Vibrotactile pattern discrimination and communality at several body sites

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In a series of experiments, the effects of spatial layout on vibrotactile pattern perception were explored by testing the ability to discriminate between two sequentially presented patterns that share active elements in the same spatial locations. Two-dimensional displays were used in order to examine the functional relationship between discrimination performance and pattern *communality*, defined as the sharing elements, on different body sites. Accuracy of discrimination judgments was inversely proportional to communality, regardless of the number of pattern elements. For compact arrays fitted to the finger, palm, and thigh, the effects of communality appeared equivalent. The similarity between finger and thigh functions is remarkable, considering the dramatic differences between these sites in receptor components and structure. When these data were compared with those from arrays with distributed contactors, performance was substantially better with well-separated pattern elements. Such findings help to explicate how information from apposed patterns can best be delivered to the skin through tactile communication systems.

The perception of visual patterns has been studied extensively at the levels of sensory, perceptual, and cognitive processing. Compared with the study of vision, that of tactual pattern perception has a short and limited history. Perhaps as a result of this short history, and because of the spatial nature of stimuli that appeal to both senses, attempts are often made to analyze tactile pattern perception in terms of the extensive working knowledge of visual systems (e.g., Loomis & Lederman, 1986). Indeed, it has been shown that there are a number of dimensions along which the visual and tactual senses appear to share common processing strategies (Marks, 1978; Piéron, 1952; Uttal, 1973), even though complex spatial pattern perception appears to be poorer on the skin. Loomis (1982, 1990) has suggested that tactual pattern perception is the same as the perception of blurred visual patterns, as is revealed in similar effects on identification performance of pattern characteristics such as size and presentation mode. Other studies of the processing of visual and tactual patterns, however, have suggested a number of important differences between the two systems. In one instance, Loomis (1993) recently found that characteristics of lateral masking stimuli differentially affect the perception of Braille patterns for the two senses as a result of a strong difference in the salience of dotted or

broken line stimuli. Such findings remind us that the biological differences in the sensory apparatus between touch and vision necessitate independent empirical examination of tactile pattern perception because the basic questions previously answered for the visual modality may not serve to accurately describe pattern perception through the sense of touch.

An issue of both applied and theoretical import in vibrotactile pattern perception concerns which features or dimensions of patterns determine their perceptibility, especially in situations in which multiple patterns are presented in sequence. Distinctiveness of strings of successive tactile patterns is an important factor in the successful operation of cutaneous communication systems. Both tactile aids for blind persons that provide access to printed text (including translation into braille) and aids for hearing-impaired persons that assist lipreading rely on the ability of the user to process streams of tactile information. Such tactile sensory substitution systems, especially those that encode visual information, convey meaning through the spatial layout of active contact points (Craig & Sherrick, 1982). Even the tactile presentation of acoustic information is typically encoded with spatially distributed contactors that present different features or frequency bands of the auditory signal (Summers, 1992). At this time, there is little information to provide designers of such systems with the best approach to provide the highest degree of distinctiveness for individual patterns.

Characteristics of visual patterns that produce "good" figures that can be easily distinguished from one another have been addressed by several models of visual pattern perception (see, e.g., Garner, 1974, 1978). Such models often include an analysis of the perceived stimulus as one step in the sequence of events that occur from sensory input to response. This analysis has been characterized as

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template matching (for a review, see Chase, 1986) and as the identification of specific aspects of the stimulus (i.e., features or geons; see, e.g., Biederman, 1985). It seems clear that the highly acute visual system is particularly well-designed for appreciating visual patterns that include contours with high spatial frequencies (Ginsburg, 1986). The written alphabet is an example of a set of visual patterns that consist of such spatial features (lines, angles, and curves) arranged in a variety of configurations that have evolved over time to emphasize the contrast with one another and appeal to the capabilities of the visual system. In contrast, when the same alphabet shapes are presented to the finger by the vibrotactile array of the Optacon, a reading machine for blind persons (Moore & Bliss, 1975), the crisp clean lines and angles that are apparent visually are not readily felt even by practiced observers. The density of receptors in the eye is high, resulting in a finely grained, almost seamless view of the visual world. The fingertip, however, has punctate sensitivity because of a relatively low density of receptors. The tactile view is more akin to a pointillist's painting. As a result, the tactile system has poorer spatial acuity, and alphabet patterns are perceived as fuzzy or blurred reflections of their visual counterparts (Loomis, 1982, 1990). The distinction between such letters as O and C are lost as the tactile system allows completion of the gap in the letter C. The letters N and H are also confused, as observers report, "because both have something going on in the middle of two parallel lines." From these examples, it seems clear that the sharp spatial features that contribute to high discriminability for the visual system do not hold for the tactile system. And yet, the pattern characteristics that would be most appealing to the tactile system are still to be determined. For example, it has been shown that movement, which was once believed to be so critical for pattern perception (Geldard, 1961; Loomis, 1974), is less critical for accurate perception of letter-like vibrotactile patterns (Craig, 1980; Phillips, Johnson, & Browne, 1983; Sherrick & Cholewiak, 1977).

