec. Craig and Baihua found however, that if location were provided as an additional cue, performance levels were comparable to those found in the Hirsh and Sherrick study. The performance levels for the same-site condition were significantly better than those obtained for the separate-site conditions. Craig and Baihua speculated that the same-site performance may have been superior because the subjects were not forced to switch their attention from one site to another and hence were using different cues to determine temporal order in the same-site condition. One potential cue is the formation of a composite pattern of the two stimuli. This pattern would differ as a function of the temporal position of the two patterns thereby providing a basis for the temporal order judgment.

In the same series of experiments Craig and Baihua tested the effect of another variable on temporal order judgments; relative stimulus intensity. In a same-site condition, the more intense stimulus was perceived as trailing the less intense. The same intensity imbalance had a much smaller effect when the stimuli were delivered to different locations, with the more intense stimulus perceived as occurring first.

Temporal order judgments are affected by a number of variables: a) the number and location of stimulators, b) the type of discrimination required, and c) stimulus intensity levels. It is apparent that there is no single value that can be given to represent the capacity of the tactile system to process temporal information. A number of temporal order limens have been reported, but each is predicated on a different combination of variables. A series of experiments that is based on a specific combination of variables that most closely approximates those to be employed in this study, was conducted by Hill and Bliss (1968b). A detailed review of the entire series of experiments will be covered in the section dealing with the tactile system's capacity for resolving spatiotemporal information. It should be noted at this point, however, that the Hill and Bliss (1968b) study, using point stimuli delivered to two loci (both ipsilateral and bilateral), established the limen for temporal order at about 26 msec. Their data also indicated that this limen decreased for more closely spaced ipsilateral stimuli to approximately 12 msec; a value similar to the threshold for order of two patterns determined by Craig and Baihua (1988) for their same-site condition. When the number of loci stimulated was increased from two to three, the limen for temporal order was nearly doubled to about 52 msec. The data from the Hill and Bliss study will be used to establish the range of temporal variables to be investigated in this study.

Touch and Spatial Discrimination

According to Boring (1942), the two-point limen and the error of localization, both of which were first studied by Weber in the mid-19th century, have been the most common measures of tactile spatial acuity. Weinstein (1968), in a comprehensive study of tactile spatial acuity, measured both the two-point limen and the error of localization at a number of body sites for both sexes. Of direct interest to any investigator in the area of tactile sensory substitution, is the fact that the fingertips are among the most sensitive sites for both measures. Although, as Geldard (1957) put it, "... the two-point limen does not live in the utilitarian world of communication" (p. 119), the relatively good spatial acuity of the fingertips coupled with their accessibility and dexterity make them the most practical sites for the delivery of the spatial and temporal information normally transmitted by the visual system.

Given the constraints of the tasks in the current study, particularly in terms of localizing the stimuli, there are three tactile phenomena whose potential effects should be considered. The first of these phenomena, apparent movement, is the sensation of movement experienced by a subject when presented with transient pressures of equal intensity to two separate positions. The time between these two stimulus events is critical to the perception of apparent motion. Hill and Bliss (1968b) established an optimal SOA range of 12-110 msec; a range that overlaps to some extent the intervals proposed for the current study. It is therefore conceivable that subjects, when faced with the task of localizing the stimuli, could mistakenly localize a stimulus based upon the perception of tactile stimulation brought about by the phenomenon of apparent tactile movement.

The second of the three sensory phenomena, masking, might also be considered a possible impediment to the correct spatial localization of vibrotactile stimuli. Masking occurs when the delivery of one signal in close spatial and/or temporal proximity to a second signal alters the processing of the stimuli to the extent that subject response performance is affected. Although masking effects are certainly more pronounced when the intensity of what is designated as the masking stimulus is raised relative to that of the test stimulus, Sherrick (1964) reported that when two transient vibrotactile stimuli of equal intensity were delivered to two separate loci there were perturbations in the perceived locations of the stimuli. This finding is particularly salient because the present experiments will be using stimuli of equal intensity. Hill and Bliss (1968a) in a study where tactile point stimuli of equal intensity were delivered to the fingers, attempted to determine whether masking could be a factor in some of the error patterns. Using two methods, the computation of a spread correlation for all finger responses and the computation of a sensitivity measure, d', they concluded that masking was not a factor. Therefore, it seems that although masking could figure in certain interactions involving tactile localization tasks, it is not likely to have a profound effect upon the results of the current study.

The third factor, facilitation, can be described as a condition where two stimuli in either close spatial or temporal proximity to each other may facilitate detection and/or perceived magnitude of the other. Verrillo and Gescheider (1975) found that the subjective magnitude of one stimulus increased as a result of the presentation of a prior stimulus. This effect was obtained when the individual stimuli were of the same frequency, which will be the case in the current study. They also observed facilitation effects well within the range of SOAs used in the current study (0-260 msec). Further evidence of facilitation comes from a Craig (1968) study in which two vibratory stimuli presented simultaneously to two loci required less energy to be detected than did a single stimulus. My study will be dealing with suprathreshold values, so that the task is not simply one of detection. At a very general level, however, it seems possible that an facilitory effect might occur in the present study under conditions where the subject is required to localize two stimuli delivered bilaterally, to corresponding loci.

A final variable to be considered when discussing the spatial acuity and localizing capabilities of the skin is that of number of loci being stimulated either simultaneously or successively within a given trial. Franzen, Markowitz, and Swets (1970) in a study on spatial summation of vibrotactile stimuli, claimed that they had found evidence for a central attentional process which limited attention to only one spatial location at a time (in this instance, one finger at a time). However, Geldard and Sherrick (1972), and Sherrick (1972) have since demonstrated that subjects can correctly identify the spatial location of suprathreshold stimuli delivered to multiple loci. Additionally, Gilson's (1968) subjects successfully discriminated vibrotactile patterns where one to nine stimuli were presented to any one of 10 fingertips in successive pairs. Hill (1971) in a series of studies on high-rate processing of tactual stimuli, found that when two to three loci were receiving stimuli, the number of stimuli perceived in their correct spatial position seemed independent of whether the stimuli were delivered simultaneously, successively, or, if successively, with varying SOA values. If the number of stimuli were increased from four to six, the subject's ability to localize the stimuli changed as SOA values changed; as the number of stimuli increased, longer SOA values were required to maintain a 75% correct level. The question of whether this increased difficulty with a larger number of loci was due to memory factors or the confusion effects of so many close-proximity stimuli, was not answered. Although memory factors seem to have been suggested when Sherrick (1972), citing from a similar study, noticed that with "... five stimuli 160 msec apart, the lapse of time between onset of the patterns and the opportunity for judgment has begun to degrade processing accuracy" (p.13).

As was mentioned earlier, it is difficult when discussing time and space to examine either one or the other in isolation. In fact, most of the studies covered in this review of touch and spatial discrimination have been embedded in the temporal dimension simply because the stimuli have been delivered successively, thus providing conditions for spatiotemporal stimulation.

Touch and Spatiotemporal Interactions

Within the tactile domain there are a number of phenomena strongly associated with the interaction of space and time. Two of these phenomena, apparent motion and masking, have already been discussed. A second pair of phenomena, the Tau effect and the Kappa effect, are well defined and easily discerned effects. They are, however, encountered in the literature less frequently because neither seems as exploitable as apparent motion nor as potentially intrusive as masking. The Tau effect, where the perception of distance between two stimuli is to some extent determined by their temporal separation (i.e. given a constant spatial distance, a shorter temporal interval induces the perception of a shorter space than does a longer temporal interval), was originally demonstrated in the tactile modality by Helson and King (1931), and later by

Lechelt and Borchert (1977). In the latter study, Lechelt and Borchert felt that the data suggested "...that judged spatial extents...depend more upon the relations of the temporal intervals than upon the actual spatial separations between stimuli" (p. 193). The Kappa effect is the converse of the Tau effect and can be defined as the perceived lengthening of the temporal interval as the spatial distance between the corresponding stimuli increases (Yoblick & Salvenky, 1970). These phenomena, particularly the Kappa effect, may play a role in the current study, since the spatial distances will vary while temporal intervals remain constant. However, since stimuli are being delivered to discrete spatial loci (i.e. individual finger pads), the effect should be minimal.

Review of Hill and Bliss Spatiotemporal Tactile Studies

The Hill and Bliss studies cited earlier, provide a comprehensive set of background referent conditions for any tactile experiment attempting to dissociate the effects of time and space and hence, are of specific significance to the current study.

Based on a series of studies using point stimuli delivered to the fingers, Hill and Bliss (1968b) examined the information processing capacity of the skin, specifically attending to the spatiotemporal properties of tactile information processing. Within this paradigm, they generated the following questions: 1) What is the minimum temporal separation between point stimuli that will allow the subject to correctly order them in time? 2) Is this minimal temporal separation a function of the spatial separation of the stimuli? 3) If the number of loci receiving point stimuli is increased from two to three, will this minimum temporal separation remain the same?

Briefly, the experimental procedure used to examine these questions was as follows: Out of a possible 24 interjoint locations on the fingers (excluding thumbs) of each hand (12 per hand), two or three loci were stimulated with air jet stimulators (as described in Bliss, Crane, Mansfield, & Townsend, 1966). The stimulus duration was 2.5 msec. The SOA values were 0 msec (simultaneous), 12 msec, 60 msec, 110 msec, and 210 msec. After each trial, the subjects used alphabetical labels to report the position of each stimulus. The data were then analyzed in terms of fraction of positions correctly identified (content) and fraction of positions perceived in the correct sequence and the correct location (content and order).

Within the framework of the questions listed above, the results indicated that for 2 stimuli (n = 2), performance for content correct was at the 95% level even when the stimuli were delivered simultaneously, suggesting for that task, at least, SOA was necessary for correct identification of spatial localization of the stimuli. However, the minimum SOA required for correct identification of the spatial localization plus temporal sequence of the stimuli was 26 msec.

Regarding question two, the spatial separation for stimuli presented to the same hand seemed to affect the sensitivity of order judgments; as spatial separation between stimuli decreased, subject's judgments of temporal order improved.

For the final question, dealing with increasing the number of loci, when n = 3, the spatial localization accuracy remained high even with simultaneous presentation of the stimuli. However, the percentage of correct temporal order judgments dropped dramatically, and the temporal order limen increased to approximately 70 msec.

In a subsequent series of experiments, the number of loci was increased to four and to six, thus making it even more comparable to the current study. It was found that when n = 4 and n = 6; 195 msec and 340 msec, respectively, were the thresholds for temporal order. Hill concluded that to correctly order stimuli from an increasing number of loci, longer SOA values would be needed. In addition, Hill found that when n = 4 and n = 6, the ability to spatially localize stimuli was dependent upon SOA values. This finding was contrasted with the fact that in the Hill and Bliss (1968b) study, where n = 2 and n = 3, content correct scores seemed independent of SOA values. Therefore, the ability to identify stimuli in the correct temporal sequence as well as in the correct spatial position is dependent upon SOA, at least when the number of loci receiving stimuli is more than three.

With reference to these results, Hill and Bliss (1968b, p. 289) made the following observation: "Obviously, the transmission of information in the tactile sense is limited by both spatial and temporal interactions. The presentation of a tactile point stimulus either simultaneous with, or in close proximity to, another point stimulus will affect the accuracy of perceiving that stimulus."

Touch and Attention

Early studies of the effects of attention on the perception of tactile stimuli were primarily signal detection tasks. Franzen, Markowitz, and Swets (1970) investigated the possibility that attention was the limiting factor in a detection task involving two stimuli. They concluded that there was no indication of spatial summation, nor were the subjects successful in attending to more than one locus. This prompted the authors to posit a single-channel model of attention for vibrotactile stimulation. This was inconsistent with Craig's (1968) assertion that subjects were able to attend to two fingers simultaneously. To address these disparate results, Shiffrin, Craig, and Cohen (1973, p.330) asked the question, "Does the ability to detect the presence of a near threshold vibrotactile stimuli at a given spatial locus depend on the total number of loci that are being monitored simultaneously for signals?" The experimental procedure in this study was as follows: A vibrotactile stimulus was delivered either to one of three possible loci (simultaneous), or to a series of specific precued loci (successive). The three loci receiving stimuli were the thenar eminence on the right hand, the left index finger, and the volar surface of the forearm. The authors felt that most attention models would predict that successively delivered stimuli would be easier to process than simultaneously delivered stimuli. However, their 1973 study found no such advantage. This finding was taken to indicate the existence of an unlimited-capacity model requiring very little attention for detecting near threshold stimuli.

In 1974, Sullivan and Turvey attempted to provide a tactile analogue to verbal short-term memory (STM) studies by presenting serial suprathreshold tactile stimuli to the phalanges of either hand. Two aspects of this study are particularly relevant to the current study: First, the tactile stimuli were delivered successively and were to be recalled in both the correct spatial position as well as in the correct temporal order; and second, the subjects, in one condition, were asked to perform a distractor task during the interval between the delivery of the stimuli and the response.

Because in the no-distractor condition there was a performance decrement on the later trials, it was inferred that tactile STM is vulnerable to the influence of prior stimulation. The proactive interference was eliminated by lengthening, to several minutes, the intervals between trials. Therefore, proactive interference is a factor to be kept in mind in any paradigm involving the rapid delivery of stimuli to multiple loci. In addition, the distractor task impaired retention, and forgetting reached asymptotic levels at about 6 sec. Thus, in light of the Sullivan and Turvey results, it is possible that proactive interference as well as increased attentional demands could influence the subject's responses.

One of the limitations encountered when dealing with the tactile sense is the fact that for the most part, information is processed serially rather than simultaneously as in the visual system. In an effort to enlarge each "chunk" of sequentially delivered tactile information, there have been attempts to expand the display area for tactile sensory substitution devices. A consideration investigators must keep in mind, is whether this expansion is best served by keeping the delivery of stimulus information ipsilateral, or if the ability to attend to multiple stimuli is facilitated by the increased spatial separation that results from the bilateral delivery of the stimuli. Craig, Green, & Rhodes (1985) tested the efficacy of ipsilateral versus bilateral placement of a tactile vocoder display (a two-dimensional vibrotactile array that displays the spectral pattern of speech information). Performance was better in the bilateral condition. A second study, in which vibrotactile patterns were presented to two adjacent fingers or to two fingers on opposite hands (Craig, 1985), again resulted in superior performance for the bilateral condition. An obvious explanation for the better bilateral performance is that the stimuli delivered to the ipsilateral sites are subject to masking effects. Craig (1985) agreed, at least in part, with this explanation, however he added that masking alone is not sufficient to account for the extremely large differences in the two conditions. He speculated that, "The two processes, masking and attention, may represent two aspects of the skin's ability to organize patterns spatially". And that, "... bilateral presentation of two patterns permits much greater flexibility than does ipsilateral presentation: Subjects may either attend to a single site, no masking, or attend to two sites with little attentional deficit" (Craig, 1985, p. 509).

The purpose of this review of attentional factors and how they relate to tactile discrimination is not so much to provide absolute reference values as it is to point out that attention is a factor to be considered when seeking to establish the most viable method by which a tactile-visual substitution system can transmit information. A system that is too attentionally demanding may drain attentional resources to the extent that the user quickly becomes stressed, fatigued, and unable to cope with any other simultaneously occurring stimuli.

Summary Outline of Historical Review

Characteristics of touch and temporal discrimination:

1. The temporal order limen for stimuli delivered to two finger loci is about 26 msec (Hill & Bliss, 1968b).
2. The temporal order limen can be reduced to approximately 12 msec if the ipsilateral stimuli are delivered to adjacent sites on the same finger (Hill & Bliss, 1968b).
3. As the number of loci receiving stimuli increases, the temporal order limen also increases. For example, if the number of stimuli is increased from two to three, the temporal limen jumps from 26 msec to 52 msec (Hill and Bliss, 1968b).

Characteristics of touch and spatial discrimination:

1. Tactile two point discrimination and error of localization studies have established the fingertips as highly sensitive areas of the body (Weinstein, 1968).
2. Apparent motion can affect perception of spatial location at SOAs that range from 12 msec to 200 msec (Hill & Bliss, 1968b).
3. Although masking effects may interact with the ability to correctly identify the spatial position of tactile point stimuli, Hill and Bliss (1968a)

claim that these effects are negligible within the the paradigm of their study.

4. Localizing capability for tactile stimuli delivered to the fingers is independent of SOA for one to three stimuli. If the number of stimuli exceeds three, subjects require longer SOA values in order to accurately localize the stimuli (Hill, 1971).

Characteristics of touch and spatiotemporal interactions:

1. The temporal limen appears to decrease as spatial separation is decreased (Hill & Bliss 1968b).
2. If temporal intervals remain constant while spatial distances vary, temporal order judgments may be affected (Yoblick & Salvenky, 1970).

