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Masking, information integration, and tactile pattern perception: A comparison of the isolation and integration hypotheses

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Abstract. Two competing models of the effects of pattern element proximity, masking, and perceptual integration on the discriminability of spatiotemporal vibrotactile patterns are compared. Kirman's 'integration hypothesis' predicts that pattern perception is facilitated by a process of perceptual integration which requires that pattern elements be presented in close spatial and temporal proximity. Conversely, the 'isolation hypothesis' predicts that the strong masking effects which occur when pattern elements are presented in close proximity impede the perception of patterns. Traditional masking studies do not provide a fair test of these two hypotheses because they rely on methods that measure the subject's ability to identify the target when the target is presented in conjunction with the mask, rather than the discriminability of the complex percept resulting from the integration of the target and mask. To account for this, a new procedure was devised where the amount of interelement masking and the discriminability of the pattern as a whole were measured independently as the spatial and temporal separation of the pattern elements were varied. As expected under both hypotheses, masking between pattern elements increased as either the spatial or the temporal separation between them was decreased. The pattern discrimination data also support the isolation hypothesis in that the patterns were discriminated less well with increasing temporal element separation with a similar but nonsignificant trend in the case of spatial separation. It is concluded that this new methodology should be applied to a wider range of tactile pattern processing situations in order to assess the generality of the results obtained.

1 Introduction

A critical review is presented of the role of masking and perceptual integration in the processing of vibrotactile patterns, like those employed in tactile prostheses for the profoundly hearing impaired [see Sherrick (1984) and Weisenberger and Miller (1987) for reviews of these devices]. This analysis suggests several ways in which these issues should be explored, one of which is highlighted via an illustrative experiment.

Most tactile speech prostheses present the user with a spatiotemporal representation of the speech signal such that the momentary intensity of acoustic energy in a given frequency bandwidth is encoded as the amplitude of a vibration presented to a specific transducer in a linear array of skin-mounted vibrators. This type of display entails brief temporal pattern element separations, and also frequently includes close spatial separations between transducers. At these narrow spatial and temporal separations strong masking effects are known to occur between tactile stimuli. In the case of temporal proximity it has been found that tactile masking effects are strongest when both stimuli are presented together, then decline rapidly as the stimulus onset asynchrony (SOA) is increased to about 100 ms, before entering a more gradual decline in strength at longer SOAs (Craig 1983a; Evans 1987; Evans and Craig 1986, 1987; Gescheider et al 1989; Gilson 1969; Kirman 1984, 1986; Lechelt 1986; Schmid 1961). Similarly, tactile masking appears strongest when the target and mask

(1) It has been found that stimulus onset asynchrony, rather than interstimulus interval, is the primary temporal determinant of the strength of masking (Craig 1983b).
are presented to the same site, with steady declines in the extent of masking as the spatial separation between these stimuli is increased (Gescheider et al 1970; Gilson 1969; Snyder 1977).

1.1 The isolation and integration hypothesis
Kirman (1973) outlined two competing views on the role of masking in the process of tactile pattern perception. The first of these, called here the 'isolation hypothesis', postulates that tactile masking phenomena impede the accurate perception of tactile patterns. This implies that tactile pattern perception will be best when these masking effects are minimised.

Brown et al (1967) embraced this view in their solution to the 'problem' of interactions between stimuli in tactile patterns, which included the following elements: stimulating as few sites as possible, ensuring that these sites are widely distributed across the body surface, and stimulating only a single site at any given time. All these measures aim to reduce masking between pattern elements by increasing the spatial and/or temporal separation between those elements.

The second position discussed by Kirman (1973), called here the 'integration hypothesis' posits instead that tactile masking phenomena reflect the operation of integrative mechanisms for information organisation which facilitate the perception of complex patterns. In his words: “Masking ... is but the negative manifestation of perceptual organisation whose function is to detect relevant information in the environment, not to obscure it” (Kirman, 1973, page 64).

The core of this hypothesis is that the salient perceptual content of a pattern lies in the relationships between pattern elements. These relationships are represented at the sensory level by the interactions between these elements, rather than by the individual properties of the elements. The corollary of this is that sensory systems require the presence of these interactive or relational aspects of patterns if optimum pattern processing is to occur. As Richardson and Frost (1977) summarise: “Like all perceptual systems, the cutaneous system responds best to relations between stimuli, not to individual point loci of stimulus energy. High acuity in vision and fine pitch perception are possible because of myriad interactions among receptors and not in spite of them” (page 268).

What does this hypothesis imply about the role of masking in pattern discrimination, and consequently about the optimum spatial and temporal relationships between tactile pattern elements? When Kirman (1973) claimed that masking is the negative manifestation of this integrative process he was not, as it might appear, labelling the process of masking as simply an unfortunate by-product of perceptual integration. He believed that the process of masking is one of the means by which perceptual integration proceeds, with the disruptive nature of observed masking phenomena resulting from the types of task traditionally employed in studies of masking.