One prominent factor that affects the perceptibility of pairs of vibrotactile patterns is their use of shared locations on the skin or common elements on sets of stimulators. Specifically, vibrotactile pattern discrimination has been shown to be influenced by the degree of "communality" between patterns (Aston & Weed, 1971; Geldard & Sherrick, 1965; Gilson, 1968; Gottheil, Cholewiak, & Sherrick, 1978; Horner, 1991). *Communality*, a term coined by Geldard and Sherrick (1965), who studied pattern discrimination with stimulators distributed over the whole body, is a physical measure of pattern similarity defined as the degree to which two patterns share active elements in the same spatial locations. These elemental or integral parts of a pattern, whether made up of individual or multiple vibrators, will be referred to here as *cells*. *Communality level* describes the percentage of individual cells that two patterns have in common. Consider a simple example in which a pair of patterns is constructed of three from a set of six spatially separate cells. The first pattern includes cells numbered 1, 3, and 6, while the second in-

cludes cells numbered 2, 4, and 6. Since both of these patterns include Cell 6, there is 33% communality when they are paired, because they share one of their three cells. When such pairs of spatially distributed vibrotactile patterns are compared in a discrimination task, performance has typically been found to be inversely proportional to communality: Error rates increase when the proportion of cells shared by two patterns is large. This general relationship has been shown in several studies of spatially distributed patterns. Gilson (1968) studied pattern communality by using a number of suspended vibrators. In this case, pattern elements consisted of individual vibrators on the fingers of the two hands. Aston and Weed (1971) similarly presented patterns to corresponding points on the eight fingers through a tactile Vocoder, a device used to encode analogues of speech, and examined communality interrelations. Gottheil et al. (1978) was the first study to use a dense vibrotactile array (in this case on the thigh) to examine the influence of communality on discrimination of random or symmetrical patterns. In subsequent studies, using the thigh matrix, the effects of duration (from 300 to 1,200 msec) and presentation mode (static, scanned, moving slits) on discrimination performance were also examined; similar functional relationships were found between errors and communality (Cholewiak, 1977). More recently, with a limited pattern set consisting of one or two lines (allowing only two levels of communality) presented to the fingertip, Horner (1991, 1992) was also able to demonstrate that the major factor responsible for degrading discrimination performance was the communality of the pair. Thus, it appears that the presence of common spatial information within a number of such patterns is detrimental to accurate discrimination judgments.

Among these studies, the best discrimination judgments (lowest error rates) occurred for low levels of communality presented by the whole-body display used by Geldard and Sherrick (1965). However, a system requiring contactor sites to be spread across the body's surface to maintain the distinctiveness of patterns would prove to be at least inconvenient, given present technology (Cholewiak & Wollowitz, 1992). But bringing the contactors closer together (such as in a dense array) raises the possibility of spatial interactions that can occur readily on the skin's surface. Does communality have the same effect on discrimination of patterns presented with devices more typical of current displays such as compact tactile arrays? The spacing between contactors on these dense arrays is usually matched as closely as possible to the spatial acuity of the body site for which the array is designed (see, e.g., Daley & Singer, 1975, for a discussion of the design of an array to fit the back). It is possible that discrimination performance of patterns on dense arrays could be based on the locations of the pattern cells. Such spatial features, if appreciated, could serve functionally as tactile "geons." Yet identification of these features might suffer precisely because the vibrator spacing is so close to the spatial acuity of the site. On the other hand, it is also possible that the density of such arrays al-

lows for appreciation of the pattern as a whole, providing for more ready comparisons between sequentially presented patterns (with one pattern serving as a "template" to be matched to the next). The improvement or degradation of pattern discrimination with dense arrays should shed light on these alternative underlying mechanisms of tactile pattern perception.

