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Tactile pattern perception

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Abstract. Because efforts to use the cutaneous sense for conveying speech and visual information have met with only partial success, it would be useful to understand better the pattern-sensing capabilities of touch. This paper is an account of the sensory and perceptual factors known or hypothesized to limit the tactile perception of simple two-dimensional patterns, with special attention to the limited spatial bandwidth of touch.

1 Introduction

Interest in tactile pattern perception has grown in the past decade and a half as the result of the development of a number of prosthetic devices for the deaf and blind that convert speech or optical patterns into tactile patterns. Even though a few of these devices, most notably the Optacon (Bliss 1969; Linvill and Bliss 1966), have been moderately successful in providing the sensorily handicapped with useful information, research with them has reinforced the conclusions of earlier investigators (DeGowin and Dimmick 1928; Major 1898; Zigler and Barrett 1927; Zigler and Northrup 1926) that the cutaneous sense, especially when compared with vision, has rather limited form-sensing capability when the patterns are impressed upon the skin (Apkarian-Stielau and Loomis 1975; Hill 1974; Kirman 1973, 1979; Loomis 1974; Scadden 1971). Even tactile reading, where the subject has control over exploration and character sampling rate, falls far short of visual reading, as evidenced by the relatively low reading speeds of Optacon and braille readers (Bliss 1978; Bürklen 1932; Lappin and Foulke 1973; Merry 1937; Nolan and Kederis 1969). The immediate concern of this paper is to consider the factors that limit the tactile perception of form, with an emphasis on those factors that most differentiate between touch and vision in their capacity for sensing small two-dimensional patterns. Although this concern is rather narrowly focused, it provides a convenient structure for treating many of the facts pertaining to tactile pattern perception.

At the same time that interest in tactile form perception has been on the increase, there has been growing support for the 'active touch' point of view set forth by David Katz (Krueger 1970) and Gibson (1962, 1966), one indication being a recent symposium with active touch as its focus (Gordon 1978). The goal of this approach is an understanding of the 'haptic' perception of the size, shape, and texture of three-dimensional objects. Central to this position is the assertion that the hand should properly be considered the sense organ for touch rather than the mechanoreceptors, and that emphasis ought to be on the active seeking of information by the exploring hand. A nice extension of this position has been made by White (1970) and White et al (1970) to the case of active scanning with the Tactile Vision Substitution System (TVSS), an electronic device that converts optical images registered by a television camera into tactile images displayed upon the back or abdomen. Unquestionably this theoretical position has merit, for besides its phenomenological validity it brings to the fore many of the amodal aspects that touch shares with vision. However, it is not very conducive to an understanding of the pattern sensing capabilities of the tactile sense as it typically is used in sensory substitution.

This paper, adopting quite a different stance, attempts to comprehend a variety of facts pertaining to the tactile perception of two-dimensional patterns in terms of functional properties of the cutaneous sense, a number of which are ordinarily labeled as 'sensory'.

2 Factors limiting tactile pattern perception

The following section considers those factors known or hypothesized to limit tactile pattern perception. Their categorization is based partly on phenomenological grounds and partly on conceptual grounds. Future research may reveal that two or more of these factors are in actuality manifestations of a common underlying process.

2.1 *Spatial resolution*

A recent development in the study of vision has been the assimilation of concepts of linear systems analysis, in particular, those of Fourier analysis. In addition to promoting alternative ways of thinking about how image processing is carried out by the visual system (Campbell and Robson 1968; Blakemore and Campbell 1969; Campbell 1974; Ginsburg 1978; Kabrisky et al 1970; Pollen et al 1971), the concepts have been useful in the more practical and theoretically neutral matter of characterizing the spatial sensitivity (spatial filtering properties) of day or night vision (Campbell and Green 1965; Cornsweet 1970; Sekuler 1974) much as a lens designer would characterize the image-forming properties of a lens.

Within this framework any spatial pattern of luminance can be represented as the sum of sinusoidal luminance gratings of varying frequency, amplitude, phase, and orientation. The modulation transfer function (in the context of vision) specifies how the various spatial frequency components in the stimulus lose contrast in the transfer from stimulus pattern to perceptual response. With the assumption of linearity, the resulting perceptual pattern is the superposition of those altered spatial frequency components. One outcome of the linear systems approach has been the realization that spatial resolution (the upper limiting spatial frequency transmitted by the system) alone does not specify visual spatial sensitivity; rather, one needs to specify the contrast attenuation (and phase shift, if any) at spatial frequencies lower than the upper limiting frequency. It would be desirable to characterize the cutaneous sense (at each body locus) in the same way, but the problem of presenting sinusoidal gratings to the skin has barely been considered, much less solved[1]. Even so, the value of these newer concepts is that they encourage one to take into account the spatial (and temporal) filtering of sensory processing and thus to consider what gets through the filter and is available for further processing by the higher brain centers—those involved in recognition[2].

By virtue of the stimulators available the conventional measure of tactile spatial resolution has been the two-point limen. Because a two-point target such as this is not a narrow bandwidth pattern, strictly speaking, it is not the proper target for measuring spatial resolution (the upper limiting spatial frequency); nevertheless, the inverse of the two-point separation serves as a rough estimate of the upper limiting frequency.

[1] Daley and Singer (1975) did vary the frequency of square-wave gratings presented to the surface of the back by use of a version of the Tactile Vision Substitution System. However, because there was no way to adjust grating contrast $[I_{max} - I_{min})/(I_{max} + I_{min})]$ independently of average grating intensity, they were able to obtain only an estimate of spatial resolution, which defines a mere single value of the modulation transfer function by way of the contrast sensitivity function.

[2] The way in which linear systems concepts are used here is purely descriptive without any presumption as to whether sensory information is coded neurally in the space domain or in the spatial frequency domain (see Sekuler 1974).

At this point it should be noted that spatial resolution alone does not determine the spatial bandwidth of the cutaneous sense. For any local region of the body used as a sensing surface, bandwidth is limited at the low frequency end by the spatial extent of usable skin surface as well as by attenuation of the lower spatial frequencies resulting from lateral inhibition (von Békésy 1967). Although it is implicitly recognized throughout the remainder of this paper that the skin sense is more aptly considered a band-pass spatial filter than a low-pass filter, the focus will be on its limited sensitivity to the higher spatial frequencies.

The three primary factors that would seem to limit spatial resolution are considered below.

2.1.1 *Static mechanical properties of the skin.* When a point stimulus is impressed upon the skin, the spatial gradient of skin deformation is considerably more shallow than that of the stimulus. This spreading of the pattern of deformation is obviously a consequence of the mechanical properties of the skin tissue (Taylor and Lederman 1975; Tregear 1966). Clearly, when a complex stimulus pattern with spatial detail exceeding the conformability of the skin is impressed upon the skin, the resulting pattern of deformation is only a smeared facsimile of the stimulus. However, the contribution of this spatial spreading is probably negligible except for the fingertips and the tongue, body loci for which resolution determined by spatial spreading is probably close to that imposed by neural factors.

2.1.2 *Mechanical wave spreading.* It is well established that stimuli transiently applied or vibrating in contact with the skin give rise to traveling waves on or beneath the surface of the skin (Moore 1970; von Békésy 1955). To the extent that traveling waves excite the mechanoreceptors involved in sensing form along their travel, the effect is one of 'blurring' the pattern of mechanical stimulation.