If masking is one aspect of the process by which perceptual integration occurs, then it follows that optimum pattern perception will not result when masking is minimised. This does not mean that the conditions which yield the maximum amount of masking are also those which lead to optimum pattern perception. For example, while spoken words presented at ten times the normal rate would be subject to stronger than normal masking effects, it is unlikely that they would be perceived as well as they would at a normal rate of presentation. Thus the optimum level of masking for the purpose of pattern perception would seem to lie somewhere above the point where no masking occurs but below the point of maximum masking.

In summary, according to the integration hypothesis masking represents the occurrence of a beneficial process of perceptual integration. The consequence of this in terms of the optimum level of spatial and temporal separation between elements in a
tactile representation of speech is that these parameters should be set so that masking effects are strong, yet not necessarily at their maximum. In contrast, according to the isolation hypothesis all masking effects are disruptive to pattern discrimination, and thus should be minimised in tactile communication systems, for example by decreasing the spatial and temporal proximity of pattern elements. The decisive question is thus whether masking either results in or involves the generation of a beneficial integrated representation of the target and mask.

1.2 Masking and perceptual integration

Although there is some dispute concerning the mechanisms underlying masking, there is widespread agreement that temporal integration of the target and mask is one of the primary factors underlying masking effects in vision (Breitmeyer 1984; Breitmeyer and Ganz 1976; Felsten and Wasserman 1980; Turvey 1973). Craig (1980, 1981, 1982) was amongst the first to propose that a process of integration also occurs in tactile masking. He presented subjects with patterned stimuli, such as letters of the alphabet, via an Optacon in either static (that is all elements at once) or one of several sequential (that is elements or groups of elements displayed in turn) modes (Craig 1981). He found that at relatively long display times these different presentation methods led to divergent levels of pattern recognition accuracy. However, at very brief durations performance was similar, in terms of both accuracy and error patterns, regardless of display mode. Craig (1981, 1982) concluded that the sequentially presented pattern elements were integrated together at brief display durations, yielding a representation which was identical to that produced in the static mode. This process of integration between pattern elements appears to be restricted to a temporal window of approximately 100 ms duration (Craig 1982).

Subsequent research has confirmed the role of integration in both forward (Evans 1987; Evans and Craig 1987) and backward (Evans and Craig 1986) tactile masking. Evans and Craig (1986) presented tactile patterns consisting of various one, two, or three line-segments and then used a masking stimulus covering all the points included in any of the patterns. The subjects reported the presence of more lines than were actually presented which suggests that elements of the mask were being integrated into the representation of the target. Again, this effect ceases as SOAs greater than 100 ms.

Beyond this critical 100 ms duration Evans and Craig (1986) still found evidence of masking. The difference at these longer SOAs was that the subjects’ errors now reflected a failure to discriminate the target from other patterns containing the same number of lines, rather than misjudgments concerning the number of lines in the patterns, which suggests that some process other than integration is responsible for tactile backward masking at SOAs greater than 100 ms. Evans and Craig (1986) attributed this long-SOA masking effect to a process whereby the mask interferes in the extraction of higher-order relational details from the target. They found no evidence of interruption effects like those reported in some visual masking studies.

It appears that this integrated representation of the target and mask consists of an overlay of the features of each stimulus, rather than some random or incomplete mixture of their features (Evans 1987; Evans and Craig 1987). For example, Evans (1987) presented target and mask pairings such that if all features of both stimuli were preserved in the integrated representation, then that representation would correspond with one of the forced-choice responses available to the subjects. Under these conditions the subjects frequently identified the target as being the one which would result from such an integrated overlay of the target and mask. Clearly a random or an incomplete mixture of features from the target and mask is unlikely to result in a percept which is readily identifiable as that which would result from an ‘exact’ overlay of all target and mask features.
While these data suggest that the integrated representation of the target and mask is a faithful overlay of the two stimuli, Evans (1987) has shown that the relative strength of the features contributed by each stimulus varies depending upon the order in which they are presented. In a backward-masking situation subjects frequently gave the mask pattern as their response to the identity of the target. This trend was absent in a forward-masking situation, and was diminished in the backward-masking condition when the relative amplitude of the target was increased. Evans (1987) interpreted these results as showing that the features of the temporally trailing stimulus were more strongly represented in the integrated percept than were those of the first stimulus.