Another aspect of tactile pattern perception that must be addressed is unique to the sense of touch: the sensory apparatus extends over the whole body. Over this surface, a wide range exists in biomechanical properties (Tregear, 1966), the complement of underlying tactile receptors (Andres & Düring, 1973; Cholewiak & Collins, 1991; Sherrick & Cholewiak, 1986; Verrillo & Gescheider, 1992), as well as in the dimensions of tactile patterns processed by different receptor types (Johnson & Hsiao, 1992). Many basic measures of tactile sensitivity, such as vibratory threshold (Weinstein, 1968), spatial acuity (Stevens, 1991), and sensitivity to movement (Essick, 1991), also show considerable variation over body loci, but comparisons of functional properties more directly related to tactile communication have been studied less well (see, e.g., Verrillo, 1966). In one of the few studies of vibrotactile pattern perception on sites with different receptor profiles and skin types, Cholewiak and Craig (1984) examined discrimination and identification on the finger and the thigh with a simple set of 10 patterns consisting of single lines, paired lines, or distinct areas on dense two-dimensional tactile arrays of contactors. In the identification task, a pattern was presented and observers were asked, "Which of the 10 patterns was felt"? In the discrimination task, two patterns were presented and the observer indicated whether the members of the pair were identical or different. They found differences between sites in the absolute levels of performance for both tasks, but in opposite directions. Specifically, observers were able to learn to identify the patterns far better when the patterns were presented to the finger than to the thigh, yet discrimination performance was superior on the thigh, illustrating a dissociation between the two tasks (see also Horner, 1991; Horner & Craig, 1989). The discrimination data, however, did suggest that there is a functional similarity in processing across sites (i.e., the shape of the curve describing the relationship of performance to stimulus onset asynchrony was the same for both sites). The reasons suggested by the authors for these mixed results are rooted in differences in the cues used by observers to make the two types of judgments, but also in differences between pattern perception at these body sites. The authors suggest that the stimulus consists of a number of features or dimensions, some of which are simply not appreciated if the task demands can be met by attending to others. It is evident that some of the features or dimensions of stimuli that are clearly perceived when the stimuli are presented on the finger were not available at the thigh, given the poor identification performance at this site. Yet the sensations available or emergent when pairs of patterns were presented were suf-

ficient to allow very good discrimination judgments at the thigh.

Thus, it is not a given that patterns presented to one body site will be perceived to be the same if they are presented on another site. There appears to be a kind of restrictive funneling of pattern apprehension capability as one moves from the fingertip to less sensitive and less acute sites, similar to that seen for other basic measures of tactile sensitivity (see, e.g., Cholewiak & Collins, 1991, Fig. 2.13). Specifically, observers can, to a certain degree, appreciate shapes such as lines or angles presented to the fingertip with these arrays in a pictorial manner. That is, observers will feel linear sensations on the fingertip in locations isomorphic to visual representations; that is, an L shape usually feels as an L looks. This is not the case with comparable stimuli presented to the thigh with equivalent displays and presentation parameters. On the thigh, subjective impressions from both trained and inexperienced observers indicate that such lineal patterns tend to collapse into intensive foci distributed over the display area. The resulting impressions are often distinct enough to make accurate identifications but are sufficiently different from pictorial representations to result in minimal transfer when the finger is subsequently tested with the same set of patterns (Cholewiak & Collins, 1988). As one examines data from the finger and the thigh, it appears that, although appreciation of spatial details is lost with the reduction in spatial acuity, the ability to make intensive discriminations and global localizations still remains.

The effects of communality on pattern discrimination will be studied here on the finger, the palm and the thigh, sites representative of different skin types (glabrous, palmar-plantar [a form of glabrous], and hairy, respectively—see Tregear, 1966). Given the differences between the finger and thigh both in performance and in the sensations described by observers, this comparison will shed light on the issues raised by Cholewiak and Craig (1984). Does communality uniformly affect tactile pattern perception on these different sites? Or does the relatively high spatial acuity of the finger allow it to operate on a different set of features of random spatial patterns? Thus, it would be useful to know whether the functional relationship between communality and discrimination is dependent on site. From a more utilitarian point of view, because tactile aids for hearing-impaired persons are placed on many different body locations (Summers, 1992), it would be important to know whether the processing of stimuli at the different sites is equivalent—whether the same set of patterns presented to different sites would be equally distinct and discriminable. Finally, two of the sites to be studied are on glabrous skin (the palm and finger), while the third (the thigh) is classified as hairy skin. These skin types vary considerably in their complement of receptor systems and measures of tactile sensitivity. Data from physiological studies of pattern processing on the most acute of these sites, the fingertip, suggest that the spatial response properties of spe-