Characteristics of touch and attention:

1. Human subjects can attend to the simultaneous delivery of stimuli to two loci (Craig, 1968).
2. Tactile STM decays rapidly to asymptotic levels within about 6 sec (Sullivan & Turvey, 1974).
3. Tactile STM is vulnerable to proactive interference for up to several minutes (Sullivan & Turvey, 1974).
4. Discriminability is better for bilaterally delivered vibrotactile patterns than for

ipsilateral presentations (Craig, 1985). This bilateral advantage may be due to a combination of reduced masking effects and enhanced attention.

GENERAL METHOD

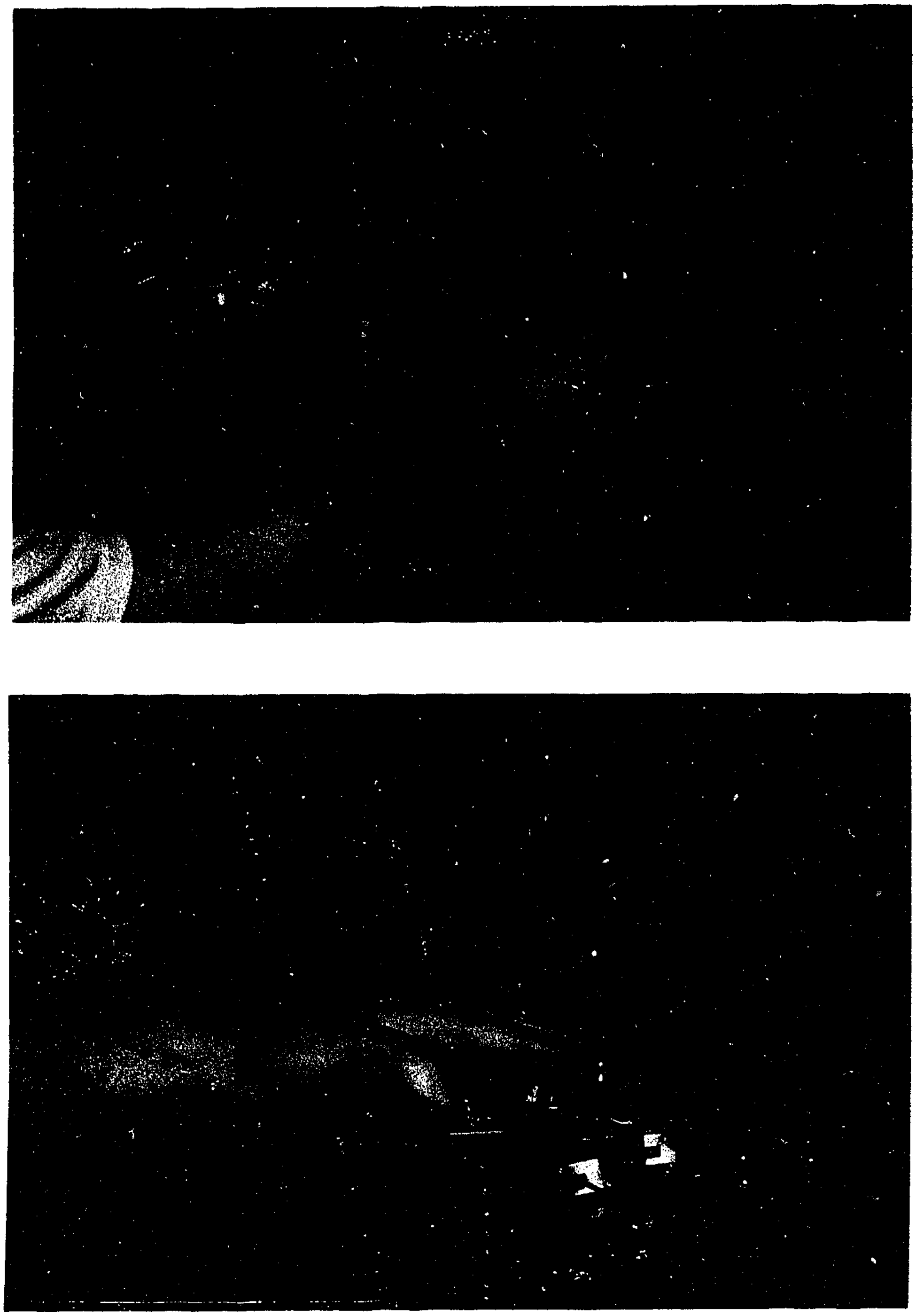
Although eight separate experiments comprised this study, the same subjects, apparatus, and general procedure were used. A description of those experimental manipulations specific to each experiment is presented when experiments are detailed separately.

Subjects

The subjects were two right-handed males and one right-handed female. Hand dominance was defined by the preferred use of one hand for tasks such as writing and other routine motor tasks. All of the subjects had participated in an extensive series of pilot studies similar to this study and had established response levels that were no longer subject to significant improvement as a function of continued practice.

Apparatus

A custom-designed, computer-controlled stimulus generator and programmer provided precise control of the intensity, number, locations, and temporal parameters for the stimuli. Each tactile stimulus was delivered as a brief burst of five, two-msec rectangular pulses. Because the interpulse separation was approximately 250 μsec, the total tactile stimulus pulse duration was [illegible]entially 10 msec. The pulses were transmitted to a bi[illegible] [illegible]ezoelectric transducer. The contactor was a [illegible] rod [illegible]65 cm in diameter attached to the transduc[illegible] The [illegible]as an array of 8 contactors, one for each finger o[illegible] [illegible]nds (see Fig.1), thumbs excluded. The stimulator array could be adjusted to accommodate a wide range of hand sizes to ensure direct contactor placement upon each of the pads of the distal phalanges. Depression of the contactor sufficient to contact the microswitches and generate a stimulus sequence or to record the subject's response, required a force of 20 grams.



<u>Figure 1</u>. Top and side view of the stimulus delivery apparatus.

Procedure

The subjects were seated at the simulator table with their forearms supported by armrests. The lucite contactors were adjusted to the length of each subject's fingers. To eliminate auditory cues and distractions, the subjects wore stereo headphones that continuously presented white noise. Subjects initiated the onset of each stimulus sequence by pressing any one of the contactors.

During a preliminary testing condition a modified method of limits procedure was used for each subject to determine the levels of stimulus intensity required for 100% detection. Once established, this clearly perceptible level of stimulus intensity was increased to ~15 dB above threshold level for each subject. This intensity level was matched by the pulse intensity delivered to each locus, so that pulses presented to the different loci were perceived as equally intense.

The factors manipulated or examined in this study were: the number of finger loci stimulated, the temporal intervals between stimuli, the interaction between loci and temporal intervals, and the ability to focus attention. In addition, the number of stimulus pattern repetitions (one presentation or three repetitions of the stimulus pattern) was examined.

More specifically, the number of finger loci (i.e. the spatial variable) was examined in terms of the subject's ability to accurately localize the stimuli under conditions of first simultaneous, and then, successive delivery. Examination of the temporal variable was restricted to conditions where stimuli were delivered successively and subjects were required to report temporal order as well as spatial location. To measure the ability to focus attention, subjects were asked to attend to and respond with a single hand under two conditions: 1) where only the attended hand received the stimulus pattern, and 2) where a pattern similar to the test pattern was delivered to the unattended hand as the test pattern was being delivered to the attended hand. Subjects were told to ignore the stimuli delivered to the unattended hand. As well, they were not given any information regarding the nature of the stimuli being delivered to the unattended hand.

Random configurations of the tactile stimuli sequences were generated in a file prior to testing and were available as the source for the stimulus patterns. For all conditions, the subjects responded to the stimulus pattern by depressing the contactors through which they believed the stimulus to have been presented. As soon as the contactors were depressed, the responses were recorded by the computer and, at the end of each trial, displayed (indicating correct or incorrect) on a video monitor directly in front of the subject.

When conditions involved only simultaneously presented stimuli, the subjects were aurally prompted by the computer to alternate between the right and left hand when making the initial response to a stimulus pattern. Apart from being asked to finish responding with the first hand before beginning a response with the other hand, subjects, without regard for any specific order, were simply to depress those contactors they perceived to have been activated during the stimulus sequence. In those conditions where the stimuli were delivered successively, the subjects were instructed to depress the contactors through which they received the stimulus in the same order as that of perceived presentation. As well, to be consistent with the effort made in all other conditions to preclude a first-hand advantage being conferred on a particular hand, the pattern was alternately delivered first to the right hand, then first to the left hand.

For those conditions that involved the delivery of stimulus patterns only to the attended hand, subjects were asked to place the unattended hand on the stimulator table adjacent to the apparatus. As mentioned above, the responses to simultaneous stimuli were to identify the spatial location of stimulus delivery; responses to successive stimuli were to preserve the order of presentation as well as spatial location.

Each condition in all of the experiments was tested by five sets of 40 trials each, resulting in a total of 200 trials, or stimulus patterns per condition, per subject.

Explanation of Terms and Reporting Procedures

Before considering the individual experiments, general terminology and reporting methods used in the subsequent chapters will be briefly specified.

First, a _session_ consists of five _sets_ of 40 _trials_ (or _stimulus patterns_), and a _stimulus_ is the actual 10-msec pulse.

In each of the experiments, the scores of the three subjects reflected essentially similar functions in that response accuracy either improved or decremented at approximately the same rate as a function of the independent variable, and, as such, were combined for data analysis.

Although laterality was a factor being investigated in each of the experiments, aside from Experiment 1 there was never any significant difference between the right and left hand beyond that of a very slight, but persistent, right-hand preference.

Experiments 2, 4, 6, and 8 contain a condition where a pattern of stimuli is delivered to the unattended hand. As it was originally thought that these stimuli would distract the subject and cause response scores to decline, these stimulus patterns will be referred to as the distractor patterns.

All data values are reported in terms of proportion of correct responses (i. e. .657, .788). In this regard, "content" refers to the correct identification of spatial location, and "order" to the correct identification of spatial location in the correct temporal order. Hence, order scores can never exceed content scores.

Table 2 is provided to illustrate the progressive expansion of spatialto spatiotemporal tactile pattern perception from Experiment 1 through Experiment 8.

Table 2

Conditions for Eight Experiments of Current Study

	Spatial Condition	Temporal Condition		1 vs 3 Pattern Repetitions	Attention/ Distractor Condition
Experiment #		IHI	SOA		
Exp.1	x			x	
Exp.2	x				x
Exp.3	x	x		x	
Exp.4	x	x			x
Exp.5	x		x	x	
Exp.6	x		x		x
Exp.7	x	x	x	x	
Exp.8	x	x	x		x

EXPERIMENT 1

This experiment focused exclusively upon the correct identification of the spatial location to which the stimulus was delivered. Temporal aspects were eliminated by delivering the stimuli to all target locations simultaneously. Specifically, Experiment 1 consisted of the simultaneous delivery of pulses to both hands and fingers in the following configurations: 1) two fingers of each hand (4 loci), and 2) three fingers of each hand (6 loci). For the first session (five sets of 40 trials each), each stimulus pattern was presented once before the subject responded. In the subsequent session the stimulus patterns were presented three times prior to subject response, with a 250-msec interpattern interval (IPI).

The questions addressed in this experiment included: a) Was subject performance differentially affected by a triple pattern delivery versus a single pattern delivery? b) Did increasing the number of loci simultaneously stimulated result in a performance decrement? c) Because this was a spatially oriented task involving stimulation of both hands, was there a laterality preference?

The factors considered for the analysis of data were pattern delivery (one time versus three times), number of loci (two fingers versus three fingers per hand), and hand preference (right or left).

Results and Discussion

When the stimulus pattern was delivered three times (.788), subject performance improved [$F(1,2) = 32.02$, $p < .05$] over that obtained when the stimulus pattern was delivered only once (.657). The actual increase in response accuracy was 14% for the four loci condition and 20% for the six loci condition. Not surprisingly, as the number of loci receiving stimuli increased from four (.742) to six (.572), performance dropped sharply [$F(1,2) = 32.10$, $p < .03$]. There appears to have been a slight right hand advantage (right, .740; left, .706) that may have simply been due to the fact that all of the subjects were right-hand dominant [$F(1,2) = 20.85$, $p < .05$].

When the data from Experiment 1 are compared to the data from the Hill and Bliss (1968b) study (see Fig. 2), it must be remembered that their subjects could receive the stimuli on any one of 24 finger loci, whereas the subjects in this study were required only to attend to eight possible finger loci. Obviously, the spatial localization task was far more difficult for the Hill and Bliss subjects. Yet, despite the differences in response accuracy, the functions were quite similar, indicating that perhaps common mechanisms were underlying performance changes.

Although the task required only that each stimulus position be localized, and did not include any temporal ordering demands, four to six stimuli presented simultaneously for a duration of just under 10 msec is a significant amount of information to be perceived and recalled after so brief a presentation. This is reflected by the fact that even with the reduced number of potential sites for stimulation, the performance level for the subjects in Experiment 1 did not reach a 75% correct level for either the four- or six-loci one-time presentation conditions. Only under the triple-presentation, four-loci condition were subjects correct more than 75% of the time.

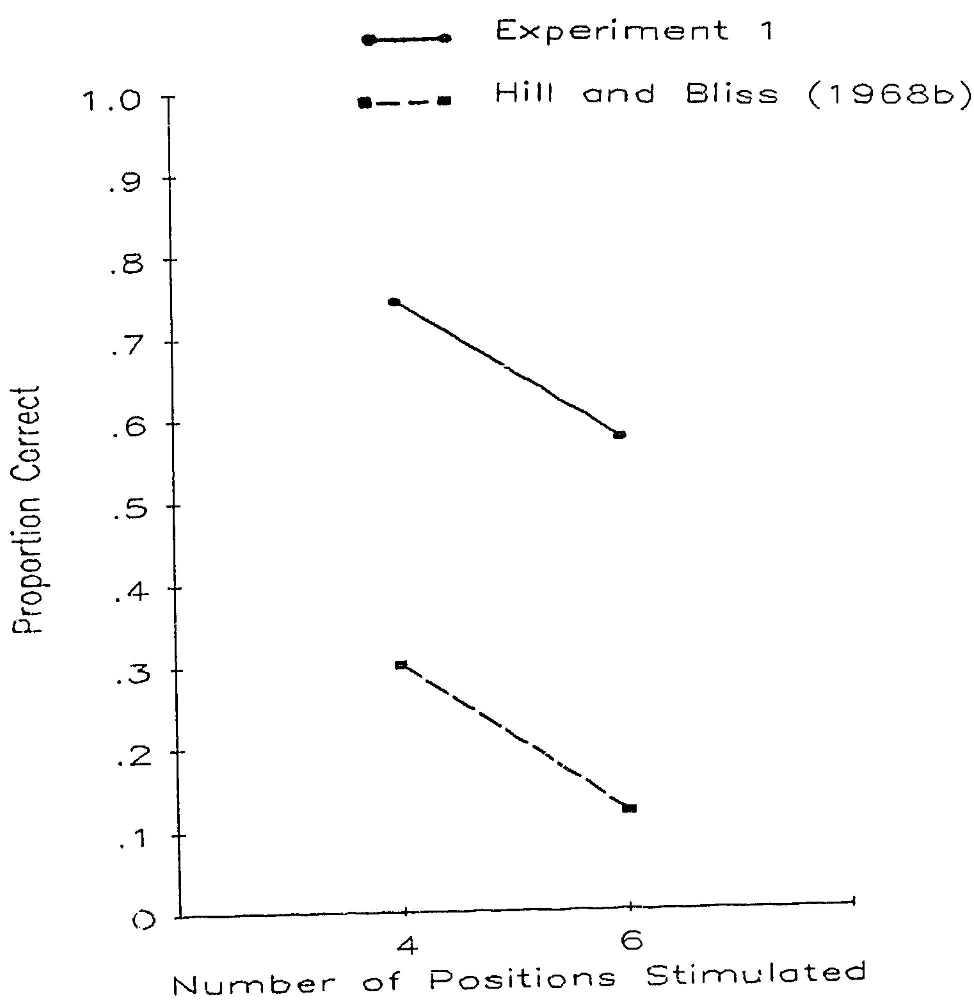


Figure 2. Proportion of correct responses as a function of number of loci stimulated for Experiment 1 and Hill and Bliss (1968b). Data points represent mean correct reports of spatial location; i.e., content scores.