In conclusion, it appears that at SOAs less than approximately 100 ms the tactile system is capable of integrating information from successively presented patterns into a single perceptual representation which seems to preserve the feature of both the target and the mask. Beyond this critical duration, tactile masking seems to be due to a higher-level process of interference between target and mask. Finally, the observation that the perceptual representation of the target and the mask consists of an integrated representation of the features of each stimulus is consistent with the claim of the 'integration hypothesis' that masking is one component in a general process of perceptual integration.

1.3 Is perceptual integration beneficial?
Clearly, it seems that touch is capable of perceptual integration, particularly over brief time periods, and that this process is intimately associated with the occurrence of masking. Both these findings are consistent with the integration hypothesis. The remaining issue in assessing the integration and isolation hypotheses is thus whether this process of integration is beneficial or disruptive to the processing of tactile patterns.

Other modalities, such as hearing, routinely process patterns which include temporal element separations well within those at which strong masking occurs. Although it is possible that this occurs in spite of masking and integrative effects, there is evidence that information organisation mechanisms exist which only come into play at these brief SOAs. For example, if subjects are presented with a rapidly alternating series of high and low tones, then two separate percepts are detected: a high-pitched stream and a low-pitched stream (Bregman and Campbell 1971). Van Noorden (cited in Bregman 1990) demonstrated that this effect dissipates as the SOA between tones is increased. Clearly, the grouping of sounds on the basis of their similarity in frequency may be beneficial in tracking a single auditory event against a background of competing events.

Craig (1985) attempted to assess the effects of integration on the processing of tactile patterns by presenting random pairings of the letters X and O sequentially with an Optacon-based display. The subjects either judged whether the two letters in a pair were the same or identified the pair of letters as a whole, for example whether the pair was 'OO' or 'OX'. Craig reasoned that the first task would require the subjects to focus upon aspects of the individual letters—a process which might be impeded by masking. On the other hand, he thought that the second task might force the subjects to integrate the two stimuli. Performance on both tasks was found to be similarly poor.

To temper his failure to demonstrate beneficial tactile integration, Craig (1985) noted that the types of patterns which he used may not have been amenable to constructive integration. For example, the letters X and O if integrated would yield, in Craig's words, an "indistinct blob" (Craig, 1985, page 245), rather than a meaningful pattern.
In his study Craig (1985) highlighted the issues which must be addressed in testing the integration hypothesis. First, it is necessary to present the subject with a task which allows any positive effects of tactile information integration to be revealed. Second, it is necessary to ensure that information is presented to the skin in a way which allows beneficial integrative effects to operate. Both these points are consistent with Kirman's (1973) criticism of attempts to extrapolate pattern perception ability from the results of traditional masking studies.

What is wrong, in this context, with the tasks used in traditional masking studies? Consider the letter and line discrimination tasks by Evans and Craig (Craig 1981, 1982, 1985; Evans 1987; Evans and Craig 1986, 1987). In these studies the subjects were presented with a meaningful target, such as a letter of the alphabet, in conjunction with either a similarly meaningful mask or an energy mask. The subjects' task was to identify either the target or some aspect of the target. Performance was best when the two patterns were presented far apart in time, and worst when they were temporally proximate.

This does not show that the isolation hypothesis is correct in positing that the integrated representation of the target and mask which is generated at close temporal separations carried little useful information. In support of the integration hypothesis it can be argued that the tasks used in conventional masking studies do not allow an accurate assessment of this issue. The integrated representation of the target and mask does not directly tell the perceiver what the target feels like, rather, it tells the perceiver what the target-and-mask event feels like. Under these conditions, observers do not respond randomly. Evans and Craig (Evans 1987; Evans and Craig 1986, 1987) found that the subjects' responses frequently reflected many aspects of how this integrated percept should appear. In this case it is clear that, far from being devoid of information, these integrated percepts contained much information. Further, this information did accurately reflect many features of the actual stimuli. Of course, we may ask what use a perceptual representation is if the perceiver cannot extract certain key items of information—in this case the identity of one of the stimulus letters—from it. There are three answers to this question.

First, subjects can extract the identity of a letter or simple pattern from an integrated tactile representation with minimal experience provided the display only includes that one stimulus. In their masking studies Evans and Craig frequently measured masking in terms of the change in letter or pattern identification rates between target alone and target-plus-mask conditions. A tactile display of a single alphabetic character presented by any means is still subject to masking forces. The individual stimuli (vibrating pins in Evans and Craig's study) from which the representation of the letter is constructed are themselves both targets and masks. Each point of stimulation must exert masking forces on adjoining points while at the same time being subject to masking effects due to those adjoining stimuli.

Under these conditions of simultaneous presentation and close spatial proximity strong masking effects must occur, yet the subjects achieve relatively high letter identification rates [for example 75% correct in Craig's (1983a) study]. In contrast, Craig (1982) has shown that the accuracy of identification of an individual letter falls as a function of increasing SOA if the letter is presented in two successive halves. As the level of masking between letter elements should decrease as the SOA between successive letter halves increases, this indicates that the accuracy of tactile pattern perception does not always decrease as the level of masking between pattern elements increases.