2.1.3 *Neural organization.* For any given locus, spatial resolution must be determined in part by any one or more of the following properties of neural organization: (i) the density of mechanoreceptive units innervating that region of the skin; (ii) the size and spatial sensitivity of the receptive fields of these mechanoreceptive units; and (iii) the number of neurons in the cortical projection areas representing that same region of the skin.

The findings of Vallbo and Johansson (1978) nicely illustrate the limiting roles of properties (i) and (ii). Even for the finger pad, which has nearly the smallest two-point limen (3 mm) of all body surfaces (Weinstein 1968), the distribution of mechanoreceptive units is rather sparse (Vallbo and Johansson 1978) with the smallest receptive fields being of the order of 2 mm in diameter (Johansson 1976). As evidence of (iii), it has been known since the classical evoked-potential mapping studies of Woolsey (Werner and Whitsel 1973) that the area of somatosensory cortex representing each body locus is greatly out of proportion to the surface area in question; body loci of greater functional importance (such as the fingers) are represented by larger areas of the cortex than less important loci, even though the latter, such as the trunk, may have much greater surface area. More recent micro-electrode studies of the relay and projection centers of the lemniscal system (Mountcastle 1961; Werner and Whitsel 1973) show that the peripheral receptive field sizes of higher-order cells are related to body loci in predictable fashion—those body areas (like the finger) represented by disproportionately large cortical areas have small receptive fields, and vice versa. These findings can all be understood in terms of neural convergence and divergence within the ascending pathways.

Whereas the role played by mechanical wave spreading in limiting spatial resolution is uncertain, the role played by neural organization is not. The close correspondence

between the static two-point limens across body loci and the cortical areas subserving these loci leaves little doubt that the two-point limen under these conditions is for the most part neurally determined (von Békésy 1957; Weinstein 1968).

2.2 *Interactions between stimuli more widely spaced than the resolution limit*
In addition to the spatial interaction between two point stimuli that are so close as not to be resolved, there are other interactions that are considerably more extensive. These interactions have been well documented in two classes of experiments: one dealing with 'phantom' sensations, and another with cutaneous masking.

2.2.1 *Phantom sensations.* A phenomenon to which von Békésy devoted considerable work, and which is summarized in his book (von Békésy 1967), is the interaction of two point stimuli manifest as a phantom sensation. Under some conditions the two stimuli are experienced as a single point somewhere in between the exact location depending upon the relative intensity of stimulation, relative timing of onsets, and the sensitivity of the skin (Alles 1970; Gescheider 1970; von Békésy 1967). Under other conditions, especially when the two stimuli are located at widely separated body loci (eg the two hands), the phantom is perceived as a weak third sensation located between the two stronger sensations corresponding to the stimulators (Alles 1970).

A second type of phantom sensation that has also received considerable attention (Geldard 1975, 1978; Geldard and Sherrick 1972) is associated with the phenomenon known as cutaneous saltation. When several pulses are delivered in rapid succession first to one stimulator and then to a second, phantom sensations are felt at discrete and evenly spaced locations between the two stimulators. Saltation has been demonstrated with vision (Geldard 1976) and audition (Sherrick 1975) as well.

Phantom sensations pose a concern to those wishing to use the skin as a substitute for the retina or cochlea, for they may cause considerable spatial distortion of the input pattern as it is represented neurally.

2.2.2 *Cutaneous masking.* Equally likely to cause distortions in the sensory representation of the stimulus pattern are the cutaneous masking effects that extend over considerable distance (Kirman 1973). It has been amply shown that perception of a brief electrical or mechanical stimulus can be completely suppressed by a much stronger stimulus, either simultaneous or nearly simultaneous with it. Typically masking is studied by measuring the elevation of the detection threshold of the test stimulus in the presence of the masker. Using brief current pulses delivered to the fingers, Uttal (1960) observed that masking decreased as the separation between test and masker increased. Schmid (1961) and Rosner (1961) also used electrical stimulation of the fingers and found a strong dependency of threshold elevation on the relative phase of mask and test, with the greatest masking occurring when the masking stimulus preceded the test by several milliseconds. Sherrick (1964) investigated masking with mechanical stimulation; like Schmid and Uttal, he observed the effect of spatial separation and relative onset. He also found that masking occurred with long vibratory presentations (500 ms) as well as with brief (20 ms) mechanical transients. In addition, he found that a test pulse (350 ms) pulsating every second was masked considerably more by a mask which came on simultaneously than by a mask which was left on continuously, indicating that a large part of the masking effect is a result of interactions of the transient neural signals associated with onset of the mask.

That electrical as well as mechanical masking effects occur when the test and mask are on separate fingers, or even separate hands, implies that to some degree interactions at higher centers are involved. Further support for this conclusion comes from the work of Gilson (1969a), who studied the effects of maskers placed at widely scattered locations on the body. He observed that maximum masking

occurred for a relative phase of onsets of test and mask which depended upon the longitudinal separation of mask and test. When the relative onset times were adjusted (for each location) to compensate for the different latencies of arrival in cortical centers, maximum masking occurred, suggesting simultaneous interaction at these higher levels. Another study by Gilson (1969b) demonstrated that multiple maskers placed at widely different locations summate in their threshold raising effects, again arguing for a central interaction.

The more recent work on cutaneous masking has focused on the large differences in masking obtained between different psychophysical methods. In general the threshold tracking procedure (method of limits) gives much greater contralateral masking than does forced-choice discrimination (Gescheider et al 1970), while the two methods give quite similar results for ipsilateral masking (Craig 1978; Gescheider et al 1970). It has been suggested that the dimensions along which the subject makes his judgment concerning presence of the test vary with the task (Craig 1978; Gescheider et al 1970; Gilson 1974; Snyder 1977) and that criterion shifts must account for a good deal of the contralateral masking that has been reported.

2.3 *Temporal resolution*

Cutaneous temporal resolution limits tactile pattern perception by placing absolute upper bounds on the rate at which a single pattern can be perceived when scanned sequentially (either by the exploring hand or in presentation by a vibrotactile display) and on the rate at which two or more consecutive patterns can be perceived.

The inverse of the upper limiting temporal frequency to which the cutaneous sense responds might seem the appropriate measure of temporal resolution. Information is available about the sensitivity of touch to the full range of temporal frequencies (Kenshalo 1978). However, the evidence is now overwhelming that human cutaneous sensibility owes its high frequency sensitivity (100 Hz and above) to the Pacinian corpuscles (Gescheider and Verrillo 1979; Merzenich and Harrington 1969; Verrillo 1968; Verrillo and Gescheider 1979), which have very large receptive fields (Johansson 1976); as such they must contribute little to the tactile perception of fine spatial patterns. One would thus be mistaken in treating the reciprocal of the upper limiting frequency as the measure of temporal resolution in the processing of form; moreover, although the Pacinians are sensitive to very high frequencies, the fact that at threshold they exhibit temporal summation up to 1 s (Verrillo 1965) suggests that there might be some low-pass element in the pathway carrying the signals from the Pacinians. Since the Rapidly Adapting and Type I Slowly Adapting mechanoreceptive units have the smallest receptive fields (Johansson 1976) and presumably account for the relatively fine spatial sensitivity of glabrous skin in the hand (Vallbo and Johansson 1978), it seems reasonable to look to their temporal sensitivity functions for a measure of temporal resolution pertaining to tactile pattern perception. At present, however, the determinations of these functions (Hensel and Konietzny 1979) are still sketchy. Moreover it is quite possible that the site limiting temporal resolution is not at the mechanoreceptors, but at some more central level.