EXPERIMENT 2

As in Experiment 1, the task was designed to assess the subject's ability to process the spatial components of a stimulus sequence. However, instead of responding with both hands, the subjects were instructed to attend to and respond with only one hand. The subjects were not given any information regarding the nature of the stimulus patterns being presented to the unattended hand, and were asked to focus their attention on the hand designated to respond. There were three types of patterns delivered for both the two and the three finger condition: 1) a pattern delivered to only one hand; 2) spatially and directionally identical patterns delivered to both hands, (i.e. the left hand would receive stimuli to the little finger and ring finger; the right hand would receive stimuli to the index finger and middle finger, in that sequence), henceforth referred to as the spatial pattern; and 3) a pattern delivered to both hands where the patterns delivered were identical in terms of the specific fingers being stimulated (i.e. the left hand would receive stimuli to the little finger and ring finger; the right hand would receive stimuli to the little finger and ring finger, in that sequence), and referred to as the mirrored pattern. The hand to which the subject attended was alternated between sets of trials so that 200 trials were presented per hand for each distractor/no distractor condition.

Of interest in this experiment was the degree to which the stimulus delivered to the unattended hand affected the subject's responses with the attended hand. Specifically, was the degree and extent of the effect determined differentially by the type of distractor pattern delivered?

When analyzing the data, the factors considered were attention (one hand receiving stimulus target pattern versus one hand receiving target pattern simultaneously with other hand receiving distractor pattern), number of loci (two fingers versus three fingers per hand), and hand preference (left or right). A subsequent analysis compared the effect of the type of pattern delivered to the unattended hand (spatial versus mirrored) and the number of loci stimulated.

Results and Discussion

There was a significant number-of-loci effect [$F(1,2) = 99.78$, $p < .01$] in that the scores for two loci (.896) were much higher than those for three loci (.588). When averaged across all conditions, the presentation of a pattern to the unattended hand facilitated the scores of the attended hand (.715, no distractor; .769, with distractor). This significant result [$F(1,2) = 27.87$, $p < .05$] must be qualified in that the facilitation effect was entirely associated with the mirrored pattern. It was initially anticipated that a distractor, regardless of pattern type, might disrupt attention to the attended hand and, as a consequence, response scores would decline. In addition, it was felt that, depending on distractor pattern type, there might be a difference in the degree of decrement caused by the distractor.

The decision to use the spatially and directionally identical (spatial) patterns was based upon Lechelt's (1974a,b,) findings that when subjects were asked to count sequences of transient tactile stimuli, their performance was better when the stimuli were a series of successive taps in a zip pattern (where stimuli are delivered in a directionally identical sequence), as opposed to a ping-pong pattern (where stimuli skip back and forth between fingers and/or hands). Because the patterns delivered to both the attended and unattended hand in Experiment 2 were presented simultaneously, the zip pattern, by necessity, was presented in a temporally "static" form. For subsequent experiments within the current study, which are characterized by successive delivery of the stimuli, it was felt that if the pattern delivered to the unattended hand faithfully duplicated the directional sequence of stimuli delivered to the attended hand, the resulting pattern would be "zip-like".

The second type of distractor pattern, labeled the identical pattern (mirrored), was included because of a reference in a Craig (1968) paper to the phenomenon of statistical summation. In that instance, the task was one of detection, and statistical summation was the term used to describe the probabilistic improvement for detecting the stimulus when there was more than one stimulus being presented. Based on this, it seemed that a stimulus delivered to the right index finger would be easier to identify in its correct spatiotemporal position if the distractor stimulus were being delivered to the identical spatiotemporal position on the opposite hand, rather than to a noncorresponding loci.

When the data were examined to determine the effects of the two types of distractor patterns, it was found that if the mirrored pattern were presented, content correct performance improved considerably (see Fig. 3), and when the distractor was the spatial pattern, content correct performance declined slightly compared to that achieved when no distractor was present. If the two distractor patterns are directly compared [$F(1,2) = 163.76$, $p < .01$], the mirrored pattern is profoundly and consistently superior (.925) to that of the spatial pattern (.626). Performance fell off sharply as the number of loci increased, except when the mirrored pattern was presented to the unattended hand, resulting in a significant Loci-number x Distractor-pattern interaction [$F(1,2) = 80.95$, $p < .01$]. Therefore, delivering what amounted to simultaneously presented redundant mirrored information to the unattended hand caused performance levels for the six-loci condition to improve almost to the point of becoming equivalent to performance for the four-loci condition. Because the stimuli were delivered simultaneously, performance was measured using content correct. This result seems to provide at least one potential answer to Sherrick's question as to how best to increase the rate of improvement for larger numbers of loci as a function of increasing SOA; provide redundant information.

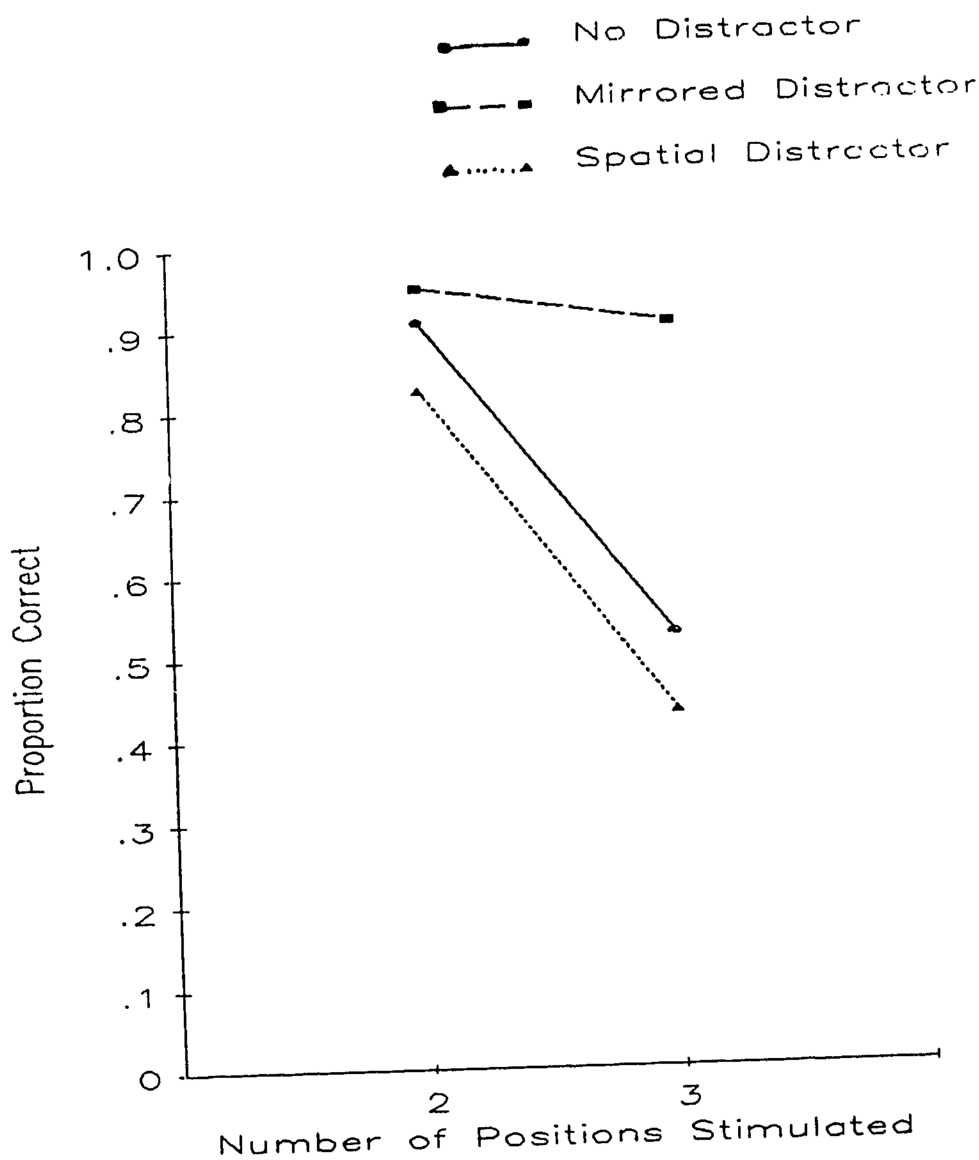


Figure 3. Proportion of correct responses as a function of number of loci on the attended hand receiving stimuli in Experiment 2. Data points represent mean correct content scores.

EXPERIMENT 3

A temporal component was introduced in Experiment 3 by separating the stimuli presented to each hand by a 250-msec interhand interval (IHI). Apart from the addition of the interhand interval, the procedure followed in Experiment 3 was identical to that of Experiment 1.

Therefore, pattern delivery (one time versus three times), number of loci (two fingers versus three fingers per hand), hand order (hand that received the stimulus first versus hand that received the stimulus second), and hand preference were the factors considered for the primary analysis of the data. An additional analysis was planned to determine if the presence of the IHI affected performance as compared to performance on Experiment 1 where all stimuli were delivered simultaneously.

Results and Discussion

As in Experiment 1, delivering the stimulus pattern three times resulted in improved performance [$F(1,2) = 17.69$, $p < .05$]. However, the degree of improvement was not as large, probably because performance levels increased due to the presence of the 250-msec IHI. Response scores declined significantly [$F(1,2) = 191.77$, $p < .01$] as loci were increased from four (.891) to six (.775), although the decrement was not as pronounced as that seen in Experiment 1. Response accuracy was clearly superior for the hand receiving the stimuli first [$F(1,2) = 89.14$, $p < .02$], regardless of whether it was the right or left hand (.865, first; .800, second). Curiously, when compared to the left hand, the right hand benefited more when receiving the stimuli first, and suffered more when it was the second to receive the stimuli.

The most noteworthy result in this experiment is the fact that the presence of the 250-msec IHI enhanced performance for all conditions [$F(1,2) = 27.60$, $p < .05$]. As illustrated in Table 3, a 250-msec IHI improved performance as much as the triple delivery of the stimulus pattern. In terms of subject performance, it appears as though the temporal expenditure of 250-msec yields as much improvement as the 530 msec required to deliver the pattern three times. Further, in the four-loci condition, the addition of the triple pattern delivery to the already IHI-enhanced response accuracy improved performance an additional 7%, increasing the temporal cost by 1010 msec (or 474%). Because of the relatively large amount of time consumed in exchange for so small a performance improvement, the triple pattern does not appear to be a very promising approach, particularly when considering the essential elements of a sensory substitution system; namely, rapid and accurate information transmission and acquisition.

Table 3

Percent Content Correct for Pattern Repetition versus Interhand Interval Facilitation

Condition	# of Repetitions	(4 loci)	
	1 Repetition	3 Repetitions	% Improvement from Triple Pattern
No IHI (Exp.1)	74.2	86.3	14.0
250msec IHI (Exp.3)	85.8	92.3	7.0
% Improvement from IHI	14.5	6.5	
		(6 loci)	
No IHI (Exp.1)	57.2	71.3	19.8
250msec IHI (Exp.3)	71.3	83.7	14.8
% Improvement from IHI	19.8	14.8	

EXPERIMENT 4

Experiment 4 was similar to Experiment 2, except that it included a 250-msec IHI. Subjects were required to attend to and respond with only one hand. Again, two types of distractor patterns were delivered to the unattended hand: spatial and mirrored. The hand to which the subject attended was alternated between sets of trials so that 200 trials were presented per hand for each condition. As before, the delivery of the initial pattern was alternated between hands so that in this experiment, the IHI occurred prior to the delivery of the stimuli to the attended hand 50% of the time.

The factors examined in the analysis of variance were, the type of pattern delivered to the unattended hand (spatial versus mirrored), number of loci (two fingers versus three fingers per hand), and hand preference. Also, the results of Experiment 4 were compared to those of Experiment 2 to determine if the 250-msec IHI contributed to improved performance.

Results and Discussion

The results for Experiment 4 were similar to those obtained in Experiment 2. The increase from two loci (.947) to three loci (.645) was significant [$F(1,2) = 511.89$, $p < .01$]. When the effects of the two distractor patterns were directly compared, the mirrored distractor patterns resulted in higher scores (.905) than those achieved with the spatial distractor patterns (.687). This difference in scores was significant, [$F(1,2) = 101.54$, $p < .01$]. The presence of a 250-msec IHI did not appreciably affect scores. It would appear that the enhancement effect obtained when a mirrored pattern is being presented to the unattended hand remains relatively constant regardless of whether the distractor is presented simultaneously with, or 250 msec before or after the patterns are presented to the attended hand (see Table 4).

There was a significant interaction between the number of loci stimulated and the type of distractor pattern [$F(1,2) = 48.89$, $p < .02$]. As the number of loci increased from two to three, the discrepancy between the response accuracy for spatial and mirrored conditions increased.

Table 4

Percent Content Correct with Mirrored Distractor; No Interhand Interval versus 250-msec Interhand Interval

Condition	Mirrored Distractor Pattern	
	4 Loci	6 Loci
Exp. 2 (no IHI)	94.8	90.2
Exp. 4 (250msec IHI)	96.3	84.7
	No Distractor Pattern	
Exp. 2	90.6	52.4

EXPERIMENT 5

This experiment included a greater temporal component. The stimulus patterns were delivered simultaneously to both hands, but the fingers were stimulated successively. Four levels of stimulus onset asynchrony (SOA) for the successive finger patterns were tested; 60 msec, 160 msec, 260 msec, and 360 msec. Subjects were instructed to respond not only with the spatial locations at which the stimuli were felt, but also in the same temporal order that the stimuli were perceived to have been delivered.

As with Experiments 1 and 3, pattern delivery (one time versus three times), number of loci (two fingers versus three fingers per hand), and hand preference were all factors considered in the data analysis. Because of the additional temporal component, there were two new conditions incorporated into the data analysis; content versus order (where content is the correct identification of spatial location and order is the correct identification of spatial location in the correct temporal order), and the four SOA values.

Results and Discussion

When compared to single pattern presentation, delivery of the stimulus pattern three times improved performance both for content (.721, one time; .821, three times) and temporal order (.471, one time; .552, three times). Over both conditions, content and order, the improvement was significant [$F(1,2) = 28.91$, $p < .05$]. For content correct values, the degree of improvement (in terms of triple pattern delivery versus single pattern delivery) was slightly less than that of Experiment 1 (down 4% for four loci and 5% for six loci). This was expected because the successive delivery of the stimuli provided the subjects with additional time to process each stimulus, hence the scores for the single pattern condition were elevated, although still inferior to the triple pattern condition, relative to those of the triple pattern repetition. Again, increasing the number of loci receiving stimuli resulted in rather pronounced performance decrements (.751, four; .531, six). This was significant at [$F(1,2) = 33.05$, p, $< .05$].

The results of this experiment confirmed the expectation that recalling where an event occurred should be easier than remembering both when and where it occurred (see Fig. 4). When data were summed over all other conditions, response accuracy was higher for content (.771) than for order (.511), which was significant at [$F(1,2) = 319.8$, $p < .01$].

As expected, the successive delivery of the stimuli enhanced performance over that obtained with simultaneous delivery of the stimuli [$F(1.6,3.1) = 16.82$, $p < .02$]. The enhancement effect (for correct order) steadily increased commensurate with increasing SOA resulting in a significant Loci x C/O interaction [$F(1,2) = 571.20$, $p < .01$]. However, it is apparent, when examining Fig. 5, that the improved performance came about as a result of increased response accuracy within the temporal ordering component, reflected by the significant Order x SOA interaction, [$F(1,2.1) = 37.67$, $p < .05$]. As illustrated in Fig. 6, it is also apparent that, with the exception of the 60 msec SOA, lengthening the SOA plus delivering the pattern three times improved performance over that achieved with identical SOA values and only a single pattern presentation.