In summary, the reason that subjects have difficulty identifying the target when successive letters are used as the target and mask may be that the integrated representation of the target and mask no longer directly tells the observer what each individual letter feels like. In contrast, when a single letter is presented, with the strong masking
effects present being due only to the interactions between elements constituting that letter, the integrated representation does directly tell the observer about the form of the letter, thus accounting for the relative ease with which these stimuli can be identified.

Second, this argument suggests that we can identify some integrated tactile percepts, with difficulties arising either as the complexity of the integrated representation increases or when we are required to identify one of the components of the integrated representation. Of course, it is possible that performance on these types of task may improve with training. In all complex sensory tasks considerable experience and practice are required before the observer can make efficient use of the available information. For example, individuals who have visual defects rectified after long periods of dysfunction often do not achieve normal visual function, even though there is evidence that their peripheral visual mechanisms are functioning normally (Valvo 1971). Loomis (1981) has interpreted this observation as showing that "...normal form perception depends upon processes of perceptual integration that either develop with experience or require continued stimulation for normal functioning" (page 10). Clearly, it is unwise to expect that touch can innately perform tasks of a complexity which hearing and vision cannot solve without practice.

Third, the communicative value of speech is not dependent upon what a given speech event sounds like to the listener. All that matters is that the listener can consistently discriminate that sound from other speech sounds. Spoken words are often discriminated as much by their context as by their individual physical properties. Indeed, the listener need not be directly aware of the component sounds from which larger speech units are constructed. For example, Savin and Bever (1970) and Warren (1971) have shown that listeners can identify syllables more readily than they can the phonemes from which the syllable is constructed. Put simply, the extraction of the component parts of a pattern is not a prerequisite to the identification of that pattern. Consequently, the important issue in tactile pattern perception is the ease with which a given pattern can be uniquely discriminated from other patterns, not the extent to which individual components of that pattern can be identified.

Aside from explaining the relative failure of observers to identify individual elements from within integrated tactile percepts, these three points show why conventional masking methodologies are not suitable for showing the communicative value of these integrated tactile percepts. To summarise, these methodologies do not present the subjects with a task which we can reasonably expect them to perform without training, nor do they allow the subjects to demonstrate their capacity to discriminate between the percepts resulting from different patterns of stimulation.

2 Alternative ways to measure the effects of masking

There are at least two types of task where these limitations do not apply, and which thus allow an assessment of the predictions made by the isolation and integration hypotheses. First, we may look at element and pattern identification studies where the subject has the benefit of training. Obvious examples of this type are the numerous attempts to train individuals to interpret tactile speech transforms. While this type of study cannot reveal beneficial effects of masking, unless the results are compared with those of an equivalent study in which only the extent of masking is varied, it can show whether or not masking, as the isolation hypothesis claims, leads to inadequate levels of pattern identification.

A second approach, which does not impose the training load of learning to extract component elements from integrated percepts, is suggested by the earlier argument that the important issue in pattern perception is the extent to which a given pattern is uniquely discriminable, rather than the discriminability of its component elements.
In this case, the most appropriate task in assessing tactile pattern processing ability is to ask the observer to compare discretely presented tactile patterns. If the spatial and temporal proximity of the elements of each discrete pattern are varied, then the isolation and integration hypotheses offer different predictions concerning the ease with which this task can be performed at each level of pattern element proximity. As the proximity of the pattern elements is increased, the level of masking between pattern elements—and consequently the extent to which an integrated perceptual representation is generated—should also increase. If these conditions of close pattern element proximity are detrimental to the process of pattern perception, then the ease with which the two patterns can be compared should decrease with element proximity. However, if, as the integration hypothesis maintains, the occurrence of perceptual integration is beneficial to the process of pattern perception, then the ease with which the patterns can be compared should increase as the proximity of the pattern elements is increased to some optimal level.

Unlike conventional masking studies, in which the observer is required to identify the target from an integrated representation of the target and mask, this task requires the observer to discriminate the pattern of stimulation generated by the integration of a number of targets and masks (the mutually interacting elements of the pattern) from that generated by the integration of a different set of elements. The advantage of this approach is that it removes the need for the experimenter to make assumptions about what the stimulus will feel like to the subject, and consequently how the subject will describe the stimulus through his/her response. The level of performance achieved on this type of task simply reflects the extent to which the subject can discriminate between differing patterns of stimulation. As was suggested earlier, this ability seems to be central to the success of any language, be it an auditory, tactile, or visual one.