cific receptor systems are responsible for encoding the information presented by arrays such as the Optacon (Gardner & Palmer, 1989; Johnson & Hsiao, 1992; Van Boven & Johnson, 1994). Furthermore, it is known that the relative density of at least one of the more important of these populations (SAI) varies considerably over sites as close together as the finger and palm (Vallbo & Johansson, 1978, p. 44). Consequently, it would not be unexpected that a pattern discrimination task might show consistent variation over these sites.

In the series of experiments to be reported here, the examination of communality is extended for the first time to include comparable patterns presented with dense vibrotactile arrays on a number of body sites. Communality will be varied while pattern discrimination on the thigh, palm, and fingertip is measured, allowing for a direct comparison among the different sites. Discrimination judgments may be made with minimal knowledge of the stimuli, and they require little learning because unique identification of stimuli is not required. Thus, discrimination tasks provide an elemental test of pattern-processing capability and serve as a tool for testing perceptual processing early in learning. Appreciation and understanding of the similarities and differences among these loci could be of importance when transfer of training from one site to another might be critical, or when devices are to be applied to a number of potential places on the skin. Finally, such a study could disclose which sites possess the functional acuity that would provide for the relatively fine judgments that are required for one to excel in identification tasks, overcoming the potential disadvantages of possible spatial interactions in dense arrays.

GENERAL METHOD

Apparatus

The three body loci will be tested with vibrotactile arrays specifically designed to match the spatial acuity of each (i.e., with varied contactor spacing), allowing examination of the sites under equivalent conditions (see, e.g., Cholewiak & Craig, 1984; Daley & Singer, 1975). In these arrays, the contactor separation is only slightly larger than the error of localization on the corresponding site. If the contactor spacing did not vary with site, interpretation of the data would be complicated by the effects of the acuity of each locus.¹ For example, although the palm has somewhat better acuity than the thigh as measured by the classical methods of two-point discrimination (10 vs. 40 mm, respectively) and error of localization (5.5 vs. 12 mm; Weinstein, 1968), the stimulator systems, each having unique contactor spacings, have equivalent resolution. The calculated ratios between the average contactor separation in each array and the error of localization at the corresponding site are 1.27, 1.45, and 1.25 for the finger, palm, and thigh, respectively. In contrast, in Geldard and Sherrick's (1965) whole-body study, the separation between the closest pair of vibrators—those across the abdomen—was much larger (by at least a factor of 10) than the error of localization at that site (c. 10 mm).²

The larger arrays and the associated hardware and software are described in detail by Cholewiak and Sherrick (1981). Briefly, the thigh array is composed of 64 contactors in an 8×8 arrangement with 15-mm center-to-center separations. The contactors themselves are hemispherical nylon tips, c. 5 mm in diameter. The suspension for the individual vibrators is vertically adjustable so that

the entire array might be fit to the curvature of the ventral surface of the thigh. When properly adjusted, the matrix rests comfortably on the skin with a static force of approximately 10 g per contactor. The interface, connected to an IBM-PC/XT-compatible computer, allows for independent control of intensity on each of the 64 vibrators. The patterns in these experiments were presented by vibrating the relevant contactors at a rate of 250 Hz. The palm array is driven by the same hardware/software system. The primary difference between these two arrays is their size and method of fitting: The palm array has 64 contactors with approximately 8-mm center-to-center separation. The heights of the 2-mm-diameter contactors are fixed to the curvature of an "average" palm. When the site to be studied was the fingertip, the array from a reading machine for blind persons, the Optacon RID (Telesensory Systems, Inc., Mountain View, CA), was used. This device provides for presentation of dense vibrotactile patterns onto the left index fingertip with a 144-vibrator 6-column $\times$ 24-row array that measures 12.7×29.2 mm (Cholewiak & Collins, 1990; Craig & Sherrick, 1982). The vibrators in the rows are centered 1.27 mm (50 mil) from one another, while those in the columns are centered 2.54 mm (100 mil) from one another. A custom-designed interface allows for control of pattern generation on the Optacon with an IBM-PC/XT-compatible computer. The fingertip patterns were presented with the 230-pps characteristic frequency of the Optacon display.