An alternative means of arriving at a measure of temporal resolution is to measure the minimum detectable separation between two brief tactile pulses, delivered either at the same location or at two adjoining locations. Several different experiments done in much this way have come up with estimates ranging from 2 ms to 40 ms (summarized in Kenshalo 1978). On the basis of this type of experiment, it would appear that the cutaneous sense exhibits a temporal resolution somewhere between that of vision and audition. However, whether this measure of resolution pertains to cutaneous pattern perception remains to be seen.

2.4 *Other limiting temporal factors*
Temporal resolution places an absolute limit on the rate at which stimulus information can be processed, but it is not the only limiting temporal factor. An additional factor that may be relevant to tactile pattern perception is the central process involved in judging temporal order. In the relatively simple task of judging which of two stimuli came first, a time interval of at least 18 ms is required (Hirsh and Sherrick 1961). Given that this value is more or less the same for different sensory modalities as well as for judgments between modalities (Hirsh and Sherrick 1961), a central perceptual process is implicated. When the task also requires identifying the spatial locations of the tactile stimuli, not known in advance, the additional processing demand raises the threshold for discriminating temporal order to 26 ms (Hill and Bliss 1968a). When three stimuli must be located and temporally ordered, the threshold for correctly ordering each pair averages approximately 100 ms (Hill and Bliss 1968a). A concept analogous to sensory temporal resolution is the central processing rate at which the incoming sensory signals are organized and compared against information stored in memory. This and the preceding two factors are obviously interrelated, so much so that attempting to draw sharp boundaries between them makes little sense.

2.5 *Perceptual integration*
Even if all critical information about a stimulus pattern were to reach cortical levels without loss of fidelity, it may fail to be properly integrated in the recognition stage. With vision there is evidence of both 'hardwired' and learned components in the perceptual organization of patterns and it is obvious that recognition itself is an 'intelligent' process that draws upon past experience as well as a general knowledge of the world. Perhaps the most compelling evidence that pattern perception is limited by these higher-level processes comes from studies of patients who have had vision restored by cataract removal or by implantation of a corneal prosthesis (Gregory and Wallace 1963; Valvo 1971). Despite indications that many basic sensitivity measures (eg visual acuity, color vision) are normal or nearly so, functional vision is almost totally lacking. The presumption is strong that normal form perception depends upon processes of perceptual integration that either develop with experience or require continued stimulation for normal functioning. It is certainly reasonable to suppose that if these processes limit visual pattern perception, they limit tactile pattern perception as well. A more extensive discussion of the role of perceptual integration in tactile pattern perception is presented by Kirman (1973).

2.6 *Limited attention*
Finally, even if pattern fidelity were to be preserved in the course of sensory processing and the mechanisms of perceptual integration were adequate for the task, the pattern might nonetheless not be perceived as a consequence of insufficient attentional capacity. A traditional view (Neisser 1967) is that at some central level of sensory processing a bottleneck occurs where the rate of sensory information reaching that level exceeds its processing capacity. Under these conditions of limited channel capacity the observer can choose either of two strategies. One is to distribute attention evenly over the entire sensory field and thus process any portion of it less than perfectly. The other is to 'focus attention' on a subset of the sensory field and in so doing process it more completely at the expense of diminished processing of the unselected portion. Conceptually, limited attention is distinct from the spatial interactions considered earlier. To the extent that a subject can 'focus attention' at will on designated stimuli in the sensory field such that concomitant changes in detectability, discriminability, or recognizability are observed, there would seem to be

evidence of a central channel-capacity limitation; 'hardwired' spatial interactions would not be expected to vary with attentional changes.

In the visual literature a number of studies have established that the visual system has a substantial capacity for processing spatial patterns. Shiffrin et al (1973b) found that four letters in four locations could be analyzed for the presence of a target letter as accurately when presented simultaneously as when presented sequentially. Donderi and Case (1970) found that for displays of up to fourteen elements, the time needed to decide whether all elements were the same geometrical shape was independent of the number of elements. Finally, an experiment by Sperling et al (1971) demonstrated that up to 100 letters per second (in spatial arrays of nine or sixteen letters presented in rapid succession) could be scanned for the presence of a numeral.

Needless to say, the spatial processing capacity of the cutaneous sense falls far below that of vision. Studies of tactile attention, for obvious reasons, have been limited to using very simple stimuli, typically single points at several locations.

There are at least two studies that specifically address the issue of whether tactile attention is limited. Franzen et al (1970) obtained results they interpreted as indicating limited attention in the detection of two signals. Shiffrin et al (1973a), on the other hand, argued that the results they obtained as well as those of Franzen et al (1970) indicate no limitation for the detection of a target in any of three locations. However, their finding does not categorically rule out limited attention, for the detection of a single target in one of several possible locations is a relatively simple task.

It is reasonable to suppose that a limited central channel capacity would manifest itself most under conditions where more than one evaluative decision (detection, discrimination, identification) must be made in response to a single stimulus exposure. Thus, for example, when an observer is scanning a single three-dimensional object with the index fingers of both hands, the attentional demands would seem to be much less than when two different objects are being scanned. Clearly the attentional demands depend more upon the coherence of the stimulus than on the area of the surface of the skin being used for sensing. Much of the later discussion will be devoted to the perception of patterns which satisfy this vague notion of coherence (such as geometric shapes, letters, and objects). What immediately follows is a brief review of a class of experiments investigating the perception of patterns that lack any intrinsic coherence.

The first study (Bliss et al 1966b; Hill and Bliss 1968b) investigated the abilities of subjects to report the locations of multiple stimuli presented simultaneously. Air-jet blasts were delivered in patterns consisting of up to twelve stimuli to the twenty-four interjoint segments of the fingers (thumbs excluded). Using an alphabetic labeling system, subjects reported the segments stimulated after each presentation. When subjects were asked to report the stimuli presented to all eight fingers (whole report) the maximum number correctly reported averaged about 3·6 (out of twelve). Results obtained using post-stimulus cueing of individual fingers (partial report) suggested evidence of both a tactile sensory storage and a memory limitation in the whole-report procedure. Analysis of confusion errors showed that errors were spatially dependent—the reported segment, if in error, was generally close to the segment stimulated. The limited capacity which permits the identification of only three or four simultaneous stimuli probably reflects attentional, memory, and response limitations as well as the spatial interactions mentioned earlier.

Geldard and Sherrick (1965) and Gilson (1968) used a different experimental paradigm, one in which the roles of memory and response organization were minimized. Patterns of up to nine stimuli each were presented in successive pairs,

with the subject's task being to judge 'same' or 'different'. Both in the study with stimulators placed at different body loci (Geldard and Sherrick 1965) and in that using the ten fingers (Gilson 1968), error rate was strongly dependent on the number of stimulators and the percentage of stimuli common to the two patterns. The high error rates (eg 19% with pairs of patterns with three elements in common and one different) showed that even when response and memory limitations were minimized, there was still relatively little capacity for processing patterns of unrelated elements.