In a first attempt to contrast the isolation and integration hypotheses, an experiment was undertaken in which this new type of task was used. If the integration hypothesis is correct, then one would expect pattern comparison accuracy to improve with increasing spatial and/or temporal proximity of pattern elements, with the reverse applying if the isolation hypothesis is true. As the isolation and integration hypotheses both predict that element identification accuracy should decrease as a function of increasing spatial and/or temporal proximity of the pattern elements, a second condition was included. In this element-identification condition the subjects were required to make decisions about individual elements with the tactile patterns. This condition was included to test for the occurrence, and provide an index of the extent, of masking induced by the manipulation of the spatial and temporal separation between pattern elements, independent of the performance observed in the pattern-comparison condition.

2.1 Method
2.1.1 Subjects. The eighteen subjects tested in this experiment were paid undergraduate volunteers attending the University of Tasmania. None had extensive experience with vibrotactile stimuli.

2.1.2 Apparatus and procedure. The pattern-comparison condition employed a same-different task in which subjects compared sequentially presented tactile patterns. In contrast, the element-identification condition employed a three-alternative forced-choice task requiring the subjects to identify the most intense element within a tactile pattern. The tactile patterns consisted of three sequential 250 Hz vibratory pulses of 90 ms duration, each presented to a different site on the forearm. Six patterns were used, each consisting of a 'strong', a 'medium', and a 'weak' amplitude vibration. In order to restrict the subjects' ability to learn to identify each pattern simply on the basis of the absolute amplitude of a single element, the actual amplitude of the
The 'strong' element was varied between 35 dBm and 40 dBm from trial to trial. The 'medium' and 'weak' vibrations were set respectively 6 dBm and 12 dBm below the amplitude of the 'strong' vibration.

These tactile stimuli were generated by an Applied Engineering Super Music Synthesiser under the control of a microcomputer and were presented to the skin via the same type of tactile transducer employed in the Mini Vib tactile prosthesis. These tactile transducers measure $15 \text{ mm} \times 20 \text{ mm} \times 10 \text{ mm}$ (width $\times$ length $\times$ height) and operate via a relay coupled to the inside of the casing. Each transducer had a plastic flange glued to its underside which was used to mount the devices in a neoprene-lined clamp constructed from dense craftwood. This arrangement allowed accurate spatial separations to be maintained between the transducers while minimising any coupling effects between vibrators. The subjects rested the forearm atop the transducers, thus allowing them to set a coupling pressure which they found most effective.

Within each task, the spatial and temporal separation between pattern elements was varied in three steps. The briefest SOA used was 94 ms, a duration within Evans and Craig's (1986) 100 ms masking-by-integration stage. The second SOA used was 200 ms, a duration within their higher-level interference stage. The final SOA used was 450 ms, a duration outside the range in which masking effects are prominent.

The spatial separations used were constrained both by the size of the transducers used and by the physical dimensions of the forearm. The smallest centre-to-centre distance used between vibrators was 1.6 cm, which left a 1 mm gap between the sides of adjoining vibrators. This meant that adjoining stimulated sites lay completely within the two-point limen of the forearm region used [35-40 mm according to von Bekesy (1959) and Weinstein (1968)]. The intermediate vibrator spacing used was 3 cm, which with the width of the vibrators taken into account, meant that adjoining stimulated sites lay partially within the two-point limen of the forearm region used. The widest centre-to-centre spatial separation used was 5 cm, which left adjoining stimulated sites outside the two-point limen of the forearm region used.

As there is a difference of approximately 4-5 dB in the point of subjective equality for amplitude across this range of sites (von Bekesy 1959), it was necessary to adjust the amplitude of each pattern element depending upon the site to which it was presented. If this had not been done, the perceived amplitude difference between pattern elements would have varied with stimulus spatial separation, thus confounding any masking effects due to spatial separation.

Prior to testing, each subject underwent a calibration session in which the point of subjective equality for amplitude between each stimulated site was established by the method of limits procedure. During pilot studies, it was established that a single calibration value for each site, obtained at the median amplitude level (32 dBm) included in any pattern, was adequate to cover the whole range of stimulus amplitudes used in the experiment. The correction values obtained during this calibration session were applied to each stimulus as it was presented during each experimental trial.

The pattern-comparison condition and the element-identification condition each employed a $3 \times 3$ within subjects factorial design. The two independent variables were the temporal and spatial separation between pattern elements. As was described above, each factor had three levels. These two factors were fully crossed, resulting in nine experimental conditions. That is, each level of temporal separation was tested in conjunction with each level of spatial separation. The dependent variable in the pattern-comparison condition was the accuracy with which subjects compared the two

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$^{(2)}$ $1 \text{ dBm} = 1 \text{ mW}$ into a 600 ohm resistive load.
patterns presented on each trial. The dependent variable in the element-identification condition was the accuracy with which subjects identified the most intense element in each pattern.