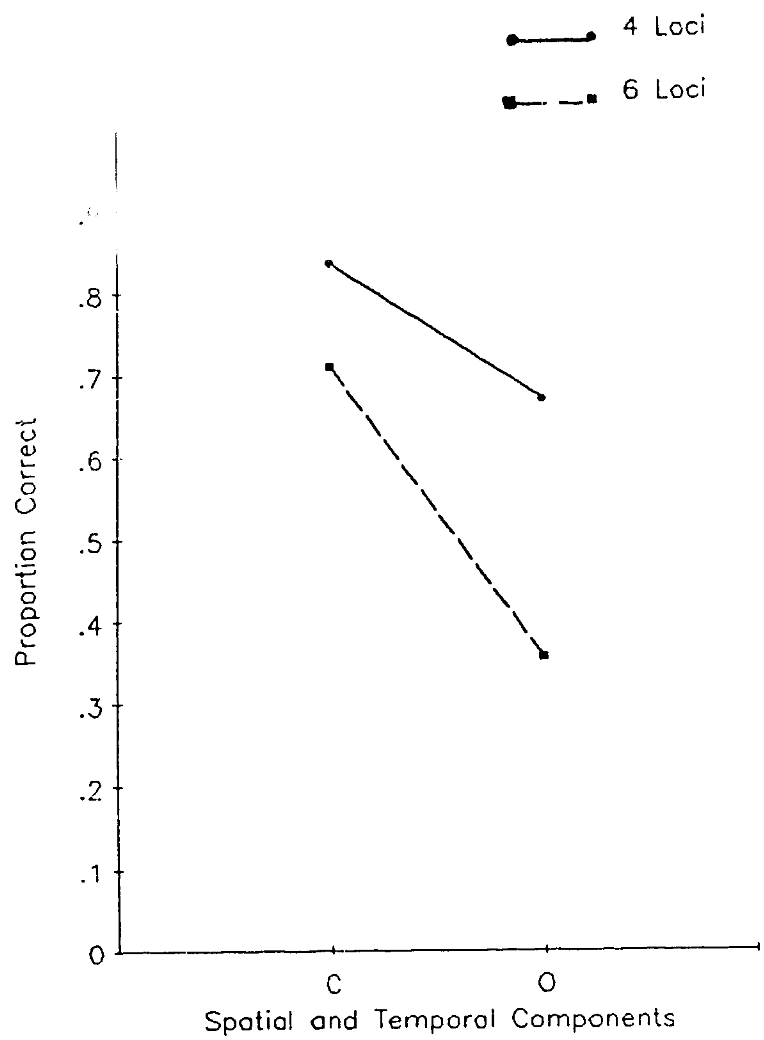
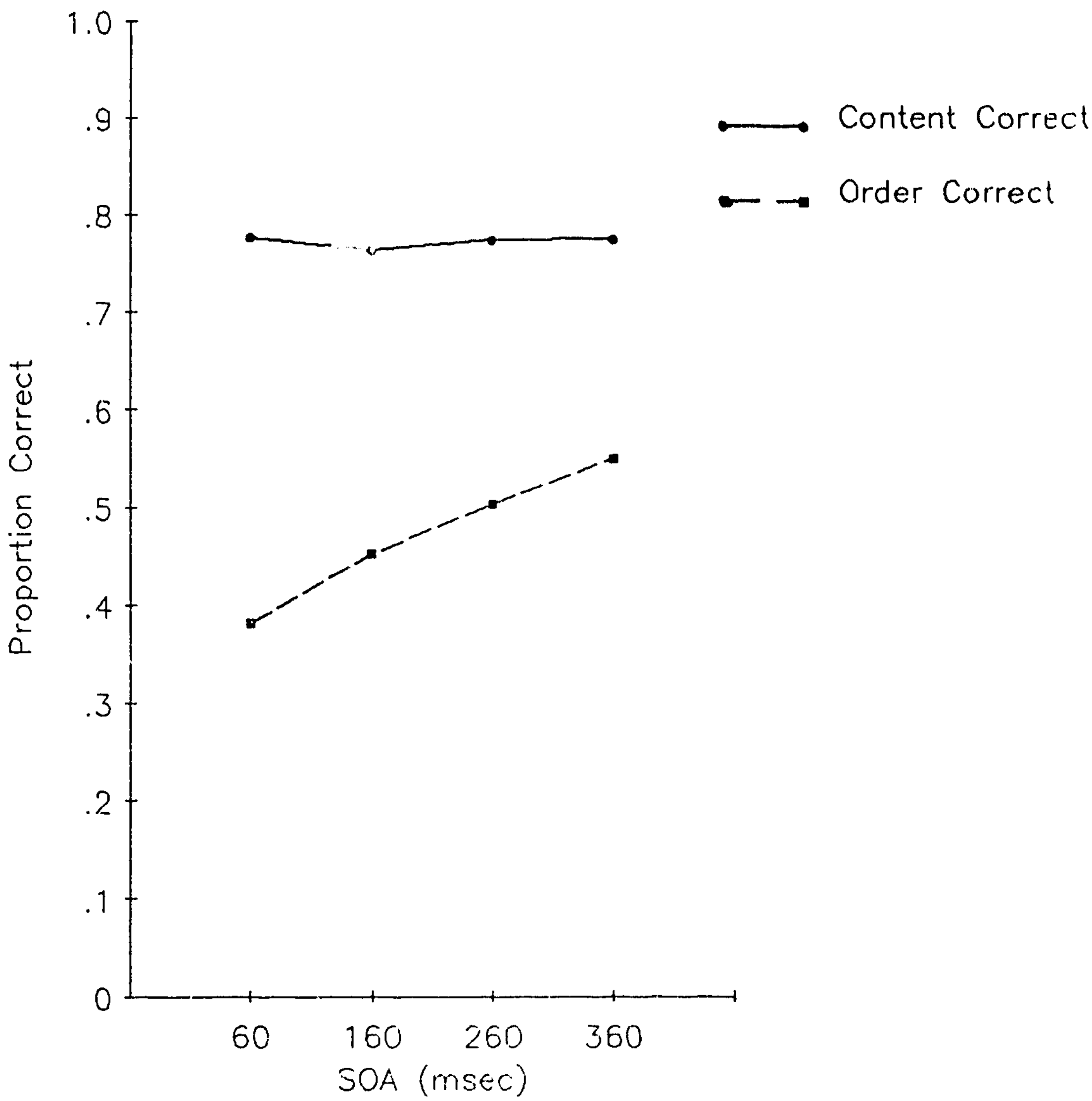


Figure 4. Proportion of correct responses as a function of content versus order (C = content correct, O = order correct).



<u>Figure 5</u>. Proportion of correct responses as a function of SOA for content and order correct in Experiment 5.

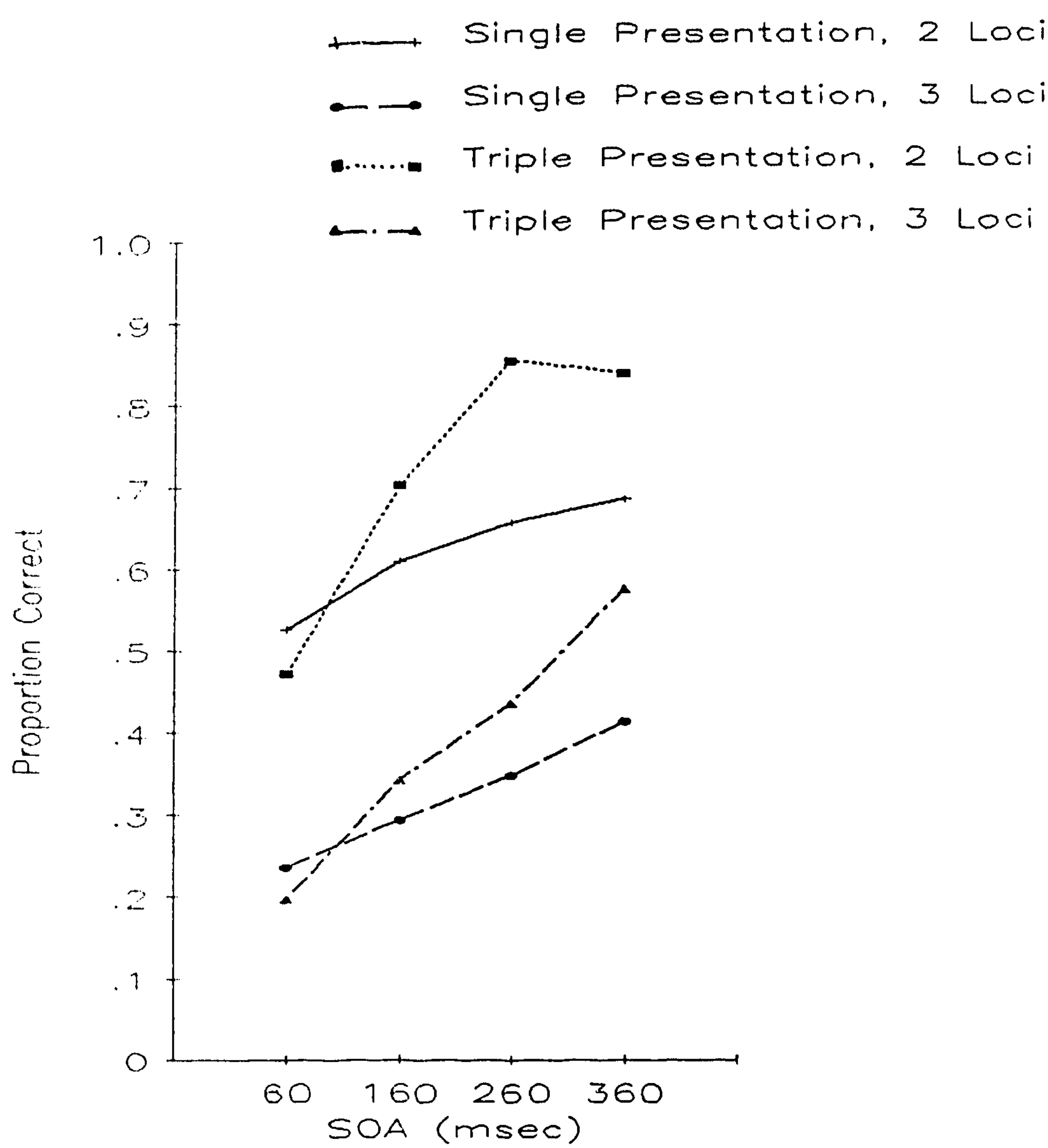
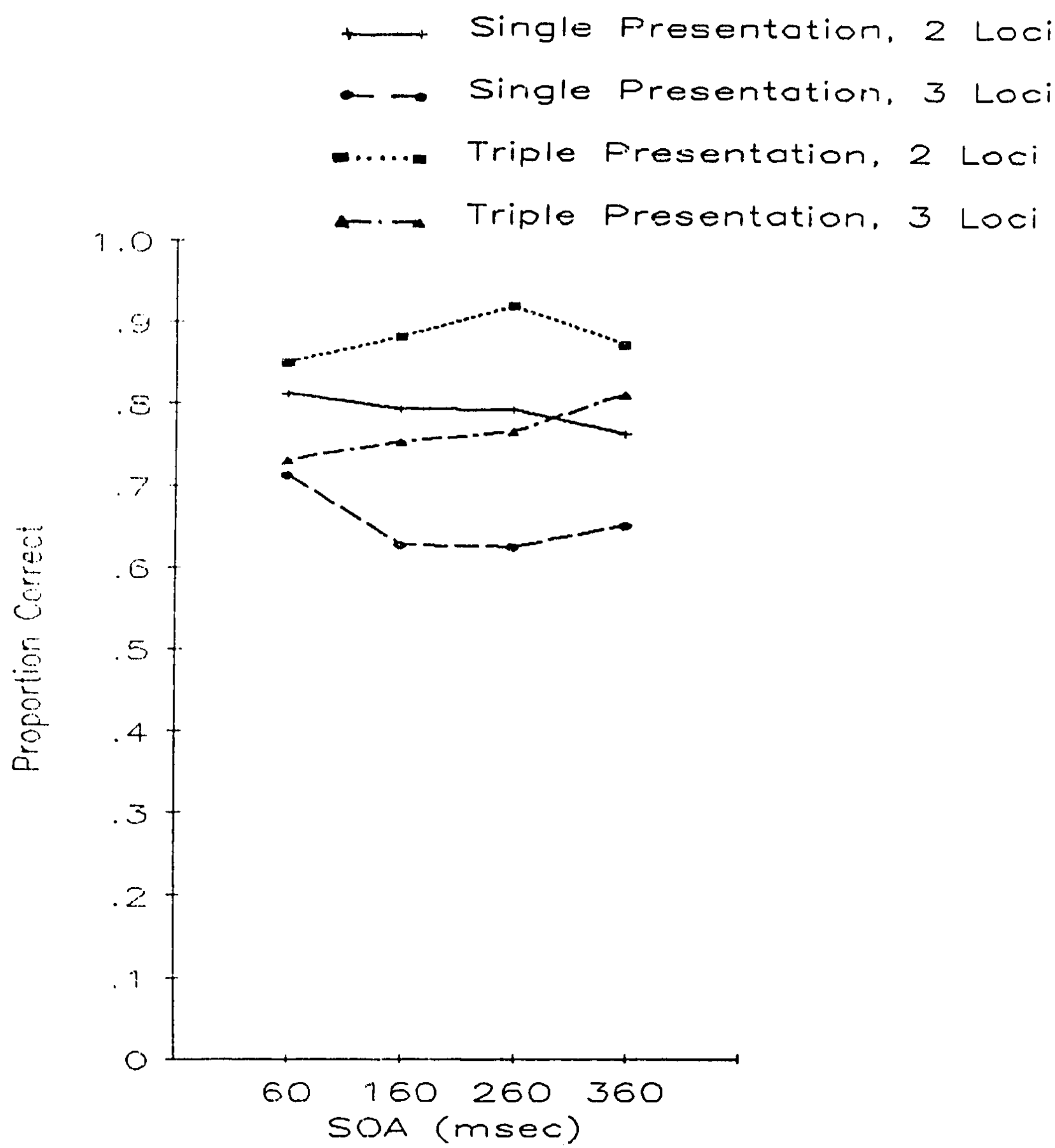


Figure 6. Proportion of correct order responses as a function of SOA. Data are presented according to the number of loci, 2 versus 3, and the number of presentations, single versus triple.

Content scores, improved somewhat when the pattern was delivered three times as compared to a single presentation (see Fig. 7). The relatively flat slope of the content scores across all SOA values might indicate that increasing the amount of time between stimuli provides the subject with a greater opportunity to attend to the ordering component, thereby devoting less attention to spatial localization. When a factor, such as repeating the stimulus pattern is added to the lengthening SOA values, correct content responses shows some modest improvement. This is consistent with the Hill and Bliss (1968b) results where content correct for two and three loci remained relatively unaffected by varying SOAs. It is, however, inconsistent with Hill's (1971) results, obtained when the number of loci was increased from four and six. These results indicated that content scores improved with lengthening SOA, suggesting that they must be dependent upon SOA values, particularly for the six-loci condition. The fact that the content scores in Experiment 5 were essentially independent of SOA, might be explained by the same factor noted in Experiment 1; namely, the subjects were attending to only eight possible sites and were, with the simultaneous



<u>Figure 7</u>. Proportion of correct content responses as a function of SOA. Data are presented according to the number of loci, 2 versus 3, and the number of presentations, single versus triple.

delivery of stimuli, scoring higher than the Hill (1971) subjects, who had to attend to 24 possible sites. Therefore, because the content scores in the simultaneous condition of Experiment 1 were already comparatively high, there was little room for improvement.

Hill (1971) also reported that content correct values dipped suddenly at approximately 60-msec SOA, down from scores obtained at 0-msec SOA. This finding prompted him to investigate masking as a possible cause. However he found no evidence for masking and speculated that perhaps the subjects switched their attention from spatial localization in the simultaneous condition to temporal ordering in the successive condition. This explanation is similar to that mentioned earlier, referring to the flat slope of the content scores with increasing SOAs. Not only was there no indication of this sudden performance decrement in Experiment 5 (see Table 5), but also it seems that performance actually improved for the 60-msec SOA condition.

Finally, there were two additional three-way interactions: Repetition x Loci x Laterality [$F(1,2) = 51.45$, $p < .02$], where the right hand was more susceptible to the effects of the other two variables than the left hand, and Repetition x Laterality x SOA [$F(1,2) = 29.20$, $p <$

.03], where again, the right hand was more profoundly affected by the other two variables.

Table 5

Proportion Content Correct for Hill (1971) versus Experiments 1 & 5: Single Pattern Presentations

	Number of Loci			
	4		6	
SOA	Hill	Current Study	Hill	Current Study
0	.58	.742 (Exp.1)	.63	.572 (Exp.1)
60	.53	.812 (Exp.5)	.45	.712 (Exp.5)

EXPERIMENT 6

Experiment 6, differed from Experiment 1 in that successive delivery with a 60-msec SOA was introduced into the attention task. The 60-msec SOA was included so that the ability to temporally order the stimuli could be assessed. The longer SOA values used in the dual hand experiment were not used because of ceiling effects. As before, the subjects were required to respond with a single attended hand, and identify the temporal order of stimuli delivery as well as spatial location.

The factors examined in the data analysis were attention (one hand without distractor versus one hand with distractor pattern delivery to unattended hand), number of loci (two fingers versus three fingers per hand), hand preference, and content correct versus order correct. In addition, a separate analysis was run to determine if the type of distractor pattern delivered to the unattended hand (spatial versus mirrored) had any effect on performance of the attended hand, for the four- and six-loci conditions.