3 The evidence from research on tactile pattern perception

In this last section of the paper, many of the facts pertaining to the tactile perception of spatially coherent two-dimensional patterns are considered in terms of the limiting factors enumerated in the preceding section.

3.1 *Spatial resolution*

It is an indisputable fact that the spatial bandwidth of a circumscribed region of skin is quite limited, especially in comparison with the retina. In what follows it is argued that a number of basic facts of tactile pattern perception reflect this salient property of cutaneous sensibility.

3.1.1 *Tactile hyperacuity.* Since the work of Weber (Boring 1942; Sinclair 1967) it has been known that tactile localization of a single-point stimulus is much finer than spatial resolution, as measured by the two-point limen (Boring 1930, 1942; Weinstein 1968; Zigler 1935); under optimal conditions, localization acuity is as much as ten to thirty times finer than the two-point limen (Loomis 1981b; Loomis and Collins 1978).

To consider this difference between localization and resolution solely within the context of cutaneous sensibility is not to appreciate its wider generality; as has been argued before (Loomis and Collins 1978), this is an effect one expects of any of a wide range of systems that can be characterized as spatial (or temporal) low-pass filters. Examples abound in the literature on the human senses, among them: (i) vernier offset discrimination tasks reveal a large disparity between relative localization and spatial resolution (Andrews et al 1973; Ludvigh 1953; Sullivan et al 1972; Westheimer 1976, 1977, 1979; Westheimer and McKee 1977a, 1977c); (ii) frequency discrimination of two high-frequency tones presented successively is much finer than the resolution of simultaneous tones measured in terms of the critical bandwidth (Licklider 1951; Plomp 1976; Roederer 1973; von Békésy 1963), which reflects the limited spatial tuning of basilar membrane motion; (iii) relative timing of transient stimuli (relative localization in the time domain) when presented to separate 'channels' (the two ears in audition; distinct spatial locations in vision or touch) is considerably more precise than is the temporal resolution of two successive stimuli presented within the same channel [eg audition and touch (Gescheider 1970), or vision (Westheimer and McKee 1977b)]. Besides the senses, a wide variety of physical systems also manifest this basic difference between localization and resolution, one such example being ground-based radar used in aircraft separation. In every case the essential reason is that spatial (or temporal) resolution is limited by the highest spatial (or temporal) frequency transmitted by the system, when it is conceived as a linear filter. On the other hand, localization (in space or time) is possible with a precision equalling only a fraction of a period of the upper limiting frequency since positional information is available as phase in each of the lower frequencies that get through the filter; however, this is not to imply that phase is the neural code for position since, as Westheimer (1978) has shown, the just detectable shift in position of a sine-wave grating is independent of its spatial frequency. One familiar account of how precise localization is accomplished physiologically is von Békésy's model of 'funneling', in which there is successively greater sharpening of the neural code for

position because of lateral inhibition at each level of neural transmission (von Békésy 1958, 1967).

Although the focus so far has been on localization, there are a number of other instances of tactile 'hyperacuity', to use Westheimer's term for the class of spatial discriminations with thresholds much finer than the resolution limit. Vierck and Jones (1969) found evidence of quite good size discrimination of objects impressed upon the arm; using plastic cylinders of varying diameters as stimuli they obtained just-noticeable size differences which were roughly ten times smaller than the two-point threshold for the same test location. In a later study Jones and Vierck (1973) demonstrated that length discrimination is also finer than gap detection in the resolution task. More recently Loomis (1981b) has looked at tactile discrimination using a variety of spatial configurations, many of which have been employed previously in studies with vision; some of these are shown in figure 1. The stimulus patterns, all of them except *3* embossed on metal by photoengraving, were sensed by the index finger using light static touch. Stimulus *1* was the König two-bar target used for measuring spatial resolution. Targets of varying size and orientation (vertical and horizontal) were presented, with the subject having to judge orientation. The resolution threshold was defined as the gap width, *s*, of the target of this type that permitted 75% correct discrimination; it averaged 1·7 mm. Stimulus *2* was the familiar two-point target, with its threshold defined in the conventional way; the average threshold value was 2·8 mm. Target *3* was a movable point stimulus that was judged to be left or right of an internalized reference position. The threshold, defined as the semi-interquartile range of the resulting psychometric function, was a mere 0·17 mm. Target *4* was part of a configuration used in measuring spatial-interval discrimination. The other half, not shown, was the standard interval consisting of a pair of bars separated vertically by 5 mm. The subject always touched the standard interval and then the variable, with the task being to say which was wider. The average threshold was a mere 0·27 mm. Configuration *5*, first used with vision by Ludvigh (1953), involved the discrimination of misalignment. With a 3 mm vertical separation between the points, the average threshold was 0·43 mm. The remaining configurations (*6*, *7*, and *8*) were all variants of the conventional vernier

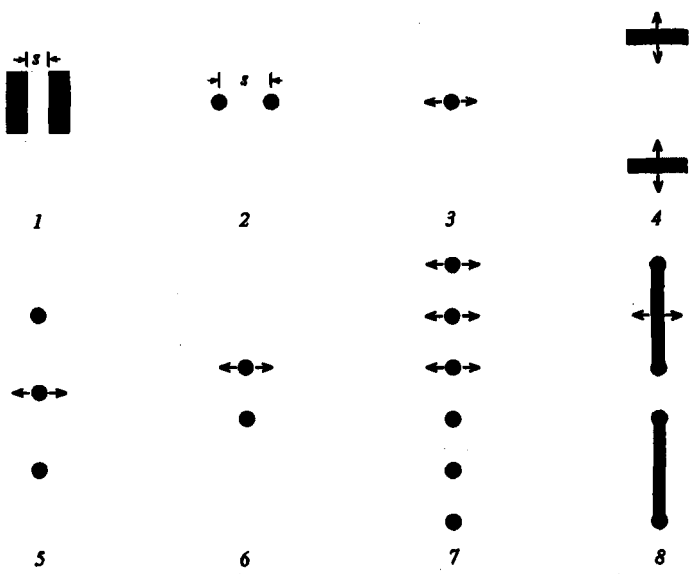

Figure 1. Tactile resolution and hyperacuity targets, from Loomis (1981b).

target, with targets *6* and *7* having a 2 mm vertical separation between points. The subject had to say whether the upper half of the target was displaced to the right or left of the imaginary line extending upward from the lower half. The thresholds for targets *6*, *7*, and *8* averaged 0·37 mm, 0·59 mm, and 0·47 mm, respectively. The discriminations involving configurations *3–8* all warrant the 'hyperacuity' label inasmuch as their thresholds were much finer than the two measures of spatial resolution obtained with targets *1* and *2*.

The more complex examples of tactile hyperacuity may be thought of in much the same way as point localization. In all cases the pattern characteristics that are critical to the spatial discrimination are largely invariant with a modest degree of low-pass filtering. This line of argument (see also Westheimer 1976) serves to eliminate any sense of paradox about hyperacuity that may exist, but hardly constitutes an explanation of it. There are, however, beginnings of a theory of hyperacuity, both for vision (Andrews et al 1973; Beck and Schwartz 1979; Sullivan et al 1972; Westheimer 1976, 1977, 1979; Westheimer and McKee 1977a, 1977c) and for touch (von Békésy 1967; Hoagland 1932; Loomis 1981b; Loomis and Collins 1978; Zigler 1935).