The order in which the subjects undertook these nine experimental conditions was counterbalanced within each of the two task types in order to control for order effects. Similarly, the order in which subjects undertook the two task types was counterbalanced.

Prior to undertaking either of the experimental tasks, the subjects underwent a screening session in which they were presented with blocks of sixty trials until they reached a criterion accuracy level on that block of $d' > 1$. Any subject who did not reach this level on either task after four blocks was excluded from the experiment. In most cases this criterion level was reached after only one block of trials, although one subject required four blocks to reach this level. Two potential subjects were excluded because they failed to reach this criterion on either the element-identification task or the pattern-comparison task.

In the screening trials for the element-identification condition the temporal and spatial separations between pattern elements were set at 450 ms and 5 cm respectively, these being the levels which both the integration and isolation hypotheses predicted would produce the easiest discriminations. In the screening trials for the pattern-comparison condition the temporal and spatial separations between pattern elements were set at 250 ms and 3 cm respectively. As the integration and isolation hypotheses differed in terms of their predictions of which particular spacings should produce the best performance, these intermediate levels were chosen to avoid prejudging which separations would produce the easiest discriminations.

Immediately after the screening session each subject undertook sixty experimental trials in each of the nine spatial-temporal separation conditions for that task type. Including the associated screening and calibration tasks, each task-type session lasted about 2 h, with the subjects receiving rest periods whenever they required. There was a delay ranging from 1 to 7 days between the two task-type sessions for each subject, dictated by his or her availability.

The subject was seated in front of a VDU with the vibrator mount placed on a waist-high table situated on the subject's dominant side. The subjects were instructed to ensure that the central of the three vibrators was positioned under the middle of their forearm (the midpoint between the wrist and elbow) before each trial. This point was marked on their forearm to enable accurate placement. The slight acoustic output of the vibrators was masked by 250 Hz centre frequency 80 Hz bandwidth noise presented via Sennheiser HD22 headphones.

Each trial was commenced by the subject pressing either of the response buttons. After 1 s the target pattern was presented to the subject. In the pattern-comparison condition, the reference pattern was then presented 500 ms after the termination of the target. This interval was chosen in order to balance the competing needs of minimising masking effects between the two patterns and minimising the memory load imposed by the task. The subjects then responded either by two-choice button-press in the pattern-comparison condition, or by three-choice button-press in the element-identification condition. They were instructed to respond as rapidly as they could while still maintaining a high level of accuracy. Accuracy of responses was indicated to the subject by feedback given after each response.

2.2 Results
2.2.1 Element-identification condition. The raw data gathered in the element-identification condition consisted of the proportion of trials on which each subject correctly identified the strongest vibration in the target pattern. Values of $d'$ were
calculated for each subject in each condition with the use of the multiple-choice algorithm described by Green and Swets (1966). Mean $d'$ scores and standard deviations are presented in Table 1 as a function of the temporal and spatial separation between pattern elements. The variability evident in the data is indicative of the differential ability of inexperienced subjects to complete this type of tactile pattern perception task.

Table 1 shows that the level of spatial and temporal separation between pattern elements did influence the amount of masking observed. The main effects of both temporal ($F_{2,34} = 57.19, p < 0.001$) and spatial separation ($F_{2,34} = 8.94, p < 0.001$) show that within each factor performance increased with each increase in element separation. However, the finding of a significant interaction between these two factors ($F_{4,68} = 2.77, p < 0.05$) indicates that these main effects alone do not fully describe the relationship between spatial and temporal separation and the strength of masking.

A posteriori analysis via the Tukey HSD test was conducted to explore the nature of this interaction. Significant decreases in the accuracy of pattern discrimination were found with each decrease in element temporal separation within each level of spatial proximity, except between the 94 ms and 250 ms SOA temporal separations at the largest (5 cm) spatial separation. While performance at this largest spatial separation was found to be significantly better than at either of the closer spatial separations at the 94 ms temporal separation, no significant differences due to spatial separation were found at either the 250 ms or the 450 ms temporal separations. Thus it appears that the strong masking effects induced at brief temporal separations can be moderated if the spatial separation between the stimuli is sufficiently wide.

The purpose of including the element-identification condition in the experiment was to confirm that the changes in the SOA and spatial separation between elements in the patterns to be used in the pattern-comparison condition did induce the desired pattern of change in the amount of masking occurring between pattern elements. The data confirmed that these manipulations did lead to the expected changes in the extent of masking.

Table 1. Mean accuracy ($d'$) of identification of elements (with standard deviation shown in parentheses) as a function of spatial and temporal separation of pattern elements in the element-identification condition. MM are marginal means.