Results and Discussion

The presence of the distractor pattern again produced a small, but significant [$F(1,2) = 62.14$, $p < .02$], increase in the response accuracy of the attended hand (.597, without distractor; .631 with distractor). This improved performance (see Figs. 8a & b) was also again associated exclusively with the delivery of the mirrored distractor pattern versus, [$F(1,2) = 1298.08$, $p < .001$]. Another observation made in the previous experiments, that content scores for the three-loci condition remained almost as high as those obtained in the two-loci condition, is granted further credibility by a similar set of data for Experiment 6 (see Fig. 8b). As before, increasing the number of loci had a significantly negative effect [$F(1,2) = 424.90$, $p < .005$], on response accuracy (.814, two; .414, three). In addition, content scores (.766) were significantly higher [$F(1,2) = 185.74$, $p < .01$] than order scores (.462).

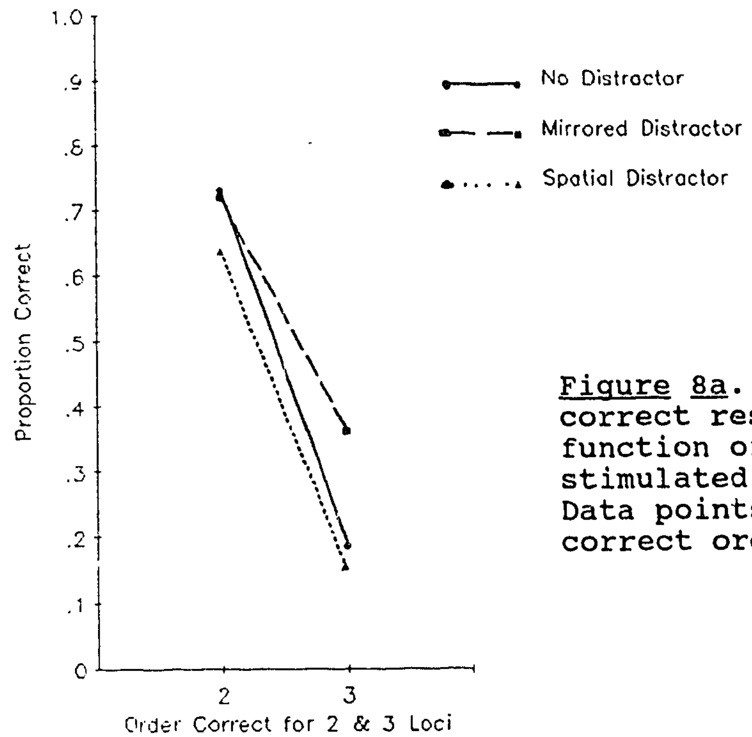


Figure 8a. Proportion of correct responses as a function of number of loci stimulated in Experiment 6 Data points represent mean correct order scores.

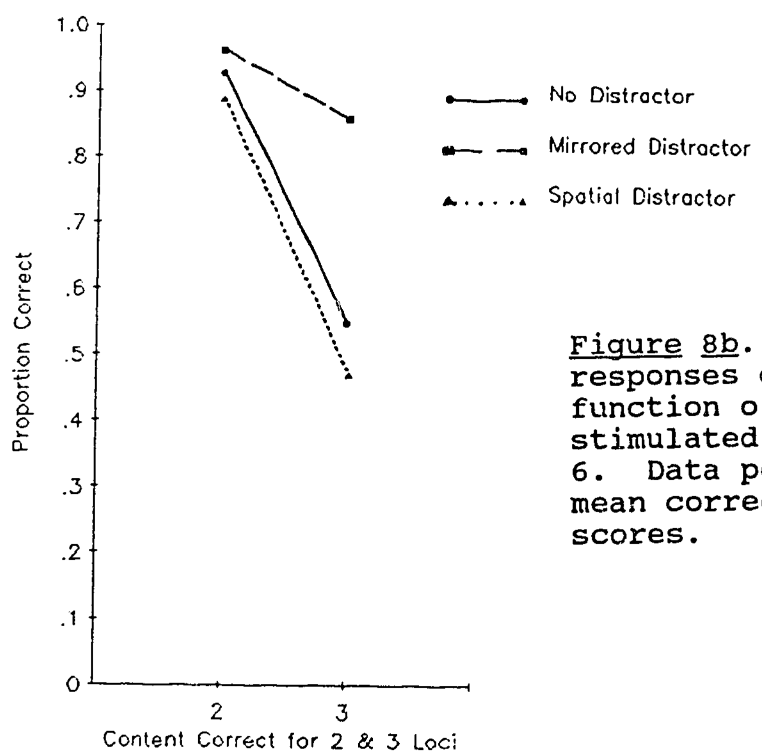


Figure 8b. Proportion of responses corrects as a function of number of loci stimulated in Experiment 6. Data points represent mean correct content scores.

There were two interactions involving distractor type. The first, Distractor x Loci [$F(1,2) = 225.81$, $p < .01$], indicated that as the number of loci increased, the spatial distractor was associated with more of a performance decrement than the mirrored distractor. The second, Distractor x C/O [$F(1,2) = 30.45$, $p < .03$], reflected the fact that distractor type influenced order more than content. An additional two-way interaction achieving significance was that of Loci x C/O [$F(1,2) = 88.40$, $p < .01$], where increased number of loci caused more of a performance decrement for order than for content.

The 60-msec SOA did not improve scores. When compared to Experiment 2, where stimuli were delivered simultaneously, scores for the no distractor condition, spatial distractor, and mirrored distractor remained relatively unchanged (see Table 6). The results suggest that a 60-msec interval is simply too brief to be of much benefit. In a series of exploratory trials it was found that increasing the SOA for Experiment 6 to 160 msec resulted in a task too easy to establish anything other than a ceiling effect. If there were to be further studies similar to this one, it might be more informative to scale down the SOA values and examine a smaller range (i.e. 0 msec, 50 msec, 75 msec, 100 msec, 125 msec, and 150 msec).

Table 6

Content Correct for Experiment 2 (no SOA) and Experiment 6 (60 msec SOA)

	Content Correct		
Condition	0 msec	60 msec	160 msec
No Distractor	0.715	0.738	0.995
Mirrored	0.925	0.910	0.998
Spatial	0.626	0.679	0.990

EXPERIMENT 7

With the inclusion of a 250-msec IHI and the retention of the SOAs, the temporal ordering response dimension was further expanded in this experiment. Subjects were again instructed to respond in terms of the perceived spatial location and temporal order of the elements in the stimulus pattern.

Conditions considered for analysis were pattern delivery (one time versus three times), number of loci (two fingers versus three fingers per hand), hand order (hand that received the stimulus first versus the hand that received the stimulus second), hand preference, content correct versus order correct, and variations in SOA values (60 msec, 160 msec, 260 msec, and 360 msec). As in Experiment 5, an additional analysis was performed to determine if the addition of the 250-msec IHI affected response accuracy. It was expected that the presence of the IHI would be associated with improved response accuracy because stimuli from each hand could be processed successively rather than simultaneously.

Results and Discussion

As expected, scores were significantly higher [$F(1,2) = 57.09$, $p < .05$], for the triple repetition of the pattern (.944) than for the single presentation (.842). When comparing the results of Experiment 5 (.300, no IHI) with Experiment 7 (.535, IHI) over all conditions, it is apparent that the presence of the IHI facilitates performance [$F(1,2) = 45.72$, $p < .05$]. It may be recalled that in Experiments 1 and 3, the addition of the 250-msec IHI facilitated performance as [illegible] as repeating the pattern three times. The results of Experiments 5 and 7 indicate much the same thing; the presence of the 250-msec IHI was slightly more effective at enhancing performance than was the triple repetition of the pattern (IHI = 14% improvement; triple repetition = 11.5% improvement). This improvement in temporal ordering associated with the IHI was far more pronounced at the longest SOA, as indicated by the significant Pattern repetition x Order x SOA interaction [$F(1.6,3.3) = 15.42$, $p < .05$]. At 360 msec, IHI = 21% improvement; triple repetition = 8.5%. However, with the maximum SOA of 360 msec plus the 250-msec IHI, performance (based on order correct) for the 6-loci condition was no better than 70% correct. When considering the data including triple repetition, performance peaks at 90% at a temporal cost of 4.5 sec per trial.

As has been the case throughout this series of experiments, increasing the number of loci from four (.884) to six (.712) is associated with lower scores [$F(1,2) = 167.43$, $p < .01$].

Among the other factors considered, lengthening the SOA values improved response accuracy [F([illegible]) = 106.52, $p < .01$]. The function relating SOA to performance was steeper than that obtained for the same series of SOA values in Experiment 5 (see Fig. 9), primarily because of the presence of the 250-msec IHI. If a train of stimuli are delivered simultaneously to both hands, lengthening the SOA between each of the stimuli does little to facilitate performance. In a totally successive situation, where first one hand, then the other receive the stimuli, such that only one stimulus is presented at a time, performance is enhanced as the SOA grows longer. This observation applies to both content correct and order correct, as is indicated by Figs. 9, 10a & b.

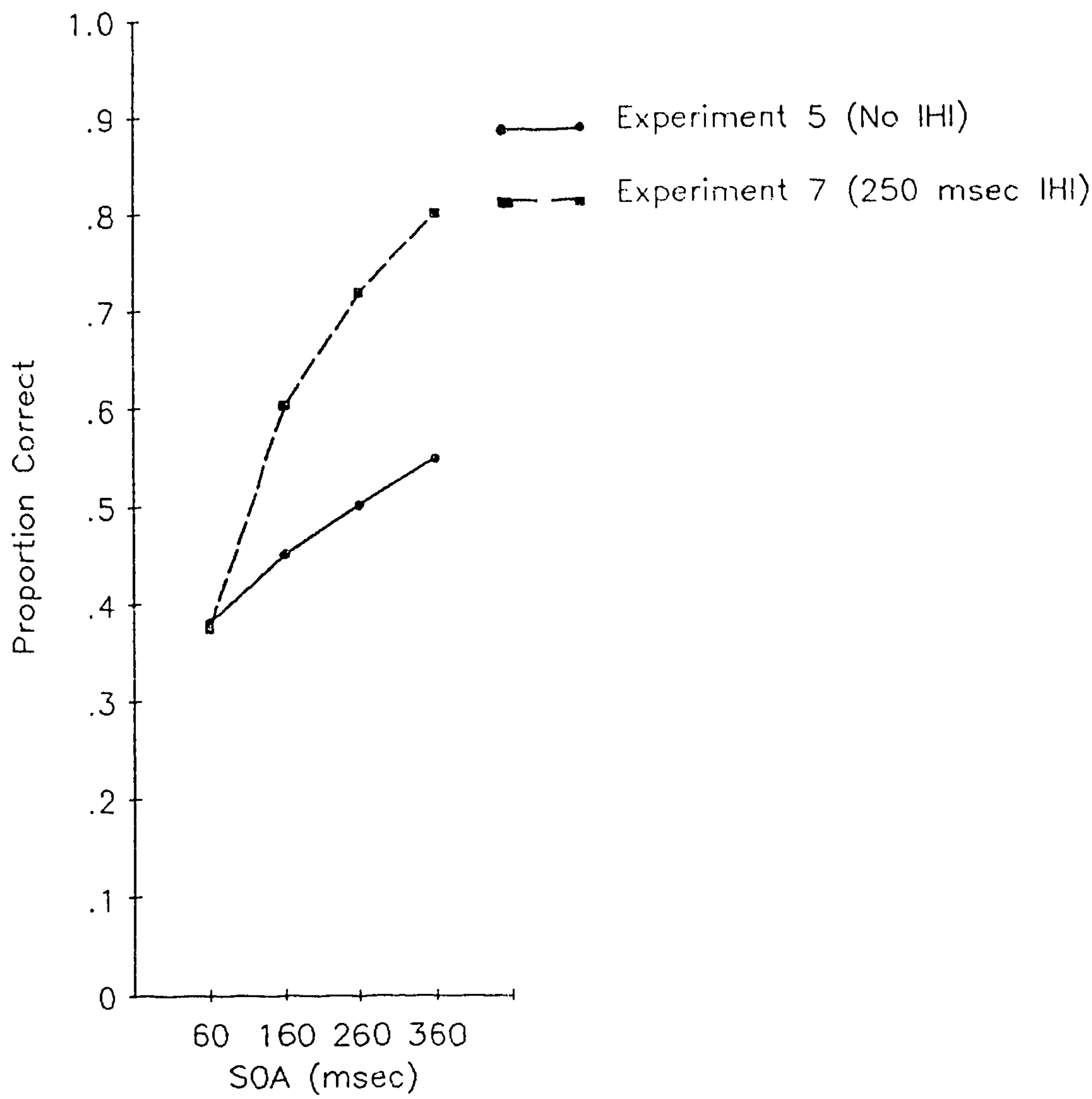


Figure 9. Proportion of correct responses as a function of the varying SOAs. Data points represent mean order correct.

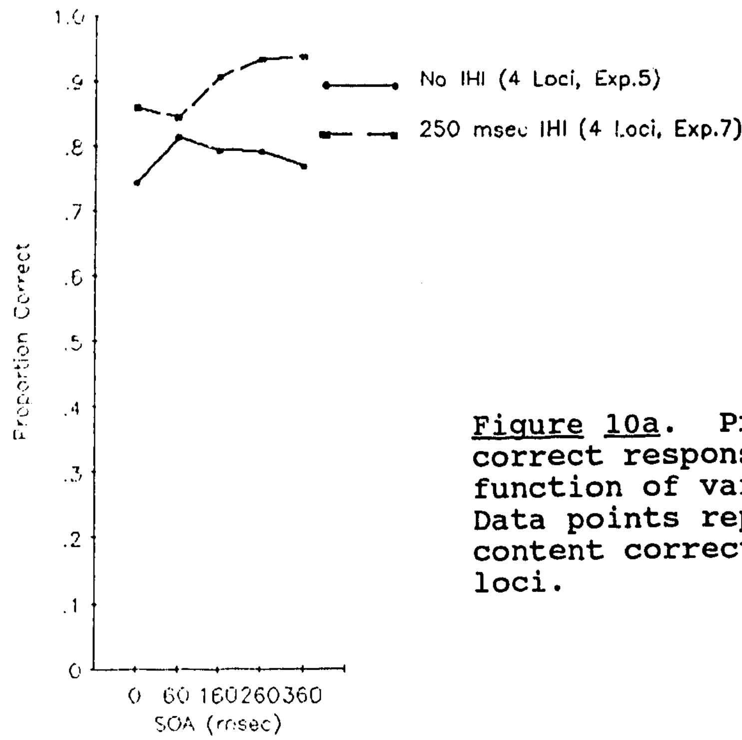


Figure 10a. Proportion of correct responses as a function of varying SOAs. Data points represent mean content correct for four loci.

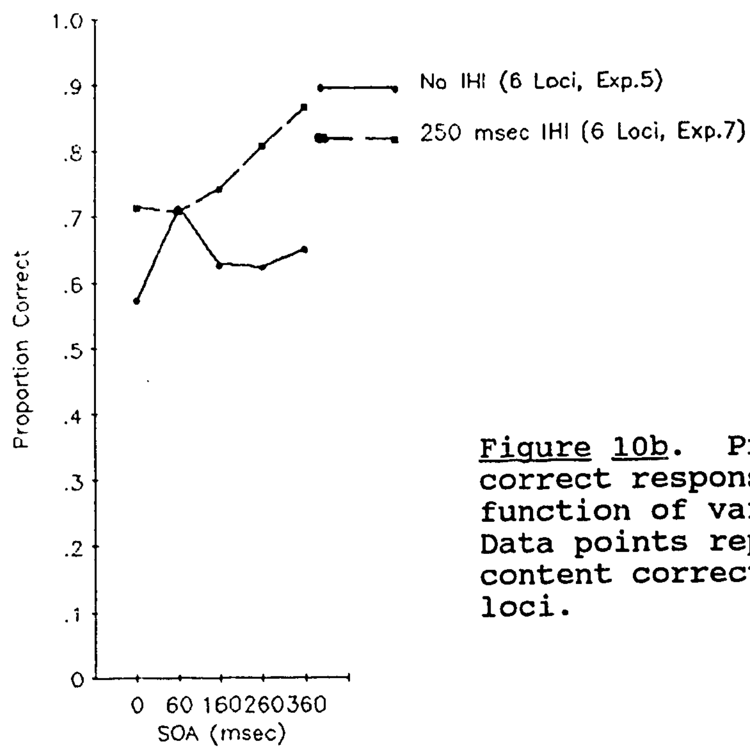


Figure 10b. Proportion of correct responses as a function of varying SOAs. Data points represent mean content correct for six loci.