In the second experiment, a vibrotactile sensation magnitude standard was established in each session. A single vibrator was used to generate the standard: a 20-mm-wide, 40-mm-long beam-mounted piezoceramic Bimorph bender with a 5-mm hemispherical contactor rested with about 10 g of static force on the left dorsal forearm, approximately midway between wrist and elbow. Threshold of the standard was determined by the method of limits, and its intensity adjusted to produce a perceived magnitude of 14 dB SL. The intensity of the communality pattern set was adjusted to match the apparent magnitude of the vibration on the arm by presenting the vibration on the arm and members of the pattern set on the finger in alternation. While the stimuli alternated, the observer adjusted the Optacon intensity until the sensations were approximately equivalent. The standard was established at the beginning of each session, and matches were made prior to each block. Since different numbers of vibrators were involved in each of the three blocks of each session, different levels of sensation magnitude would result if patterns were presented at the same intensity level (Cholewiak, 1979).

Stimuli

Pattern construction. The stimulus patterns in this study were designed according to some of the general principles outlined in Gottheil et al. (1978), in which communality was examined on the thigh with a large vibrotactile matrix. First, pattern cells consisted of more than just a single contactor, to ensure that they could be distinctly felt. Second, pattern cells were randomly but evenly distributed across the array to avoid symmetry, while at the same time trying to avoid large differences in the center of gravity between patterns having the same numerosity. Finally, in the case of one of the experiments to be reported, the number of cells in a pattern set was varied.

In the experiments with the thigh and palm arrays, patterns were, in fact, identical to the randomly distributed eight-cell patterns used by Gottheil et al. (1978). Each cell was constructed of 4 contiguous vibrators in a 2×2 arrangement. A pattern consisted of eight such cells (totaling 32 vibrators) on the square matrix display. The random placement was constrained by requiring that two cells fall in each quadrant of the array to ensure against extreme differences in center of gravity among patterns. When the fingertip was the site to be studied, individual pattern cells consisted of six contiguous contactors in a 2 column $\times$ 3 row arrangement. A pattern was made up of three, six, or nine such cells (18, 36, or 48 vibrators, respectively) on the Optacon display. The random placement of these cells was also constrained, but because the display of the Optacon is rec-

tangular, equal numbers of cells fell in the upper, middle, and lower thirds of the array. Only the distal 18 rows of the Optacon array were used, resulting in a pattern field that measured approximately 12×20 mm.

Pattern pairs. The patterns were paired with one another for the discrimination task. Both patterns in a pair always had the same number of cells. To construct the set of pairs to be used in the study, the patterns were paired in every combination within each numerosity level, and the resulting communality levels were calculated. With the aid of these values, the subset of trial pairings of "different" patterns was drawn from the full set to create an equal number of tokens at each communality level. Depending on the amount of spatial overlap of the two patterns, many degrees of "different" could exist. Thus, a pair of patterns with no common cells possesses 0% communality, whereas a pattern pair sharing half of their cells would have 50% communality. Every possible communality was represented for each of the numbers of cells in those trial sets. In addition, half of the trials in each block were "sames," or pattern pairs with 100% communality. Representative patterns are shown in Figure 1 along with the calculated communality levels for each pair. Following the preceding procedures, sets of 30 to 40 randomly defined patterns for each of the numerosity levels were generated.

General Procedures

Patterns were presented in the "static" mode, in which all active elements were turned on for the entire pattern duration. Within a trial, two patterns were presented for a duration of 250 msec each and were separated from one another by an interstimulus interval of 1,000 msec to avoid interactions such as adaptation, integration, or masking. Regardless of site of stimulation, responses were made with the right hand on a two-button keypad. Observers were instructed to respond by pressing buttons marked "1" or "2" on the keypad, thereby indicating whether the patterns were "one and the

same" or "two different patterns," respectively. In response to a visual prompt, a single keystroke initiated the trial series. The response to a pair initiated presentation of the next pair after 1 sec of feedback and a 1-sec ready period. Feedback was provided after each trial with a brief tone in the headphones and a message on the visual display that indicated a correct or incorrect response. An opportunity for a short rest period was provided at the midpoint of each series and between the two series within a session.