3.1.2 *The superior tangibility of braille.* With all the attention that electronic prosthetic devices have received lately, it is not surprising that braille has been overshadowed. However, the fact that these devices have enjoyed only limited success makes one appreciate the virtues of braille. One is caused to wonder why braille is superior to embossed lettering as a print medium for touch reading.

It is worthwhile to consider briefly the history of braille and its predecessors (see Bledsoe 1972; Bürklen 1932; Lowenfeld et al 1969; Merry 1937). Long before experimentation with punctographic characters, Valentin Haüy introduced italicized script-style embossed letters for use by the blind (Bledsoe 1972; Bürklen 1932). This style proved not very tangible and was soon succeeded by roman type of greater simplicity and tangibility (Bürklen 1932). In the quest for even simpler styles, substantial modifications were made of some of the roman characters; one such style, developed by William Moon, was an attempt at a compromise between tangibility and visual recognizability. It proved quite successful and has coexisted with the competing forms of braille (Lowenfeld et al 1969).

The first to devise a punctographic code for touch was Charles Barbier, who proposed it for use in telegraphy (Lowenfeld et al 1969). His symbology, based on a twelve-dot cell, was adopted for use in reading by the blind, but later gave way to the much-improved code of Louis Braille, who based his symbology on a six-dot cell (see figure 2).

The question posed above is now in need of slight modification: why are braille and certain raised-line types, such as Moon's, superior in tangibility to embossed roman-style type like that used in visual print? The answer proposed here is that the spatial resolution of the fingertip falls short of that needed to sense the details of roman characters of reasonable size; consequently, many of the characters are confusable or even indistinguishable for the reason that they are similar or identical in terms of their lower spatial frequency content—that which is sensed. This is especially true of the lowercase letters, which make up the bulk of most printed text. The braille alphabet, as well as the simpler raised-line alphabets, are composed of characters which exhibit greater variation in their lower frequency content. What makes braille particularly advantageous is that it permits a high degree of tangibility (legibility) for a given character-space size; this ensures a minimum use of space, thus reducing the bulk of printed texts as well as limiting the amount of scanning required during reading. In the view presented, braille characters owe their superior

tangibility not so much to the fact that they are punctographic per se, as to the fact that the six-dot basis provides for maximum shape variation within the confines of the rectangular character space. Evidence for this can be seen in the visual demonstration of figure 2. The letter and braille sets seen in the upper part of the figure, which match well in height-to-width ratio and DC level (average intensity under back illumination), are seen to differ greatly in visual distinctiveness when subjected to substantial low-pass spatial filtering (blurring by diffusion). An experiment comparing a range of letter and braille sets varying in typography confirmed the greater visual legibility of braille characters under conditions where the character sets had been blurred by diffusion (Loomis 1981a). The variations in legibility and tangibility across the three braille sets and the five letter sets used were remarkably alike, as indicated by the high correlation coefficient ($r = +0{\cdot}98$). The experiment also replicated an earlier finding of Austin and Sleight (1952) showing that letters composed of points were no more tangible than were conventional letters composed of line strokes. This lends some credence to the view that the punctographic nature of braille characters does not account for their superior legibility.

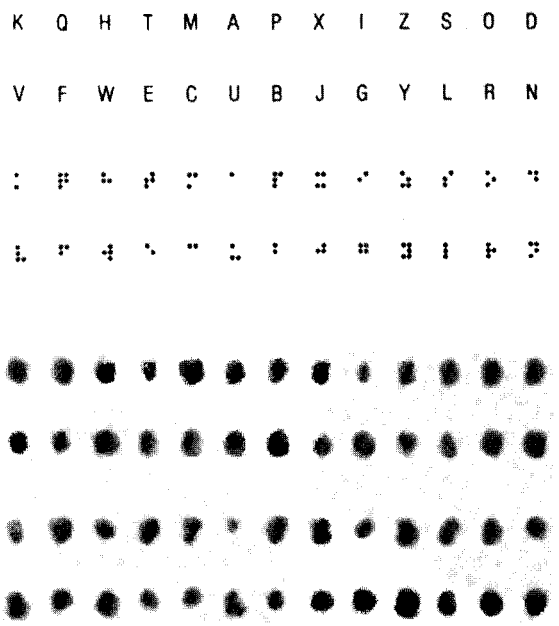

Figure 2. The upper half of the figure gives letter and braille characters based on virtually identical character-space dimensions. Corresponding alphabetic characters for the two sets are in corresponding locations. The lower half of the figure was made by blurring the negative of the upper half by means of a diffuser placed in the enlarger. The low-pass filtered braille characters are for the most part identifiable by someone familiar with braille, whereas the letters are not.

3.1.3 *The effects of stimulus size and body locus on tactile recognition.* Our everyday experience tells us that finely detailed raised patterns are more easily sensed by the finger the larger they are. Likewise, subjects attempting to recognize intricate objects or patterns with the Tactile Vision Substitution System (TVSS) invariably adjust the zoom lens of the camera to provide the largest tactile image possible. Systematic data on the effect of stimulus size is provided by a recent experiment in which embossed letters and braille characters of varying size were presented to the fingers of sighted observers (Loomis 1981a). The subjects were also visually presented with optical characters of the same size range; these characters were subjected to

optical low-pass filtering of a degree such that visual spatial resolution measured under the same conditions matched tactile spatial resolution on the finger. The average results for the three most proficient observers (out of five) are shown in figure 3. Besides showing that braille characters are both more tangible and more legible than letters throughout the range of sizes, the results indicate that the effect of increasing stimulus size is much the same for the two modalities.

This effect of stimulus size is readily understood in terms of low-pass spatial filtering. If one considers that the cutaneous sense at a given body locus exhibits a falloff in sensitivity to the higher spatial frequencies (measured in cycles cm^{-1} along the skin surface) such that no information is transmitted above some particular frequency, it is apparent that if a pattern is to be recognized it can be done so only on the basis of the lower spatial frequency content which is transmitted. Changing the size of a two-dimensional pattern corresponds in the Fourier domain to an isotropic rescaling of the two orthogonal dimensions of spatial frequency along which the pattern spectrum is represented[3]. Thus increasing the size of a pattern (effectively displacing its spectrum to lower spatial frequencies) means that more of its spectral content will fall within the sensitivity range of the sensory system, with the result that more pattern information is available to the form analyzing centers of the brain.