Scores for each hand were recorded separately according to the order in which they received the stimuli. Subject's scores were more accurate [$F(1,2) = 34.49$, $p < .05$] when responding with the first hand to receive the stimuli (.849) than when responding with the second hand (.743). The difference between content correct and order correct was greater for the second hand; 24% as compared to 18% for the first hand. This might indicate that the temporal ordering component is more sensitive to the primacy effect than is the identification of the spatial position.

Finally, the response accuracy for content (.893) was significantly higher [$F(1,2) = 347.94$, $p < .005$] than for order (.704). Although, for the triple repetition condition, at the maximum SOA value of 360 msec, the scores for correct order (averaged over four and six loci) had almost achieved parity with the content scores (.950, order; .984, content). The cost of elevating these scores, however, was a high expenditure of time. If the data from the six-loci condition are excluded, a response level of 75% correct can be exceeded via the four-loci, single-presentation condition at an SOA of 160 msec (.777). That is, four discrete taps (two per hand) can be delivered successively with an SOA of 160 msec and an IHI of 250 msec

(590 msec total presentation time), and be correctly identified both spatially and temporally 78% of the time.

Additional interactions were consistent with those found in Experiment 5. There was a Repetition x C/O interaction [$F(1,2) = 29.10$, $p < .03$] in which triple pattern repetition was more facilitory for order than for content. There were two other interactions involoving C/O; Loci x C/O [$F(1,2) = 169.46$, $p < .01$], and C/O x SOA [$F(1.1,2.2) = 31.26$, $p < .03$]. In both of these interactions order was more profoundly affected by the accompanying variable than was content. A final two-way interaction was that of Loci x SOA [$F(1.1,2.2) = 33.08$, $p < .02$], where the correct localization of the larger number of loci was facilitated more by the longer SOA values.

There was one significant four-way interaction, Repetition x Loci x C/O x SOA [$F(1.3,2.5) = 28.49$, $p < .02$], in which order was affected more by the other three variables than was content.

EXPERIMENT 8

As with Experiment 7, all temporal aspects of the experiment were fully incorporated into the task by the successive delivery of the stimuli to both hands and fingers. As well, two stimulus patterns (spatial versus mirrored), were delivered to an unattended hand while subjects attended to and responded with a single hand.

Examined in the data analysis were the effects of the two types of distractor, number of loci, hand preference, and content correct versus order correct. A separate analysis was performed to determine if the overall results of this experiment, which included an interhand interval, differed from the results of Experiment 6, which did not have an IHI.

Results and Discussion

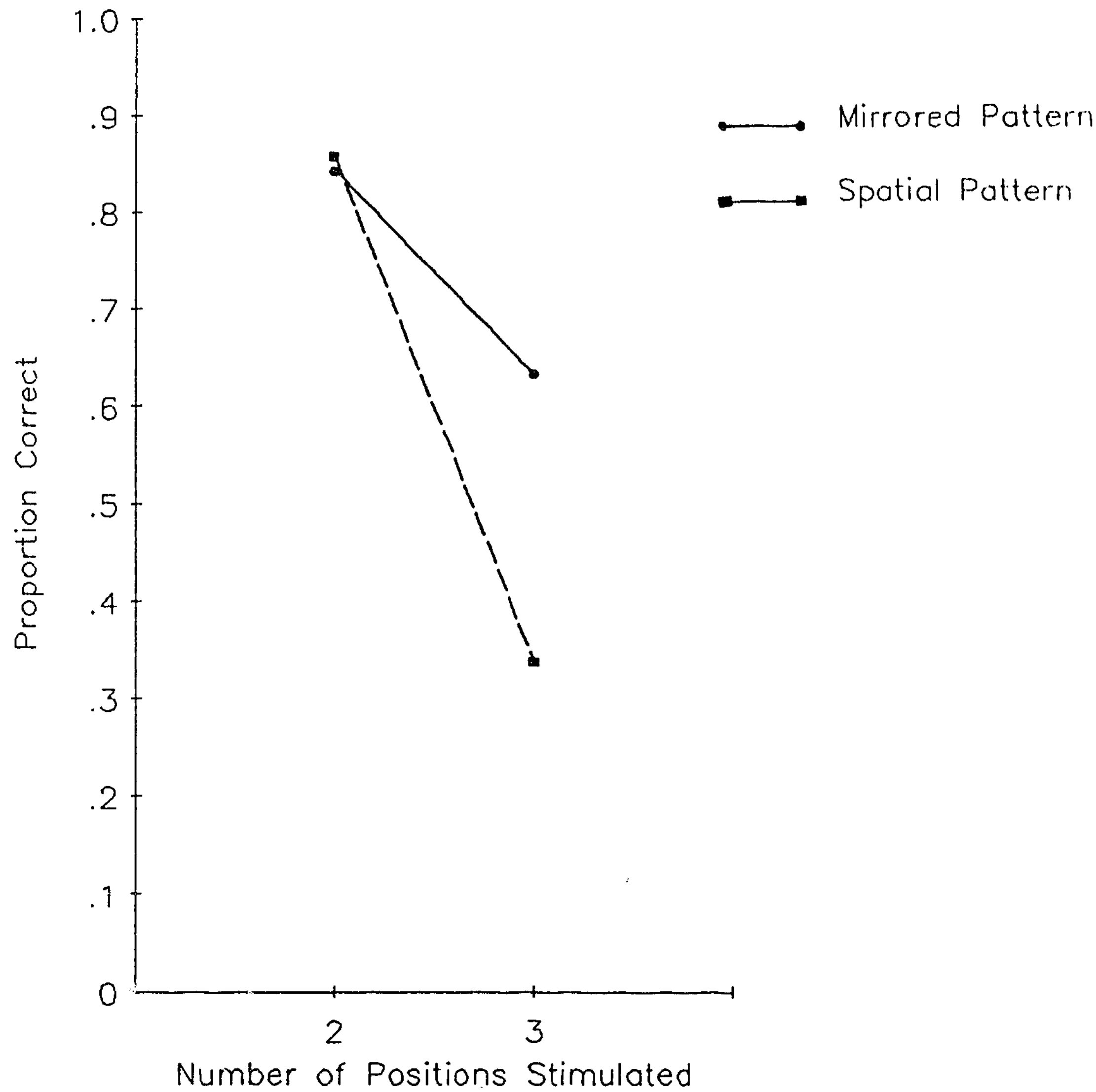
In this last experiment, the mirrored distractor pattern (.735), when compared with the spatial pattern (.599), seemed once again to have been associated with improved response accuracy, [$F(1,2) = 34.00$, $p < .05$]. Also consistent with the results in the three previous experiments, performance became significantly less accurate [$F(1,2) = 535.78$, $p < .002$], as the number of loci receiving stimuli increased from two (.851), to three (.486).

The final factors examined in the original ANOVA were content and order correct. As expected, scores for content (.892) were considerably higher [$F(1,2) = 1536.02$, $p < .001$], than those for order (.508). When compared to Experiment 6, which did not have a 250-msec IHI, both the content and order scores in Experiment 8 were slightly higher. As was the case in Experiments 2 & 4, the 250-msec IHI did not appreciably enhance performance.

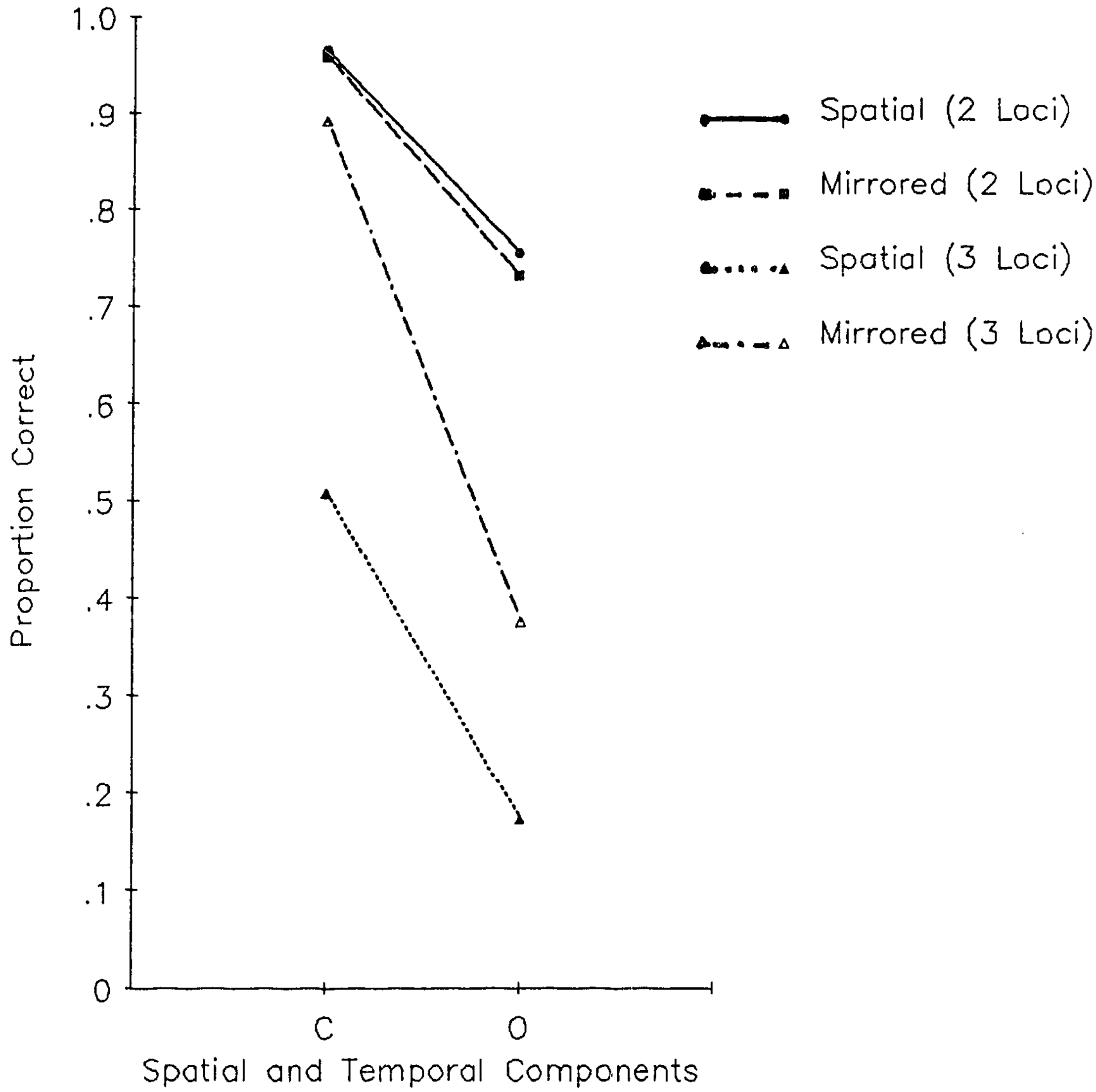
When the ANOVA results were examined for possible interactions, it was found that neither the spatial nor the mirrored distractor pattern seemed to have much of an effect on the response scores for the two loci condition (see Fig.11). However, for the three loci condition, the mirrored pattern was clearly associated with the higher scores [$F(1,2) = 27.97$, $p < .05$]; a Number-of-loci x Distractor-pattern interaction. Other interactions included: Distractor x C/O [$F(1,2) = 47.04$, $p < .02$], in which the mirrored pattern was more facilitatory for order than for content; Loci x C/O [$F(1,2) =$ [illegible], $p < .04$], where the higher number of loci was associated with more of a decrement in scores for order than for content; and

Distractor x Loci x Laterality [$F(1,2) = 22.02$, $p < .04$], where the right hand was more affected by the other two variables than was the left hand.

Although not quite achieving significance, another interaction involving content versus order, number of loci, and the type of distractor pattern, indicated that even though correctly ordering the stimuli under the three loci condition was difficult, the performance obtained with the mirrored distractor pattern was 546% better than that obtained with the spatial distractor pattern (see Fig. 12).



<u>Figure</u> <u>11</u>. Proportion of correct responses as a function of number of loci receiving stimuli in Experiment 8. Data points represent mean content correct.



<u>Figure 12</u>. Proportion of correct responses as a function of content correct versus order correct in Experiment 8 (C = content correct, O = order correct).

GENERAL DISCUSSION

The results and their implications are reviewed with respect to the major categories of factors manipulated in the eight experiments. Specifically, issues addressed will be primarily of a basic and theoretical nature, although, at the end of each section there will be a brief reference to potential practical applications.

Spatial Factors

Experiment 1 specifically measured the ability to localize tactile stimuli via the simultaneous delivery of stimuli to the fingertips of both hands. When n = 4 (2 per hand), subjects had a localization accuracy of 74%, however when n = 6 (3 per hand), the performance correct dropped to 57%. Hill (1971) reported response accuracies of 60% and 61% for the same two number of loci. The difference in scores for the four-loci condition can be attributed to the fact that subjects in Experiment 1 attended to only eight possible stimulus sites rather than the 24 sites monitored by Hill's subjects. The similar scores for the six-loci condition indicate, perhaps, that identifying the correct spatial positions of six loci is simply too difficult, in spite of the reduced number of optional sites. Thus it seems that the ability to localize simultaneously and bilaterally delivered stimuli fails to reach a 75% level when the number of stimuli exceeds three.

Experiment 2, differs from Experiment 1 only in that responses were made by a single, attended hand. In spite of the fact that stimuli were delivered to only one hand, with a maximum of three loci stimulated, performance levels did not even reach those attained under the two-hand, six-loci condition. It appears that in order to achieve accuracy levels of 75% or better, no more than two stimuli can be delivered simultaneously to a single attended hand. This is consistent with Craig's (1985) observation that in certain situations, such as a spatial discrimination task, bilateral response accuracy for the two-loci condition is much higher than that observed for the unilateral condition. Hill and Bliss (1968b) analyzed temporal resolution for one hand versus two hands and found that there was not much difference between the bilateral and ipsilateral conditions. However, at 0-msec SOA, which could only elicit spatial responses, their data indicated a much lower error rate for the two-hand condition. Another bilateral/ipsilateral study (Gilson, 1968) measured pattern discriminations made in response to stimuli delivered to the fingertips. Although the primary factor being investigated was that of pattern communality, Gilson noticed that difference discriminations were more easily made when the stimuli shifted from one hand to the other. Thus, four separate studies have all found evidence that spatial localization and/or discrimination is facilitated when stimuli are delivered bilaterally as opposed to ipsilaterally.

Relevant to this observation is the fact that in the mirrored condition of Experiment 2, where stimuli were delivered to identical sites on the unattended hand, performance for the three loci condition with mirrored distractor was above 90%, indicating that spatial discriminations were enhanced when a mirrored distractor pattern was presented to the unattended hand.

Temporal Factors

Temporal order was determined by the correct spatial as well as temporal specification of the stimulus. Experiments 1 and 2 contained no measurable temporal components. However, in Experiments 3 and 4, the stimuli were delivered simultaneously to multiple loci within each hand, but included a 250-msec IHI. Because there was no IHI in Experiments 5 and 6, delivery of the stimuli was simultaneous to both hands but successive to the multiple loci within hands. Conditions for Experiments 7 and 8 maximized the temporal component in that all stimuli, to both hands, were delivered successively.

In Experiment 3, the presence of the 250-msec IHI clearly enhanced performance with respect to content correct scores. As well, subject's response accuracy was considerably higher when responding with the hand that received the stimuli first. This is consistent with Hill's (1971) analysis of the number of stimuli correctly perceived as a function of sequence position. In Experiment 7, the parallel with Hill's results is even more apparent when the varying SOA values are taken into account. For example, in the six-loci condition, at the longer SOA values (360 msec for Experiment 7; 250 msec for Hill, 1971), the first two stimuli delivered were correctly identified and ordered the highest percentage of the time. Even though scores for the final position often improved sharply, both studies found that there was an overall decline in scores associated with the later positions. Hill suggested these results could be explained by Broadbent's (1957) first-in-first-out model, in which if short term memory (STM) is operating at full capacity, the first items in are the first items to be recalled as new items are entered. Additional observations on this primacy effect have been made by Gescheider (1966), using vibrotactile stimuli, and Rosner (1959), using electrocutaneous stimuli. Both mention that the later tactile stimuli of a sequence are perceived as less intense than the first stimuli. Possible reasons for this heightened clarity of the earlier stimuli might be that these stimuli are not subject to forward masking or merely the fact that the first few stimuli constitute a smaller, more manageable amount of information to be processed. Thus, subjects seem to remember as much of the stimulus configuration as possible, beginning with the initial stimulus, and respond accurately to the stimuli that are within the range of their own STM span.