EXPERIMENT 1

In the first experiment, pattern discrimination as a function of communality was examined with patterns presented with a dense array to the palm of the hand. This site has not been studied previously and has very different skin properties from those of the thigh. A second group of observers replicated the discrimination task on the palm but also judged identical patterns presented to the thigh. In this extension, a direct within-subjects comparison was made between the two sites.

Method

Subjects. The 5 males and 6 females who served in this experiment were Princeton University students paid for their participation and recruited by poster in the Psychology Department. An additional group of observers (5 males and 7 females) replicated the palm portion of the experiment and judged patterns presented to the thigh.

Procedure. Observers participated in two experimental sessions. For the first group of observers, patterns were presented to the palm of the hand in both sessions. For the second group of observers, the

Figure 1. Representative patterns used in the present study. On these arrays, cells are locations on the display consisting of four (in Experiment 1) or six (in Experiment 2) contiguous vibrators. In Experiment 1, patterns with eight cells (upper panel) were presented on the square palm and thigh arrays. In Experiment 2, patterns with three, six, and nine cells (lower panel) were presented to the fingertip with the rectangular Optacon array. Communality levels, the percentages of shared active cells, are indicated for the pairings of the patterns shown.

same patterns and procedures were used, but patterns were presented to the palm in one session and the thigh in the other. The order of sites was determined randomly and was counterbalanced across observers. An eight-cell pattern set, constructed according to the guidelines described above, was presented to the palm of the hand or to the thigh using the large square matrixes. Each session consisted of two series of 160 trials randomly ordered with respect to level of communality: within a series there were 80 "sames" (100% communality) and 80 "differents," although observers were not informed about the proportions used. Of the "differents," 10 pattern pairs were presented for each of the eight levels of communality: 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, and 87.5%.

The observer sat in a comfortable chair with the left hand on the vibrotactile array, or with the large matrix resting on his/her ventral left thigh. Prior to testing on the palm, a pattern was presented that consisted of the successive pulsing of each vibrator, row by row, until each had been energized. The entire sequence was then repeated. Observers were instructed to adjust the position of the hand until an even rhythm of buzzes appeared across the entire palm, ensuring proper placement and contact with all of the contactors. A 750-g sandbag was then placed over the hand and wrist to help to maintain a stable position and to produce a static force against the array of c. 20 g per contactor. When the thigh was the site for stimulus presentation, the counterbalanced, adjustable array was brought down onto the skin, the matrix adjusted to match the surface contour of the limb, and a weight added to produce c. 20 g of force per contactor. The trial series followed the general procedures described in the General Method section.

Results and Discussion

The results for both sites are shown in Figure 2, in which the mean percentage of "same" responses is plotted at each communality level. Note that percent "sames" is a measure of errors for the "different" stimuli (where communality is less than 100%), whereas it is a measure of correct responses for the "same" stimuli (where communality = 100%). This is the manner in which data have

been presented in the literature because it permits examination of the data as a continuous function across conditions, and the precedent will be followed here to allow for ready comparison. The error levels for the 0% and the 100% communality conditions are virtually identical. These are the conditions in which the members of the pair of patterns were either completely different or identical, respectively. The similarity in error level for the patterns at these communalities indicates the absence of a strong response bias. Analysis of all responses, collapsed over communality, supports this conclusion and reveals only a slight tendency for observers to respond "different" more often (in the range of 54%–56%).

Several comparisons can be made among the data plotted in Figure 2. When the difference between the palm data from the palm-only group and those from the palm-thigh group was evaluated in an analysis of variance (ANOVA) of percent errors, the two groups were not significantly different [$F(1,21) = 0.069, p > .05$]. Thus the procedural differences between the two groups did not affect the results. The major issue in this experiment, however, was to compare the effect of site on discrimination performance as a function of communality. When the two sites represented in the figure are compared, the relationship between percent "sames" and communality is almost identical. A repeated measures ANOVA of the percent errors shows that although the effect of communality is highly significant [$F(8,88) = 25.753, p < .01$], the effect of site is not [$F(1,11) = 1.271, p > .05$]. What also appears in the analysis is a significant interaction [$F(8,88) = 4.483, p < .01$]. From examining the figure, it is apparent that the interaction is the result of the fact that the thigh function is steeper than the palm curve. There seems to be a trend toward "flatter" functions for

Figure 2. Percent "same" responses in the discrimination task on the thigh and palm, as a function of the communality between the members of the discriminated pair of patterns as measured in Experiment 1. The break in the x-axis indicates that, although shown as a continuous function, percent same is a measure of errors for different pairs, but not when members of the pair are the same at the 100% communality level. Standard errors of the means are shown only on representative points for clarity.

the palm, a site that is more acute with a higher receptor density, suggesting that communality level had less of an effect on discrimination performance. In the next experiment, in which communality on the fingertip was examined, we investigated whether this trend would continue to an area of even higher density.