The variable of stimulus size is a useful one in determining whether spatial resolution of the sensory system is limiting performance. Results reported by Bliss et al (1970) support their claim that letter recognition with the Optacon in its normal usage is not limited by the spatial resolution of the finger. Although there was substantial improvement in performance as letters were increased in height from 11 mm (ten rows of the stimulator array) to 18 mm (fifteen rows), beyond that performance showed little gain (it already being 81% correct). Thus, unlike the TVSS which is apparently limited by the spatial resolution of the body surfaces for which it had been designed, the Optacon seems to have available adequate cutaneous

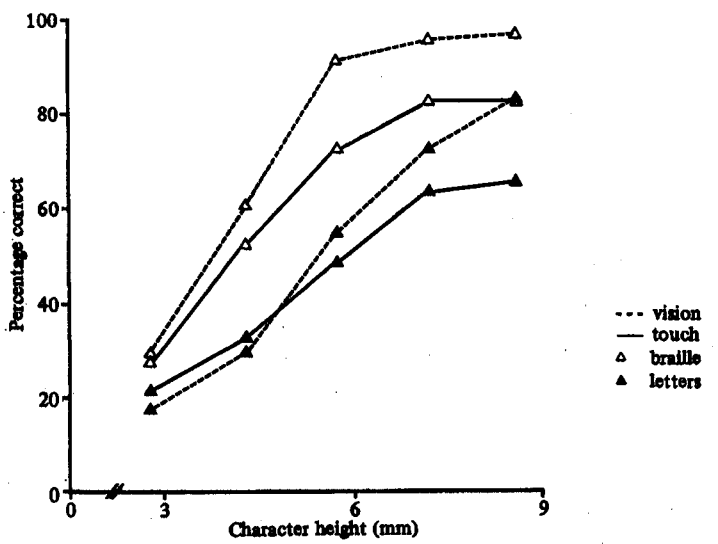

Figure 3. The results of an experiment by Loomis (1981a) examining the effect of character size on recognition. Braille characters and uppercase letters of varying size were presented to sighted subjects already familiar with braille.

[3] In addition to the rescaling of the two orthogonal dimensions of spatial frequency, there is a uniform rescaling of the amplitudes of the various components such that the total energy remains the same (Bracewell 1978).

spatial sensitivity when letters exceeding 18 mm are being read. However, given that the Optacon display occupies most of the underside of the index finger, it is apparent that there is not much spatial bandwidth in reserve for sensing patterns more complex than roman letters, a point consistent with Bliss's remark (1978a, p 245) that the Optacon has failed to permit the reading of more complex graphemes. It is also interesting to note that spatial resolution of the cutaneous receptor network activated by the 230 Hz vibration of the Optacon stimulators is considerably worse than that of the receptor network involved in the sensing of raised letters, since tactile recognition is nearly asymptotic with raised letters of 8·7 mm (figure 3), a value well below the acceptable letter size in Optacon reading.

A variable which is equally potent in its effect on recognizability is the locus of the body at which stimuli are presented. Embossed letters or braille characters which are just large enough to be identifiable under static presentation to the finger are completely undecipherable when presented to the forearm or back. Similarly, one would hardly expect the Optacon to be an effective reading aid for the blind if its vibrotactile display were placed anywhere but the finger. It seems almost too obvious to mention that recognition performance is directly related to spatial resolution of the locus at which patterns are presented; in accord with this expectation Scadden (1973) found that letter recognition with the TVSS was best with the display placed against the abdomen, intermediate with the thigh, and worst with the back, an ordering in rough agreement with that of the respective two-point limens of 34·0 mm, 45·5 mm, and 44·0 mm, respectively (Weinstein 1968).

3.1.4 *The superiority of sequential presentation over simultaneous presentation.* A method of stimulus presentation that, over a range of conditions, permits better recognition performance than static full-field display is tracing the pattern out over time with a single moving point, a method we are all familiar with as finger writing on the back. With relatively simple patterns, such as letters, it has been demonstrated with the TVSS that this method of display is clearly superior to that of full-field display (Beauchamp et al 1971). A striking demonstration of the superiority of tracing is provided by the work of Saida et al (1978). Using a vibrotactile display similar to that of the TVSS and placed against the abdomen, they compared recognition of *katakana* characters (one of the two simpler styles of Japanese character) as a function of three display modes. Whereas the two full-field conditions (stationary and moving letter) permitted only 25–30% correct recognition, sequential tracing afforded much better performance (90%).

A display method that is a compromise between the tracing and full-field display modes is scanning with a linear slit. Again, if the patterns are not too complex, this method allows better performance than does full-field display both with the TVSS (Apkarian-Stielau and Loomis 1975; Loomis 1974) and with the Optacon when smaller than usual letters are presented (Loomis 1980). An interpretation of these results in terms of low-pass filtering, which closely follows the reasoning of the earlier section on point localization, is offered below. That the superiority of sequential presentation might be a consequence of limited spatial resolution has been suggested previously by others, including Brown et al (1967) and Kirman (1973).

To see how, in principle, sequential scanning might be superior to simultaneous full-field presentation, let us start with the following idealized physical system—an electronic retina of finite extent but infinite spatial and temporal resolution feeding into an image processing stage capable of certain elementary computations on the retinal output. As an input pattern imagine a two-dimensional photographic transparency placed against the retina and illuminated from behind. The retinal representation of the transparency would be limited in spatial detail only by the

grain of the transparency. Now for the hypothetical low-pass spatial filter consider a diffusing screen placed between the transparency and the retina. If the diffusing plate is both linear and space-invariant (the Gaussian spread function of the diffuser is constant over position) and the retina is also linear and space-invariant, the image processing stage could reconstruct the relative intensity distribution of the input pattern perfectly if it were scanned sequentially by an aperture of infinitesimal extent[4]. This is so, for although the sampled light intensity at each instant of time would give rise to a Gaussian light-spread function in two spatial dimensions, the image processing stage could determine the peak intensity of the spread function and its position by some funneling-like operation and store these two values in a memory of infinite capacity. Given linearity and space-invariance of the filter, the stored values of position and intensity in image space would amount to a representation of the relative intensity distribution of the input pattern. Now if, instead, the transparency were illuminated uniformly all at one time, the diffuser output and the retinal output would be low-pass filtered versions of the transparency, for the intensity at each point is the convolution of the point spread function with the entire input pattern (rather than with the product of the pattern and the scanning aperture). Whatever information is lost in the convolution cannot be recovered by later processing, so that the retinal output in this case has less information than the retinal output obtained in the course of scanning.

To give some concreteness to the argument, consider a transparency which is simply a sine-wave grating of 10 cycles mm^{-1}. Suppose that the diffuser transmits spatial frequencies no higher than 9 cycles mm^{-1}. With uniform illumination of the grating, the diffuser output will be a uniform veil of light (a distribution having no information other than DC level). If instead the grating is scanned in the direction of its modulation with a point aperture, the output over time will be that of a Gaussian spread function modulating in overall amplitude as it moves in the image plane opposite the aperture in the object plane.

The basic argument can be readily extended to scanning with a linear slit of infinitesimal width. In this case scanning amounts to simultaneous presentation in one dimension (along the slit) and sequential presentation in the other (the direction of slit travel). From the reasoning above, this method too should lead to better pattern discrimination, for the light spread of low-pass filtering would be limited in its deleterious effect to the dimensions parallel to the slit.

Obviously the physical model presented would have to be degraded in a number of ways to begin to simulate realistically the sense of touch. First, it is clear that memory serving the sense of touch is greatly limited in capacity and can be overloaded with patterns probably no more complex than alphabetic characters or simple geometric forms. Second, the assumptions about linearity and space invariance are satisfied only under the most circumscribed of conditions. Finally, the assumption about infinite temporal resolution needs to be replaced by a more realistic one. The consequence of finite temporal resolution or persistence, of course, is that for sufficiently rapid scanning, simultaneous and sequential presentation are equivalent (cf Jones 1956; Wieland 1960).