Because the current series of experiments required subjects to attend to eight possible positions, it might be expected that the temporal order limen would be intermediate between the 18 msec limen reported by Hirsh and Sherrick (1961), who used two loci, and the 26 msec reported by Hill and Bliss (1968a), who could stimulate any two of 24 loci. I did not examine the two- and three-loci conditions at SOA values tested by Hill and Bliss (1968b) because; a) in earlier pilot studies we found the two-loci condition resulted in near-perfect scores for all subjects, and b) the three-loci condition was impossible to implement when keeping the number of stimuli simultaneously delivered to both hands equal. However, the four- and six-loci results from the current study can be directly compared to those of Hill (1971). Our temporal order limen (arbitrarily set at 75% response accuracy) for the four-loci condition is approximately 150 msec, which indicates a slightly greater sensitivity for temporal order than the 190-msec temporal order limen in the Hill study. Hill also extrapolated a temporal order limen of approximately 380 msec for the six-loci condition. At SOAs of 360 msec, in Experiment 7, the six-loci condition yielded a response accuracy of 70%, thus indicating that when the number of stimuli is increased to six, the sensitivity for temporal order found in the current study is no greater than that established by Hill's results. Hence, the smaller number of potential sites constitutes little.

A final consideration concerning temporal factors is the interaction between temporal processing of sequential stimulus presentations and memory. Specifically, at what point does lengthening the duration of the interval between stimuli yield diminishing returns as a result of memory decrement? At the maximum SOA of 360 msec for six loci, the total lapsed time per presentation is 1.71 seconds. Hill and Bliss (1968a) estimate that the duration of the tactile sensory register is about 1.3 sec and that its capacity for number of individual stimuli perceived, both in time and space, ranges from 2.7 - 7.5 sec; the large range being due to individual differences. It is therefore possible that within the temporal parameters of Experiment 8 we were approaching the limit beyond which any additional time would have resulted in memory decay.

An examination of the temporal manipulations, reveals a situation in which the temporal order limen is influenced not only by the number of stimuli, but also by the amount of uncertainty associated with where the stimuli might be delivered. This has relevance within an applied context in that the design of a sensory substitution device would have to balance between limiting uncertainty so that attention could be effectively focused, and avoiding problems such as masking and interference, which are inherent in systems that are severely constrained by spatial and temporal factors. In addition, for any single unit of information (such as a letter or any single vibrotactile pattern), that position of the unit which is first in contact with the skin seems subsequently to be the best processed and recalled (i.e. the leading edge of a letter; the first of a series of point stimuli). Consequently, for example, a sensory substitution system might exploit this phenomenon by packing the most discriminable aspects of any unit of information into the leading edge of the stimulus, rather than imbedded within the middle of the stimulus, where it would be subject to both forward and backward masking.

Spatial and Temporal Capacities and Interactions

Interactions between spatial and temporal factors can be assessed by examining how spatial localization is affected by various temporal manipulations. Findings are somewhat contradictory in that whereas Hill (1971) found that content (spatial localization) scores for four and six loci were highly dependent upon SOA values, Hill and Bliss (1968b), using two and three loci, reported that content scores did not vary with SOA. Hill speculated that the larger number of stimuli might have increased masking effects or caused additional unspecified interactions that made localizing the stimuli more difficult. Our results with four and six loci, however, were unlike Hill's in that the content scores did not change as a function of SOA. Thus it seems that content scores are not dependent solely upon SOA values, but are influenced by factors inherent in the task, such as number of loci to which stimuli might be delivered.

The localization task in the present study differs from Hill's 1971 study in three rather important ways: a) Hill's subjects could receive the stimuli on any one of 24 possible sites, as opposed to the eight options available to our subjects; b) there were three potential sites per finger in the Hill study whereas in the current study, only a single site (the distal phalange) on each finger was designated as a target area, and c) Hill's subjects had to respond verbally using a learned code, whereas the subjects in the current study responded by simply depressing the contactor through which they perceived the stimulus to have been delivered. Therefore, the subjects in Hill's study had to contend with a higher degree of uncertainty prior to the receipt of the stimuli, as well as perform the more difficult task of localizing the stimuli at one of three sites on each finger. In addition, they had to respond using a memorized verbal code, a task that in and of itself added to the memory load already imposed by the attempted recall of the stimuli.

Relevant to the issue of tactile stimulus versus verbal response is an observation made by Kantowitz and Sorkin (1983) "... stimulus-response compatibility does not depend only on the type of stimulus array or only the type of response array. Instead, it depends on the relationship between the two arrays" (p. 147). Certainly there was a much higher degree of response compatibility within the current study where subjects responded in a mode essentially identical to that of stimulus presentation. Had they responded verbally, it seems reasonable to assume that because the stimulus-response compatibility was relatively low, so, too, would be their response accuracy. Therefore, one could at least consider that the dependence of content scores upon SOA in Hill's 1971 study was as much a consequence of this variation in stimulus-response conditions, as it was a function of increased number of stimuli.

Regarding apparent motion, masking, and facilitation, and their possible effects upon task performance, subjects all reported experiencing some degree of tactile movement. They could easily confirm the sensation since visual trial by trial feedback indicated the loci actually receiving the stimuli. There was no way to quantify its effects, so its presence was simply acknowledged.

As with the Hill (1971); Hill and Bliss (1968b) studies, masking did not seem to have an effect. Results from the current study were even less indicative of masking than those in the Hill (1971) study, where at 60-msec SOA, performance dropped from that obtained at 0 msec, prompting Hill to check the data for possible masking effects. As will be recalled, he found no strong evidence for masking.

attention from site to site. As well, it was felt that even though for the most temporally extended condition in which the lapsed time would be 5.6 seconds, memory would be facilitated by the repeated presentation of the stimuli.

As expected, delivering the stimulus pattern three times improved performance, however, it might be recalled that in the simultaneous condition simply adding a 250-msec IHI to a single pattern delivery improved performance more than the triple pattern delivery. It would seem that the triple pattern delivery, which is more time consuming than a 250-msec IHI, is not an efficient means of increasing information transmission.

In some cases where the SOA values were longer than the IPI, even though response accuracy improved, subjects found the repetitions confusing. The within-pattern intervals (SOAs) were not compatible with the interpattern intervals, thus reducing temporal compatibility. In an article on temporal compatibility Klapp (1979) states, "Responses on different temporal frames can be generated in parallel only at the expense of mutual interference" (p. 377). Before incorporating repetition into the design of a sensory substitution system, temporal compatibility for within-pattern versus between-pattern intervals should be explored in greater detail.

Another of the subject's phenomenological reports concerns individual strategies and the effect that pattern repetition had on these strategies. An analogy can be made with music and hearing an unfamiliar melody for the first time. There are two commonly used subjective strategies to remember the melody. One is to simply hum the entire melody as a single connected pattern. The exact pitch intervals between each successive note are not individually rehearsed, but are subsumed within the whole melodic pattern. This type of melodic recall is immediate, spontaneous, and unrehearsed; almost as if it were taken directly from the hypothetical preattentive, short-term sensory store. However, if the melody is complex or nontraditional, or consists of a sustained, slowly changing melodic pattern, recall is likely to be more accurate if a strategy is used whereby the melody is "played back" by humming the whole pattern slowly enough to identify each pitch interval as, for example, a third, a perfect fifth, etc.

Both of these strategies were used by the subjects in the current study. When the task was most difficult (i.e. six loci at 60-msec SOA), they responded as quickly as possible to the entire pattern, and subjects reported that the triple-pattern repetition was intrusive. This observation is reflected in the data, where proportion correct for the single presentation to six loci at 60-msec SOA was .236 and proportion correct for the triple presentation was .197. If the strategy involved identifying the location of each stimulus in terms of its relationship to the spatial locations of the other stimuli (which could be done at the longest SOA, 360 msec), the repetition of the pattern was helpful (.413 for one repetition versus .575 for triple repetition). With these different strategies in mind, it seems logical that any sensory substitution device should be designed to accommodate both approaches. This would allow for quick and efficient processing or transmittal of simple and/or overlearned information, while still providing the option of a slower, more analytical approach for complex information.

The enormous amount of time consumed by pattern repetition in return for what generally are only modest gains, seems to indicate that repetition is not a particularly promising approach to adopt when designing a tactile sensory substitution device. However, a "quasi-repetition" approach might prove useful within a specific context. Since it is the leading edge, the moment of first contact, that seems to be most accurately perceived (Bliss, Crane, Link, & Townsend, 1966), perhaps this primacy effect can be further exploited by repeating only the last portion of the stimulus pattern to make it more perceptually equivalent to the leading edge.

The effects of redundancy were tested in the single attended-hand condition. Recall that stimuli were presented in each of three ways: a) only the attended hand received stimuli (no distractor condition), b) the stimuli delivered to the unattended hand followed the same spatial pattern as that delivered to the attended hand (spatial distractor), and c) the stimuli delivered to the unattended hand were to loci exactly corresponding to those receiving stimuli on the attended hand (mirrored distractor). The expectation was that response scores would decline as a result of the presentation of the distractor patterns. However, it was thought that the spatial type of distractor pattern would be somewhat less "distracting" because the directional sequence of the distractor pattern would match that of the test pattern. Further, it was thought that the complete redundancy provided by the mirrored pattern would be even less distracting than the spatial distractor. Contrary to expectations, the spatial distractor pattern was clearly detrimental to response performance while the mirrored distractor actually improved performance in accurately localizing the stimuli. The results would have been easier to interpret if in addition to the mirrored and spatial distractor patters, a third randomly generated pattern had been presented to the unattended hand.

In evaluating the advantages or disadvantages of single-hand versus dual-hand delivery of the stimuli, the obtained results seemed to be relevant to a recent finding of Kantowitz and Cooper (1985), "...if two tasks are performed that require equal and concurrent processing, performance in one task will be better on those trials where no response is required to the other channel" (p.42). If this were so, then it seems logical to expect that in the present study the highest scores should have been obtained by the single-hand, no-distractor condition, followed by the single-hand, mirrored distractor condition, then the single-hand, spatial condition; with the poorest performance expected from the two-hand, single-repetition condition. As can be seen in Table 7, this was not the case. For the two-loci per hand condition, the scores are consistently high across all experiments (ranging from .740 - .950). The high response accuracy coupled with the homogeneity of scores indicate that the task was relatively undemanding. However, when three stimuli are delivered per hand, some striking differences emerge; differences that at first glance seem counterintuitive. For instance, why are scores for a condition where subjects receive and respond to stimuli delivered to one hand, lower than the scores obtained when subjects receive and respond to six stimuli (three per hand) delivered to both hands (i.e. .470, single hand; .706, double hand)?

The lower scores for the single hand prevailed both when there was no distractor delivered to the unattended hand and when the spatial distractor was delivered to the unattended hand. The only single-hand condition in which performance surpassed that of the dual-hand task was that of the mirrored-distractor condition. This apparently atypical result can perhaps be explained by considering what features were held in common by the dual-hand task and the single-hand, mirrored-distractor condition. One feature emerged as a likely candidate as the crucial, common element: redundancy. A certain percentage of the randomly generated dual-hand stimulus patterns and all of the mirrored-distractor stimulus scores were redundant. Therefore, the very redundancy that had so strongly and positively affected the mirrored-distractor score may also have facilitated dual-hand performance. For simultaneous delivery of the stimuli (Experiments 1 & 2), 25-30% of the stimulus patterns in the dual-hand condition were redundant, i.e. both hands received absolutely identical stimuli. Of the 25-30% redundant stimulus patterns, approximately 64% of the

Table 7

Content and Order Correct for Current Study

		Content		Order	
Experiment	Number of Loci/Hand	2	3	2	3
No SOA					
1 (2 hands, no IHI)		.742	.572		
3 (2 hands, 250-msec IHI)		.858	.713		
2 (1 hand, no distractor)		.906	.524*		
2 (1 hand, mirrored)		.948	.902		
2 (1 hand, spatial)		.823	.428*		
60 msec SOA					
5 (2 hands, no IHI)		.812	.712	.526	.236
7 (2 hands, 250-msec IHI)		.843	.706	.547	.203
6 (1 hand, no distractor)		.927	.548*	.729	.185*
6 (1 hand, mirrored)		.962	.858	.718	.362
6 (1 hand, spatial)		.888	.470*	.653	.157*

* Scores that were lower than expected (see text).

responses were correct. For the 65-70% of the nonredundant stimulus patterns, response accuracy dropped to 22-25%. This explains why the scores for the two other single-hand conditions were so low. There were no stimuli delivered to the unattended hand in the no-distractor condition, hence, no redundancy. The spatial distractor pattern was structured so that pairs of stimuli were never delivered to corresponding fingers and, as with the no-distractor condition, there was, again, virtually no redundancy.

An intriguing contrast to the redundancy effect found in the current study is the effect of what Geldard and Sherrick (1965) refer to as "communality". They employed a multiple contactor system to send vibratory signals to 10 body loci. Subjects were presented with pairs of patterns comprised of 1-9 stimuli. The subject's task was to determine if the two patterns in the signal pair were the same or different. Geldard and Sherrick found that the factor contributing most to the resulting error rate was the degree of spatial and temporal communality between the pattern pairs; i.e., the more extensive the overlap amongst the elements to be discriminated, the higher was the error rate.

Gilson (1968) used essentially the same task, however, instead of the 10 rather widespread body loci, subjects received the stimuli on the distal phalanges of the 10 fingers. Gilson, too, found that communality played a crucial role in discriminability of the pattern pairs. He also noticed that if the stimuli were shifted from hand to hand, discriminability improved; a phenomenon that had not been tested using body loci. When comparing the conditions for the two experiments, Gilson realized that corresponding bilateral loci were being stimulated when using the fingers, while delivery of stimuli to corresponding body loci had been intentionally avoided. He therefore delivered stimuli to noncorresponding sites, which resulted in a 20% reduction in error rate.

Relating his results to Bender's (1952) findings that neural interactions occur when corresponding bilateral sites on the body are simultaneously stimulated, and Sherrick's (1964) evidence that masking occurs when corresponding fingertips are simultaneously stimulated, Gilson speculated that neural interactions between corresponding finger loci were contributing to the observed effects on pattern discriminability. Although the response mode task in these related studies is different from that in the current study, the results indicate that the communality effect in the discrimination task, and the redundancy effect in the localization task may reflect a common neural basis. These neural interactions have been described as a convergence of unilateral pathways before response decisions are made. If this description is a valid one, then the prediction would be that bilateral responses should be of greater strength than unilateral responses. Evidence for this type of neural convergence, referred to as neural summation, entails demonstrating bilateral versus unilateral differences that significantly exceed that which is predicted by a model of probability summation. Because the current study did not use a model for probablility summation, any attributions to neural summation are speculative.

The redundancy effect reported in the current study can also be considered from the perspective of human information processing. In the design of systems for which signal detection is of paramount importance, the system designer is likely to provide redundant coding, perhaps through two physical dimensions, which are subsequently interpreted by the user as a single dimension of information. Within the experimental parameters of the current study, instead of two physical dimensions, dual channels of a single dimension were used to provide redundancy. The single dimension was the spatial location of the, stimuli and the two channels were the two hands.

Perceptual competition, which arises as a result of the perceptual processing of closely spaced stimuli; a situation intrinsic to the task of locating point stimuli delivered to adjacent fingers, can be considered within the same context as redundancy. Commenting on Eriksen and Eriksen's 1974 study on redundancy and perceptual competition, Wickens (1984) stated, "If two perceptual channels are proximate they will both be processed, even if only one is desired. This processing will inevitably lead to some competition...at a perceptual level. If they have common implications for action, the perceptual competition will be balanced by the fact that both channels activate the same response" (p. 277).

That perceptual competition can be eliminated by some type of response compatibility is further indicated in Kantowitz and Sorkin's (1983) discussion of stimulus-response compatibility, where an even stronger compatibility relationship is found between stimulus array and response array. For example, assume that both the right and left index fingers simultaneously receive a stimulus and the subject is asked to respond with only the right hand. At the sensory level it would seem that in light of Bender's (1952) results regarding neural summation, and the fact that corresponding loci are being stimulated, the strength of the stimuli would be intensified, and thus the sensation itself. In this instance, then, given a sensation of sufficient magnitude, the most compatible motor response would be that which is specific to the modality and loci receiving the stimulus, which in this case would be the attended right index finger. If the situation were changed so that the left middle finger received the stimulus, the decision and consequent motor response, partly as a result of perceptual competition, would likely be less compelling. In addition, the geometric configuration of the stimulus would be offset, reducing the stimulus-response compatibility.