EXPERIMENT 2

In order to examine the fingertip, an area with a still greater density of receptors, the array from the Optacon was used to present a trial series essentially identical to those described above. The spatial arrangement of stimuli in this series differed from those above only because of the proportions of the array as described previously. In addition, number of cells in the pairs of patterns to be discriminated was varied over the range of three to nine cells to determine whether numerosity would have any influence on the form of the communality function obtained from this highly acute site with a dense array. An analysis of the effect of number might reveal conditions in which improvement in the ability to discriminate these patterns might be realized: Geldard and Sherrick (1965) suggested that the number of cells within a pattern might influence discrimination judgments because of pattern complexity. Following this suggestion, in their examination of the effects of number with patterns presented with a tactile matrix on the thigh, Gottheil et al. (1978) found that numerosity had no effect on performance at low communality levels. However, at higher levels (where more than 50% of the cells were shared), there were fewer errors for four-cell patterns than for eight-cell patterns.

Method

Subjects. Of the 7 male and 7 female observers in this experiment, 12 were Princeton University students recruited by poster in the Psychology Department and were paid for each session. Two of the observers were members of the laboratory staff, one of whom was naive to vibrotactile observation and one of whom was highly experienced.

Procedure. The observers participated in five experimental sessions. Each session consisted of three blocks of trials: one devoted to each of the three levels of numerosity (three, six, or nine cells). The order of numerosity levels within each session was counter-balanced across each individual's five sessions. There were 108 trials in each block, of which half were "sames" (100% communality) and half "different" (varying percentages of communality), presented in a random order. Over the five sessions, each observer judged each of the "different" pairings five times. In addition to the trials in which the 100% level of communality was represented, "different" pairs had communalities of 0%, 33%, and 67% when there were three cells per pattern. Similarly, when six cells were used, the "different" communalities included 0%, 17%, 33%, 50%, 67%, and 83%, and for nine cells, the possible communalities were 0%, 11%, 22%, 33%, 44%, 56%, 67%, 78%, and 89%. Figure 1 illustrates representative patterns from the set.

At the beginning of each session, the observer was seated in a comfortable chair with the index finger of the left hand on the Optacon array. A 750-g sandbag was placed over the hand and wrist to aid in keeping the arm immobile yet comfortable. The blocks of discrimination trials were distinguished by numerosity level of the pattern pairs. Because the number of active cells (and thus the number of vibrators) in the patterns to be tested varied, the perceived

magnitude of the sets was equated in order to eliminate the possible confound with number (see Cholewiak, 1979). A sensation magnitude standard was established by measuring threshold for 250-msec bursts of 230-Hz vibration on the forearm. The intensity level of the vibration was then raised by 14 dB (five times threshold) to provide a palpable, yet not overwhelming stimulus. At the start of each block with its new number of cells, a sensation magnitude match was made against the standard established for that session with an alternating series of bursts of the standard and patterns on the Optacon. The program cycled through all of the patterns to be used in that block, one by one. All stimuli were on for 250 msec and were presented at a rate of 1/sec. The observer was cautioned that the sensation magnitude of the patterns might vary somewhat (because different locations on the finger were stimulated by the different patterns) but that he/she should try to match the "average" sensation magnitude by adjusting the intensity control on the Optacon. After the match, the trial series began for that level of numerosity, according to the procedure described in the General Method section.

Results and Discussion

For an individual observer, thresholds for the vibratory stimulus presented to the forearm over the five sessions were typically within 2 dB of one another. Within a session, observers were readily able to match the Optacon patterns to the standard loudness. The range of intensity available on the Optacon for patterns similar to these is greater than 14 dB SL (see, e.g., Cholewiak & Collins, 1990). From data obtained previously on the finger (Cholewiak & Collins, 1990), the pattern loudness in this series was estimated to have about a 10-dB range over the three- to nine-cell pattern sets. In only one case out of over 200 trial blocks was an observer unable to match the Optacon loudness to the standard presented on the forearm. He felt that the intensity of the Optacon patterns could not be set loud enough for him to make an accurate match. The series was conducted with the Optacon intensity at its maximum level, and those data were found to fall well within the range for equivalent blocks from that observer's other sessions.