The superiority of sequential tracing or slit-scan presentation is expected only when critical information about the stimulus pattern is being lost through low-pass spatial filtering. When the spatial discriminations are simple enough not to tax even what might be very limited spatial bandwidth, slit-scan or sequential modes of presentation need not yield better performance than the static mode, as Sherrick (1979) found when single lines presented to the thigh with a vibrotactile display

[4] To keep the argument simple we ignore the effects of diffraction by the aperture.

were discriminated in terms of orientation. In most of the letter recognition studies cited above, the tactile displays were placed against either the back or the abdomen, body surfaces with notoriously poor spatial resolution (Kirman 1978; Weinstein 1968). The one exception (Loomis 1980) made use of the Optacon with its display positioned, as usual, beneath the left index finger; in the condition where slit-scan presentation gave substantially better performance than static full-field presentation, the letters were only 14 mm high, within the size range where spatial resolution is exerting its limiting influence (Bliss et al 1970). In all other work with the Optacon sequential or slit-scan presentation has not been found to give better recognition performance. In the early reading studies with the Optacon (Hill 1974; Linvill and Bliss 1966; Taenzer 1972), reading rate was found to increase significantly with the number of columns in the display. Although one might be tempted to argue that the advantage of the narrower displays was negated by the very rapid sequential presentation occasioned by reading rates well in excess of fifty words per minute [as Loomis (1974) did argue], a more plausible reason is that spatial resolution is not a limiting factor with large letters and therefore there should be no advantage at all of slit-scan or narrow display presentation. This appears to be the case, for Craig (personal communication) has found considerably better performance with static presentation than with either slit-scan presentation or modified sequential tracing. The fact that the slit-scan and sequential modes gave even worse performance than static presentation suggests that some other factor must have been operating to limit the recognition of rapidly scanned letters.

3.1.5 *Lateral masking.* A phenomenon frequently encountered with the TVSS as well as with normal exploration of raised patterns by the finger is interference with the recognition of a target pattern by stimuli located very close by. Similarly, the internal details of a complex pattern are often discerned with difficulty, if at all (Craig 1974a; Scadden 1971). This phenomenon is referred to as tactile lateral masking, in keeping with the term frequently associated with a related effect in vision (Banks et al 1979; Bouma 1970; Taylor and Brown 1972; Wolford 1975).

It is argued here that a good deal of lateral masking is a consequence of limited spatial resolution. Clearly, if the neighboring stimulus is so close as not to be spatially resolved from the target pattern, it will interfere with recognition of the target. If the target were just recognizable to begin with, this interference can result in a substantial loss in recognizability of the target. Even where the same surround is added to a variety of different targets, the constant 'veil' of spreading excitation will have a deleterious effect on recognition if there is some compressive non-linearity effectively attenuating the sensory signals representing the targets. Since Weber's law has been shown to be valid in a variety of circumstances involving cutaneous intensity discrimination (Craig 1974b; Kenshalo 1978) it would appear that even the addition of a completely uniform veil of sensory excitation would interfere with recognition of the target pattern.

Partly for the reason that all of the available vibrotactile displays are just large enough to accommodate a single letter of reasonable size, very little work has been done on pure spatial masking of letters and other patterns. One of the few studies in this area (Loomis and Apkarian-Stielau 1976) got around the problem of limited display size by presenting letters temporally across just two columns of the 20 x 20 vibrotactile display of the TVSS, a method of display that had proven quite satisfactory in earlier work. Several different masking configurations were employed with the primary variable being the separation between the masking columns and the letter-carrying columns. The transient masking effects associated with onset of the masking stimulus were avoided by initiating exposure of the mask well in advance of

the letter presentation. For a visual comparison, subjects viewed the visual monitor of the TVSS under conditions of blurring (low-pass spatial filtering). The tactile and visual results showed much the same gradient of masking as a function of the separation between masking and letter-carrying columns. Although the letters were presented temporally, one can still apply the reasoning advanced earlier—at any instant the spatial information in the letter-carrying columns was effectively veiled by the spreading stimulation from the masking columns.

This experiment confirms that in those circumstances where spatial resolution is poor in relation to the dimensions of the display, lateral masking resulting from neural and mechanical wave spreading may be significant. In view of the large and spatially extensive masking effects associated with the onset of a stimulus, however, it is probable that these also interfere with recognition in the normal usage of devices like the TVSS and Optacon, where different stimulators are activated at different times as the character sweeps across the display in 'Times-Square' fashion. Direct evidence for these transient spatial masking effects in the context of pattern recognition, however, has not yet been forthcoming. Two studies with the Optacon by Craig (1976, 1978), in which a variety of masking stimuli were presented on either side of the target stimulus in the 'Times-Square' mode, might seem pertinent, but one could as easily interpret these results (as Craig did) in terms of forward and backward masking as in terms of spatial masking. The interpretation in terms of temporal masking is quite warranted, for large interfering effects of a masking stimulus that strictly precedes or follows the target letter with static presentation have also been reported (Bliss et al 1966a; Craig 1977; Schindler and Knapp 1976). The result is that there is as yet no real evidence for spatial masking effects on letter recognition, other than those attributable to limited spatial resolution. It appears that even these are inconsequential for Optacon usage as indicated by a recent study by Snyder (1979). Once again the suggestion is that the recognition of large letters with the Optacon is not limited by spatial resolution.

3.1.6 *Analysis of scanning strategy*. When users of the TVSS, or of a similar device —the Kinotact (Craig 1974a), are permitted to explore a pattern by means of camera scanning, one observes that they frequently resort to stereotyped scanning strategies (Bach-y-Rita 1972; Craig 1974a; Scadden 1971). One strategy is to scan the perimeter of the pattern, seeking distinctive features; they do this in such a way that only one edge of the pattern is present on the display at any one time. If internal details of the pattern are needed for recognition, subjects will typically adjust the zoom setting of the camera lens to increase the size of the internal details, and where possible will eliminate all stimulation from the display other than the critical features being sought. Although these strategies allow them to minimize lateral masking by pattern elements not of concern at the moment, they do require that the subject make greater use of the motor information during scanning in order to perceptually reconstruct the pattern.

As well as being found in the use of systems like the TVSS, these scanning strategies are commonly observed in normal tactile sensing with the finger. Subjects will sometimes explore an intricate pattern by tilting the finger so that only a small part of the skin surface makes contact with an edge of the pattern. If this maneuver fails, the subject may then use the fingernail or, if available, a sharp stylus for examining the internal features of the pattern. In several ways this type of scanning resembles the methods of scanning with a slit or with a point discussed in section 3.1.4. It differs from them in that position sensing of the pattern elements is accomplished by proprioception (joint and muscle senses), rather than by cutaneous processing.

The role played by spatial resolution in limiting tactile pattern perception should not be underestimated, for spatial resolution is likely the most salient factor distinguishing touch from vision. Even the Optacon display, which by its design probably has access to more spatially resolvable points on the skin than any other existing tactile display, is still limited in terms of the available cutaneous spatial bandwidth. Although this bandwidth more than suffices for the recognition of roman characters, it is apparently not adequate for more complex graphemes (Bliss 1978a). Even if the ventral surfaces of all ten fingers could be fully utilized in a ten-finger Optacon-like display—an unlikely prospect (Hill 1974)—the total usable spatial bandwidth of touch would fall far short of that of the retina.