Although their performances indicated otherwise, all three subjects were unable to distinguish, at least consciously, between the spatial or mirrored patterns that were delivered to the unattended hand. Therefore, it appears that there was no volitional influence over the effect of the distractor pattern; the distractor was processed even though it was not attended. Relevant to this consideration is Wickens' (1984) distinction between attention and processing, "Attention is to be focused on one channel. This is not synonymous with processing, since the data suggest that processing can take place on one channel as the focus of attention is allocated elsewhere. In this sense, attention is clearly defined only in terms of a conscious intention. Processing encompasses a broader domain" (pp. 281-282).

One of the studies to which Wickens made reference was a dichotic listening task conducted by Treisman (1964), where she found evidence of semantic processing of unattended information. She then inferred that the brain is processing unattended stimuli even when consciousness and attention are concurrently active and directed to another channel. This is consistent with the subjective reports of the subjects in the current study. Scores drastically improved when the mirrored pattern was presented, yet the subjects were not consciously aware of which of the two types of distractor patterns had been delivered. To further investigate this phenomenon, subjects could be asked to perform a task that required them to discriminate between the two types of patterns being delivered to, what was in the current study, the unattended hand.

Thus it seems, at least in terms of human information processing, that redundant information, even if not the focus of the subject's attention is nevertheless processed and provides a significant amount of information to the decision-making person.

information, to be of any use to the individual, required transmission in real-time (i.e. when a blind person is using a sonar-tactile device that alerts the user to closing distances between path obstacles and the user). This is not to imply that repetition should be entirely dismissed. As mentioned in the attention section, it might prove practical to build into the sensory substitution system the capacity to provide stimulus repetition for specific situations (i.e. conveyance of crucial information, complex information, leading edges, etc.).

Another of the factors that seems effective in improving tactile performance is that of increasing the temporal interval between stimulus onsets. Again, as with the repetition factor, stimulus information transmission speed is sacrificed to achieve the improved performance. As well, the fact that it is necessary to retain the earlier stimulus information for a longer span of time, may result in performance degradation simply because the subject's memory capacity has been exceeded. To be viewed as a viable or preferable alternative to the braille and Optacon systems currently in use, any new tactile vision substitution device should be designed specifically for the tactile system's information handling capabilities to the extent that one could reasonably expect to achieve reading rates of 50-150 wpm. This would mean that letters or units of information must be processed at rates of 40-120 msec per letter; rates that impose rather severe temporal limitations upon the substitution system and the perceiver.

Concomitant with any manipulation of temporal intervals is the phenomenon of apparent motion. Because, within certain spatiotemporal parameters, apparent motion is so predictable, it might be recommended that its existence be viewed opportunistically and thus incorporated as a positive feature of tactile sensory substitution devices. For instance, Shimizu, Saida, Wake, Nakamura and Ohzu (1982) reported that apparent motion has been successfully used to connect the strokes in Japanese character writing. As well, apparent motion between two points could be used as a signal of sentence completion.

A third factor is that of bilateral versus ipsilateral stimulation. In the current research, for both spatial and temporal conditions, response accuracy improved when the stimuli were delivered bilaterally. In an effort to determine if expanding the tactile field of view would improve reading rates, Lappin and Foulke (1973) tested subjects by expanding the braille cells to cover two adjacent fingers, or, two fingers on separate hands. Performance was reduced for the adjacent-finger condition, and slightly improved for the bilateral condition. Hill (1974), using the Optacon, conducted a similar experiment. He, too, found that performance was poorer for the adjacent-finger condition, but that the bilateral condition seemed to have no effect at all. Craig (1985) speculated that the lack of effect seen in the bilateral condition was due to the fact that the left index finger was trained for the task, while the right index finger was not. In a series of studies comparing bilateral performance with ipsilateral performance, Craig (1985) consistently found evidence for improved performance for the bilateral condition. He concluded his discussion with the following recommendation: "...designers of cutaneous communication systems should consider making deliberate use of bilateral stimulation" (p. 510). Unlike repetition and longer SOAs, bilateral stimulation does not require the additional expenditure of time. The major disadvantage, of course, is the fact that both hands would be occupied, so that during times of active information delivery, any manipulation of reading material or of the substitution device itself would be difficult. To avoid this situation, bilateral sites at body loci other than the hands might be considered as potential stimulus reception sites.

The final factor contributing to improved response accuracy in the present research is that of redundancy. Trained adults can read braille at rates ranging from 60-120 wpm (Taenzer, 1970). While reading rates for the Optacon usually range from 30-60 wpm (Goldish & Taylor, 1974), Craig (1977) reports two subjects capable of reading up to 100 wpm. It is Taenzer's contention that some of the difference in the reading rate between the two methods can be attributed to the number of contractions in Type II Braille. While this may be true, there might be an additional explanation, although not necessarily exclusive, for the difference. As Foulke and Lappin (1973) have observed, some of the more proficient braille readers lead with one index finger and follow with the other. It is possible that the trailing finger is simply picking up redundant information. This conjecture is consistent with the finding in the current study that unattended stimuli delivered to corresponding bilateral loci facilitated identification of the stimuli delivered to the attended loci. As with the bilateral factor, redundancy does not require any additional expenditure of time, rather, it requires an additional stimulus reception site. Therefore, the same disadvantage cited for the bilateral condition, namely the fact that both hands would be occupied, must be dealt with in using redundancy. A similar recommendation, that stimuli be delivered to sites other than on the hands, could be made for the redundancy condition.

Because this study examined some rather basic sensory parameters, any advantage that a blind subject may have as a result of practice with the tactile processing of more complex patterns would probably be negligible. It is likely that after lengthy practice by the sighted subjects, any performance disparaties between the blind and sighted subjects would disappear. Therefore, it is reasonable to assume that the results of this study can be generalized to the blind "target population".

To conclude this section, it seems appropriate to refer to three observations made by investigators of psychophysics and sensory substitution. First, Geldard (1966)"... the approach to cutaneous communication systems must be that of first ascertaining what discriminations the skin can make with relative ease. Then by suitable engineering of the effective stimuli, coupled with appropriate coding to transmute the information to be conveyed, there needs to be worked out an orderly set of signals that fall within the skin's `language'..." (p.378). A second pertinent observation made by White et al. (1970) was that the perceptual limitations indicated by the results of psychophysical studies might not be so constraining when the context of the perceptual challenge was that of a functional task, implying that the design of tactile visual substitution devices should be considered in terms of the limitations imposed by a combination of perceptual and functional tasks rather than predicating the system design strictly upon psychophysical data from perceptual tasks. Further, as Bach-y-Rita (1980) points out, the CNS and its neural mechanisms are not immutable. Because of this neural plasticity, information can be successfully extracted in what appear to be noisy situations. Craig (1974) has found that the skin can extract information from both pictorial and abstract displays, suggesting that cutaneous information processing is not necessarily a degraded form of visual processing. This can be taken to further validate the previous observations; namely, the skin has its own optimally processed "language", and that the plasticity of the CNS provides the person with the capacity to successfully cope in situations where information is presented via a novel or substitute mode, or modality of stimulus delivery.

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Appendix

ANOVA Tables

Experiment 1

Main Effects

1.	1 vs 3 pattern repetition	[$F(1,2) = 32.02, p < .03$]
2.	# of loci (4 vs 6)	[$F(1,2) = 32.10, p < .03$]
3.	Laterality	[$F(1,2) = 20.85, p < .05$]

Interactions

1.	Rep x loci	[$F(1,2) = 0.10, p < .78$]
2.	Rep x laterality	[$F(1,2) = 0.67, p < .50$]
3.	Loci x laterality	[$F(1,2) = 5.04, p < .15$]
4.	Rep x loci x laterality	[$F(1,2) = 0.60, p < .52$]

Experiment 2

Main Effects

1.	Dist/NoDist	[$F(1,2) = 27.87, p < .03$]
2.	# of loci	[$F(1,2) = 99.78, p < .01$]
3.	Laterality	[$F(1,2) = 0.76, p < .48$]
4.	Spatial vs mirrored	[$F(1,2) = 163.76, p < .01$]

Interactions

1.	Dist x loci	[$F(1,2) = 80.95, p < .01$]
2.	Loci x laterality	[$F(1,2) = 13.56, p < .07$]
3.	Dist x laterality	[$F(1,2) = 0.35, p < .61$]
4.	Dist x loci x laterality	[$F(1,2) = 2.19, p < .30$]

Experiment 3

Main Effects

1.	1 vs 3 repetitions	[$F(1,2) = 17.69, p < .05$]
2.	# of loci	[$F(1,2) = 191.77, p < .01$]
3.	Laterality	[$F(1,2) = 0.88, p < .50$]
4.	Hand order	[$F(1,2) = 89.14, p < .01$]

Interactions

1.	Rep x loci	[$F(1,2) = 4.56, p < .20$]
2.	Rep x laterality	[$F(1,2) = 2.33, p < .30$]
3.	Rep x hand order	[$F(1,2) = 5.48, p < .14$]
4.	Loci x laterality	[$F(1,2) = 0.07, p < .80$]

5.	Loci x C/O	$[F(1,2) = 571.20, p < .01]$
6.	Loci x laterality	$[F(1,2) = 1.04, p < .40]$
7.	Loci x SOA	$[F(1.1,2.1) = 2.34, p < .30]$
8.	C/O x laterality	$[F(1,2) = 12.32, p < .07]$
9.	C/O x SOA	$[F(1.1,2.1) = 37.67, p < .02]$
10.	Laterality x SOA	$[F(1.9,3.8) = 2.04, p < .30]$
11.	Rep x loci x C/O	$[F(1,2) = 1.18, p < .40]$
12.	Rep x loci x laterality	$[F(1,2) = 51.45, p < .02]$
13.	Rep x C/O x laterality	$[F(1,2) = 3.66, p < .20]$
14.	Rep x loci x SOA	$[F(1.0,2.1) = 1.83, p < .30]$
15.	Rep x C/O x SOA	$[F(1.3,2.6) = 4.69, p < .14]$
16.	Rep x laterality x SOA	$[F(1,2) = 29.20, p < .03]$
17.	Loci x C/O x laterality	$[F(1,2) = 3.10, p < .20]$
18.	Loci x C/O x SOA	$[F(1.2,2.4) = 0.48, p < .60]$
19.	Loci x laterality x SOA	$[F(1.2,2.4) = 0.76, p < .50]$
20.	C/O x laterality x SOA	$[F(1,2) = 13.16, p < .07]$
21.	Rep x loci x C/O x laterality	$[F(1,2) = 6.32, p < .13]$
22.	Rep x loci x C/O x SOA	$[F(1.4,2.7) = 8.43, p < .07]$
23.	Rep x loci x laterality x SOA	$[F(1.2,2.4) = 3.59, p < .20]$
24.	Rep x C/O x laterality SOA	$[F(1.3,2.7) = 0.14, p < .80]$
25.	Loci x C/O x laterality SOA	$[F(1.7,3.4) = 0.28, p < .74]$
26.	Rep x loci x C/O x laterality x SOA	$[F(1.5,3.1) = 0.98, p < .40]$

Experiment 6

Main effects

1.	Dist/NoDist	$[F(1,2) = 62.14, p < .02]$
2.	# of loci	$[F(1,2) = 424.90, p < .01]$
3.	Content vs order	$[F(1,2) = 185.74, p < .01]$
4.	Laterality	$[F(1,2) = 1.91, p < .30]$
5.	Spatial vs mirrored	$[F(1,2) = 1298.08, p < .01]$

Interactions

1.	Dist x loci	$[F(1,2) = 225.81, p < .01]$
2.	Dist x C/O	$[F(1,2) = 30.45, p < .03]$
3.	Dist x laterality	$[F(1,2) = 1.92, p < .30]$
4.	Loci x C/O	$[F(1,2) = 88.40, p < .01]$
5.	Loci x laterality	$[F(1,2) = 2.12, p < .30]$
6.	C/O x laterality	$[F(1,2) = 9.00, p < .10]$
7.	Dist x loci x C/O	$[F(1,2) = 0.20, p < .70]$
8.	Dist x loci x laterality	$[F(1,2) = 0.79, p < .50]$
9.	Dist x C/O x laterality	$[F(1,2) = 0.24, p < .70]$

10. Loci x C/O x laterality [$F(1,2)$ = 0.74, $p < .50$]
11. Dist x loci x C/O x laterality [$F(1,2)$ = 0.22, $p < .70$]

Experiment 7

Main effects

1. 1 vs 3 repetitions [$F(1,2)$ = 57.09, $p < .02$]
2. Loci [$F(1,2)$ = 167.43, $p < .01$]
3. C/O [$F(1,2)$ = 347.94, $p < .01$]
4. Laterality [$F(1,2)$ = 2.44, $p < .30$]
5. SOA [$F(1,2)$ = 106.52, $p < .01$]

Interactions

1. Rep x loci [$F(1,2)$ = 4.30, $p < .20$]
2. Rep x C/O [$F(1,2)$ = 29.10, $p < .03$]
3. Rep x laterality [$F(1,2)$ = 6.51, $p < .13$]
4. Rep x SOA [$F(1.7,3.4)$ = 2.97, $p < .18$]
5. Loci x C/O [$F(1,2)$ = 169.46, $p < .01$]
6. Loci x laterality [$F(1,2)$ = 1.55, $p < .34$]
7. Loci x SOA [$F(1.1,2.2)$ = 33.08, $p < .02$]
8. C/O x laterality [$F(1,2)$ = 1.54, $p < .34$]
9. C/O x SOA [$F(1.1,2.2)$ = 31.26, $p < .03$]
10. Laterality x SOA [$F(1.1,2.1)$ = 1.59, $p < .33$]
11. Rep x loci x C/O [$F(1,2)$ = 3.09, $p < .22$]
12. Rep x loci x laterality [$F(1,2)$ = 0.66, $p < .50$]
13. Rep x loci x SOA [$F(1.7,3.3)$ = 1.21, $p < .38$]
14. Rep x C/O x laterality [$F(1,2)$ = 0.32, $p < .63$]
15. Rep x C/O x SOA [$F(1.6,3.3)$ = 15.42, $p < .02$]
16. Rep x laterality x SOA [$F(1,2)$ = 2.99, $p < .23$]
17. Loci x C/O x laterality [$F(1,2)$ = 12.30, $p < .07$]
18. Loci x laterality x SOA [$F(1.2,2.3)$ = 14.24, $p < .13$]
19. C/O x laterality x SOA [$F(1,2)$ = 19.76, $p < .05$]
20. Rep x loci x C/O x laterality [$F(1,2)$ = 7.61, $p < .11$]
21. Rep x loci x C/O x SOA [$F(1.3,2.5)$ = 28.49, $p < .02$]
22. Rep x loci x laterality x SOA [$F(1.1,2.1)$ = 0.97, $p < .43$]
23. Rep x C/O x laterality x SOA [$F(1.3,2.6)$ = 0.12, $p < .81$]
24. Loci x C/O x laterality x SOA [$F(1.3,2.6)$ = 0.87, $p < .47$]
25. Rep x loci x C/O x laterality x SOA [$F(1,2)$ = 0.26, $p < .66$]

Experiment 8

Main effects

1.	Spatial vs mirrored	[$F(1,2)$ = 34.00, p < .03]
2.	# of loci	[$F(1,2)$ = 535.78, p < .01]
3.	Content vs order	[$F(1,2)$ = 1536.02, p < .01]
4.	Laterality	[$F(1,2)$ = 2.69, p < .24]

Interactions

1.	Dist x loci	[$F(1,2)$ = 27.97, p < .03]
2.	Dist x C/O	[$F(1,2)$ = 47.04, p < .02]
3.	Dist x laterality	[$F(1,2)$ = 3.27, p < .21]
4.	Loci x C/O	[$F(1,2)$ = 26.82, p < .04]
5.	Loci x laterality	[$F(1,2)$ = 2.65, p < .25]
6.	C/O x laterality	[$F(1,2)$ = 29.16, p < .03]
7.	Dist x loci x C/O	[$F(1,2)$ = 8.20, p < .10]
8.	Dist x loci x laterality	[$F(1,2)$ = 22.02, p < .04]
9.	Dist x C/O x laterality	[$F(1,2)$ = 0.40, p < .60]
10.	Loci x C/O x laterality	[$F(1,2)$ = 5.77, p < .14]
11.	Dist x loci x C/O x laterality	[$F(1,2)$ = 3.97, p < .18]

Experiment 5 vs Experiment 7

Main effect

1.	IHI vs No IHI	[$F(1,2)$ = 45.72, p < .02]

Experiment 6 vs Experiment 8

Main effect

1.	IHI vs No IHI	[$F(1,2)$ = 7.25, p < .12]