<table>
<thead>
<tr>
<th>Spatial separation/cm</th>
<th>Temporal separation/ms</th>
<th>94</th>
<th>250</th>
<th>450</th>
<th>MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td></td>
<td>0.44 (0.39)</td>
<td>1.01 (0.62)</td>
<td>1.51 (0.68)</td>
<td>0.99 (0.71)</td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td>0.52 (0.34)</td>
<td>1.16 (0.54)</td>
<td>1.75 (0.90)</td>
<td>1.14 (0.80)</td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td>0.87 (0.35)</td>
<td>1.06 (0.45)</td>
<td>1.82 (0.66)</td>
<td>1.25 (0.65)</td>
</tr>
<tr>
<td>MM</td>
<td></td>
<td>0.61 (0.40)</td>
<td>1.08 (0.54)</td>
<td>1.69 (0.76)</td>
<td></td>
</tr>
</tbody>
</table>

2.2.2 Pattern-comparison condition. The raw data gathered in the pattern-comparison condition consisted of the frequency with which each subject correctly compared the target and reference patterns. Values of $d'$ were calculated for each subject in each condition counting same-pattern trials correctly identified as 'hits' and different-pattern trials incorrectly identified as 'false alarms'. Mean $d'$ and standard deviations for each level of spatial and temporal separation are presented in Table 2.

In the case of temporal proximity, Table 2 shows that the accuracy of pattern comparison initially increased with increasing SOA before stabilising between 250 ms and 450 ms SOAs. In the case of spatial proximity, Table 2 shows a progressive increase in the accuracy of pattern comparison with increasing spatial separation between pattern elements. ANOVA revealed that, while the trend for accuracy to increase with SOA...
was significant ($F_{2,34} = 5.07, p < 0.05$), the trend for accuracy to increase with spatial separation did not reach significance ($F_{2,34} = 1.40, p > 0.05$). No significant interaction between these two factors was found ($F_{2,34} = 1.78, p > 0.05$). A posteriori analysis via the Tukey HSD test confirmed the descriptive observation that the increase in accuracy with SOA was restricted to the 94 ms to 250 ms SOA interval.

Table 2. Mean accuracy ($d'$) of pattern comparison (with standard deviation shown in parentheses) as a function of spatial and temporal separation of pattern elements in the pattern-comparison condition. MM are marginal means.

<table>
<thead>
<tr>
<th>Spatial separation/cm</th>
<th>Temporal separation/ms</th>
<th>94</th>
<th>250</th>
<th>450</th>
<th>MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td></td>
<td>0.65 (0.36)</td>
<td>0.94 (0.40)</td>
<td>0.90 (0.58)</td>
<td>0.83 (0.48)</td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td>0.71 (0.44)</td>
<td>0.91 (0.42)</td>
<td>1.11 (0.46)</td>
<td>0.91 (0.46)</td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td>0.82 (0.33)</td>
<td>1.12 (0.36)</td>
<td>0.93 (0.57)</td>
<td>0.96 (0.45)</td>
</tr>
<tr>
<td>MM</td>
<td></td>
<td>0.73 (0.38)</td>
<td>0.99 (0.40)</td>
<td>0.98 (0.54)</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Discussion

The element-identification condition results revealed that masking between pattern elements increased as the spatial and temporal separation between elements was decreased. In the case of SOA, a significant decrease in performance was observed with each decrease in SOA. In the case of spatial separation, there was also a decrease in performance with decreasing spacing, although this effect was primarily evident between the extreme (1.6 cm and 5.0 cm) element spacings. This decrement in performance with decreasing spatial and temporal separation is the expected consequence of greater interelement masking under both the integration and the isolation hypotheses, and can be taken as confirmation that the spatial and temporal separations used in this experiment included ones at which strong masking effects occur.

In the pattern-comparison condition the subjects' performance was worst at the closest spatial and temporal element separations. In the case of SOA, performance improved between this closest separation (94 ms) and the intermediate SOA (250 ms). There was no evidence of further improvement at the longest SOA (450 ms). Performance did not vary significantly with spatial separation.

Because the results obtained in the element-identification condition showed that masking effects between pattern elements increased as both the SOA and the spatial separation between elements were decreased, the changes in accuracy observed in the pattern-comparison condition with equivalent variations in these parameters may be attributed to changes in the amount of masking occurring between pattern elements. Clearly, these results support the isolation hypothesis, which predicts a decrease in tactile pattern discriminability with increasing levels of masking, rather than the integration hypothesis, which predicts an increase in pattern discriminability as masking increases to some optimum level.

While conventional tactile pattern masking studies also show decreases in pattern discriminability as the spatial or temporal separation between the stimuli is decreased (Evans 1987; Evans and Craig 1987; Kirman 1984, 1986), the methods used by those authors are not suited to demonstrating the beneficial effects of perceptual integration predicted by the integration hypothesis. The present results, therefore, are the first to offer clear support for the isolation hypothesis under conditions which allow the predictions of both hypotheses to be tested unambiguously.