3.2 *Interactions between stimuli more widely spaced than the resolution limit*
The phantom sensations and spatially extensive masking effects, discussed earlier, are both robust phenomena that one might expect to distort the stimulus patterns as represented and thus to impede their identification; as yet, however, there is little direct evidence that they do. The masking effects reported by Craig (1976, 1978, 1979) in connection with vibrotactile letter recognition could as easily be interpreted as consequences of interference in time resulting from limited temporal resolution and central limitations on processing rate. Similarly, the lateral masking reported by Loomis and Apkarian-Stielau (1976) was manifest under conditions specifically arranged to avoid transient masking. The only data that seem interpretable exclusively in terms of extensive spatial interactions are those reported by Kirman (1978). When patterns were traced out sequentially point by point on a vibrotactile display, several systematic distortions were noted, among them: (i) perceptual overshooting of the scanning point at abrupt corners when the scanning was slow; and (ii) the perceptual smoothing of an irregular curve at rapid rates of scanning. That only a single point was present at any one time poses no problem here, for the cutaneous system has far from infinite temporal resolution (Kenshalo 1978) and these spatial interactions are already known to be dependent upon relative onset of the interacting stimuli (Alles 1970; von Békésy 1967; Craig 1978; Gescheider 1970; Jones 1956; Schmid 1961; Sherrick 1964; Wieland 1960).

3.3 *Temporal resolution and other limiting temporal factors*
Not surprisingly, there is abundant evidence showing that tactile pattern perception is rate-limited either by sensory factors (eg temporal resolution) or by more cognitive factors. One class of experiments demonstrates that when several patterns, each of which in isolation has a high probability of being recognized, are presented in close succession, recognition performance drops considerably (Bliss et al 1966a; Craig 1979; Schindler and Knapp 1976). The most extensive work on forward and backward masking in letter recognition has been done by Craig (1976, 1978, 1979). He has interpreted his masking results in terms of two processes, integration and interruption. Integration of two patterns may be thought to occur when they fail to be temporally resolved, the result being that they are partially superimposed. Interruption reflects a more cognitive process that requires time for completion. Craig has consistently found greater backward than forward masking, a result he interprets as indicating some interruption in addition to whatever integration there might be.

A second class of experiments demonstrates that the perceptual and cognitive processing of a single pattern takes time. Taenzer (1970, 1972) has shown that a display time of at least 150 ms is necessary for 95% reading comprehension with the Optacon; performance drops off rapidly as display time is decreased. Reducing the number of columns (from six to one) in the Optacon display results in the subject lowering the letter scanning rate such that character display time remains roughly constant (Hill 1974; Taenzer 1970, 1972).

Craig (1979) has also studied the effect of character display time (from 4 ms to 800 ms). Unlike Taenzer (1972) he looked not at reading rate but at the recognition accuracy of letters presented singly. More importantly he studied two modes of letter presentation, the scan ('Times-Square') mode, which is the natural display mode in reading with the Optacon, and the static mode, in which the letter is simply flashed in a fixed position within the display. He found that the static mode of display gave higher recognition accuracy for display times less than 200 ms. Even when the perceived vibrotactile intensity was controlled to some extent, scan presentation continued to give very poor performance at short durations. It is apparent that subjects have difficulty processing a letter moving rapidly across the display. This result points to a low-pass element at some level of tactile processing, either sensory or cognitive.

3.4 *Perceptual integration and limited attention*

The most obvious indication that the process of perceptual integration exerts a limiting influence on the tactile perception of form is the ubiquitous finding of large individual differences between observers, differences that have no obvious sensory basis (Bliss 1978a, 1978b; Craig 1977, 1979; Kirman 1973; Loomis 1974; Nolan and Kederis 1969). These differences must reflect variations in both innate capacities and prior experience. In virtually all studies on pattern perception, large practice effects are observed. The length of time over which practice continues to result in improvement obviously depends upon the difficulty and complexity of the task. Reading with the Optacon, which obviously depends upon more than recognizing letters, takes several years before maximum reading rates are achieved (Bliss 1978b). However, the variations in reading ability between observers seem to reflect constitutional variables even more than the effects of practice. Bliss (1978a) has presented data showing that average reading rates of Optacon readers decline significantly with age in a population of new users. Craig (1977) has come across several sighted observers who were able to read with the Optacon at rates of 70–100 words per minute with perfect comprehension after only several hours of practice; this is remarkable, as most Optacon readers, even after several years, read at rates of less than fifty words per minute (Bliss 1978b). Craig's two extraordinary observers were not simply using superior cognitive strategies in achieving these higher reading rates, for they did no better than other observers in reading with the visual display of the Optacon. Moreover, the two observers exhibited virtually no forward or backward masking in a letter recognition task with the Optacon, and no evidence of lateral masking in the recognition of shapes using the Kinotact, a device like the TVSS with its display positioned against the abdomen.

Further evidence of the limiting role played by perceptual integration is given in figure 3; these are the averaged data of three subjects in the study by Loomis (1981a). Whereas the visual recognition scores show every sign of continuing to increase on up to 100%, the tactile recognition scores for both letters and braille appear to reach a ceiling somewhat lower than this. The data of the two less proficient (and less experienced) subjects (not shown) run up against an even lower ceiling. This residual error for characters that seem of adequate size for good sensory fidelity is also a general finding with the Optacon (Bliss et al 1970; Craig 1976, 1977, 1978, 1979).

A specific issue pertaining to perceptual integration is whether increasing the field of view in Optacon and braille reading by utilizing two fingers rather than one increases reading speed and/or comprehension. Because more than one character generally is present on the combined sensory surface at each instant of time, this is no longer simply a matter of perceptually integrating a single coherent pattern. It may be that the factor of limited attention is relevant here, for two or more distinct

patterns are present in the sensory field. On the other hand, closely adjoining letters are typically elements of the same word and the word has a unity of its own at a more cognitive level; hence, at the highest level of organization during touch reading, there need not be a 'division' of attention, since the word is the elementary goal in the act of reading. Thus it seems reasonable to consider this matter of expanding the tactual field of view as one of whether the observer can prceptually integrate two or more letters that are simultaneously present.

It is known that braille readers using both index fingers read more quickly than those who use only one finger; they do so, however, by using one finger to aid in the control of scanning and to search for the next line while the other finger senses the characters (Bürklen 1932; Foulke and Berlá 1978). In a controlled experiment, Lappin and Foulke (1973) did find a slight superiority with two fingers. They made experienced braille readers scan vertical lists composed of just two braille characters with one, two, or four fingers; the task involved counting as rapidly as possible the number of occurrences of one of the two characters. They found that use of two fingers from separate hands gave better performance than one finger or all four fingers of one hand, although scanning time decreased by only 15%; use of two fingers on the same hand, however, actually gave slightly worse results than one finger. This work shows that, in contrast to visual word reading where a number of letters are taken in during a single fixation (Hill 1974; Taenzer 1970, 1972), tactile reading of characters is essentially limited to one character at a time. Hill (1974) found very much the same result with what was essentially two Optacon displays beneath the index and middle fingers. Reading performance was no better with two fingers than with just one, in spite of the fairly extensive practice that subjects received.

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