Granted the support for the isolation hypothesis provided by the present data, the next step is to apply the pattern discrimination methodology developed here to an extended range of tactile perceptual tasks in an attempt to assess the generality of...
these results. Three of the necessary extensions concern the range of spatial and temporal separations over which the results hold, the degree to which the results are affected by practice, and the extent to which they hold generally over patterns of varying degrees of complexity.

First, it needs to be demonstrated that the isolation hypothesis holds at briefer temporal separations and narrower spatial separations between pattern elements than were used in this study. Such narrower temporal and spatial separations are characteristic of the natural language systems in which masking has been claimed to have beneficial effects. For example, the duration of the noise burst associated with plosives may be as brief as 10–15 ms (Fry 1979). While the minimum spatial separation used between vibrators in this study was 1 mm, the relatively large size of these devices still left the complete patterns spread over several centimetres. In contrast, tactile reading systems like Braille employ much higher spatial densities of pattern elements. Both examples have ecological validity as pattern-recognition systems involved in the processing of natural language. The question of whether the present results extend to these small temporal and spatial separations is therefore an important one. Subsequent experiments could resolve the issue by employing temporal and spatial separations substantially below those used here.

Second, it needs to be seen whether the results reported here would have changed after an extensive period of practice. It was argued above that the design of the present experiment would minimise the need for training. The informal reports of subjects about their experiences in the experiment, however, throw at least some doubt on that argument. All subjects were questioned about what the stimuli felt like and how they had performed each task. A common response was that when the elements were widely spaced, the subject perceived a series of unassociated pulses, rather than a pattern, with the pattern comparison being performed on the basis of a pulse by pulse amplitude comparison. But when the elements were closely spaced, the subjects reported feeling a unified pattern. A common analogy offered was that it felt like a “word” rather than a discrete series of buzzes. In this case the subjects reported that they performed the pattern comparison task by judging whether the patterns felt the same, rather than by directly comparing the individual elements.

These reports parallel the conclusions reached by Garner and Gottwald (1968) in their study of the perception and learning of auditory and visual temporal patterns. They proposed that “…the perception of temporal pattern which occurs at faster rates [of element presentation] is one of an integrated sequence, is phenomenally compelling and immediate, and is a relatively passive process for the observer” (page 109).

Such phenomenal reports of the experience of patterns in which the elements were subject to masking are just what would be expected under the integration hypothesis. It is conceivable, therefore, that observers require more experience than was available in the present experiment before learning to make use of the information available in an integrated percept.

There is a growing body of evidence from the visual modality that observers do improve their target identification performance with practice in backward pattern-masking situations, but do not improve in backward energy-masking tasks (Hertzog et al 1976; Schiller 1965; Schiller and Wiener 1963; Wolford et al 1988). In Wolford et al’s (1988) study, subjects were presented with consonant targets in the presence of nonalphabetic character masks (eg ‘#’). Across a 45-day training period the subject at least doubled his target identification rate at all of the six SOAs used. In the best case (SOA = 68 ms) his performance improved from 17% correct to 94% correct. It would be useful to establish whether similar reductions in pattern masking occur with practice in the tactile modality.
Third, it is necessary to determine if the present results hold with tactile patterns that are as complex as would be needed for transforms of any significant real-world information. For example, Kirman (1973) and Richardson and Frost (1977) have argued that efficient pattern perception in any modality requires the presentation of rich patterns which include as many diverse and redundant features as possible. Speech stimuli meet these requirements, as would any significant transform of speech, but the patterns used in the present study did not; on the contrary, they were deliberately kept as simple as possible. Studies could be designed to examine whether the failure to observe beneficial integrative effects in the present study was due to a lack of richness in the particular patterns used here. Such studies might employ a greater number of pattern elements varying across a wider range of pattern element characteristics, for example amplitude, order, frequency, and duration.

These extensions to the present study will indicate whether the isolation hypothesis can be supported under conditions which more closely approximate the world of deaf subjects seeking to make use of vibrotactile prostheses. The methodology for contrasting the integration and isolation hypotheses had to be developed with the use of simple patterns and small numbers of elements so that the contrast could be made as clearly and unambiguously as possible. Now that the methodology has been developed and found suitable for contrasting the two hypotheses, it will be appropriate to apply it under conditions that offer greater ecological validity and, possibly, prospects for practical applicability. Whatever the outcome of such extended comparisons, the methodology used here should be able to provide clearer evidence than has previously been available on the information processing mechanisms involved in the perception and interpretation of tactile patterns of the sort required for the non-auditory representation of speech.

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