The data were analyzed by communality and number and plotted as the percent of "same" responses by communality with numerosity as the parameter in Figure 3. Note, as with Figure 2, that correct performance is indicated by low values when percent communality is less than 100 (few "same" responses when "different" were presented) and by a high rate of "same" responses at 100% communality. Again, the similarity in error levels for the 0% and the 100% communality conditions (c. 13%–20%) indicates the absence of a strong response bias in these data. Analysis of all responses, collapsed over communality, from the three levels of numerosity, shows that the tendency is for observers to respond "same" slightly more often (c. 57%–58% of the time), in a direction opposite to that in Experiment 1. Although not shown separately, the role of experience in these data did not appear to be important: The highly experienced observer's error levels in fact fell slightly above the mean but were still within the range for the naive observers. A repeated measures ANOVA was performed on the percent errors data common to the three levels of number (0%, 33%,

Figure 3. Percent "same" responses in the discrimination task on the fingertip as a function of the communality between the members of the discriminated pair of patterns, with number of cells in each pattern as the parameter as measured in Experiment 2. The break in the x-axis indicates that, although shown as a continuous function, percent same is a measure of errors for different pairs, but not when members of the pair are the same at the 100% communality level. Standard errors of the means are shown only on representative points for clarity.

67%, and 100% communality) for the whole group. This analysis revealed a highly significant effect of communality [$F(3,39) = 81.780, p < .01$]. In addition, the effect of number was found to be significant [$F(2,26) = 4.872, p < .05$], indicating that performance deteriorates as the total number of cells in the pattern increases. These results are reminiscent of Gottheil et al.'s (1978) data, in which four-cell pattern performance was somewhat better than eight-cell pattern performance, and they support the notion that density, reflected in the number of active cells in a pattern, has some influence on discrimination performance. The question should be raised, however, whether these differences in performance as a function of number are meaningful. It is useful to consider that the number of cells varied over a three-to-one range, whereas performance at a given level of communality varied by less than 10%. Communality appears to have been the only dimension controlling performance in any substantial way in these experiments.

GENERAL DISCUSSION

The data in Figures 2 and 3 are not only quite similar to one another, but show a strong resemblance to functions obtained on other body sites and with other vibrotactile systems. In Figure 4 are plotted the data from the present experiments as well as those from a number of other studies conducted over some 20 years in several laboratories, in which essentially the same paradigms as those briefly described earlier were employed. Regardless of site, a comparable functional relationship exists between communality level and discriminability: the more

cells that patterns have in common, the greater the likelihood that they will be perceived as being the same. As the functions in Figure 4 are surveyed, the largest apparent difference is at low communality levels. In most cases, error levels fell no lower than about 20%–30%.

In two studies, however, discrimination was so good at low communality levels that virtually no errors were made by the observers. In these two cases, contactors were well-distributed over body sites. In the first, Geldard and Sherrick (1965) presented vibrotactile patterns with individual vibrators distributed over the whole body. A typical three-cell pattern in their study might have consisted of vibrators located on the left thigh, right forearm, and right calf, for example. They found that the discrimination of these whole-body patterns was a function of the communality of pattern pairs: Lower error rates were seen for pattern pairs with few shared cells, and at the lowest levels (in which few or no cells were shared), errors dropped to zero. Similarly, Gilson (1968) measured the influence of shared pattern cells on discrimination performance with individual vibrators placed on the fingers of both hands. In this case, as in Geldard and Sherrick's study, a pattern consisted of simultaneously vibrating stimulators on some number of distinct locations in which a single independent vibrator constituted a pattern cell. Again, when stimulators were well isolated (Gilson, 1968, Experiment 3, p. 135), percent sames were found to be an increasing function of communality, the overall levels were not substantially different from Geldard and Sherrick's (1965), and performance at low levels was exceptional. This similarity is not surprising, because, as with the whole body patterns, shifts in location from fin-

Figure 4. Percent "same" responses in discrimination tasks as a function of the communality between the members of the discriminated pair of patterns, from a number of studies in which patterns were presented to the fingers, the palm, the thigh, and the whole body; the present experiments are included. The break in the x-axis indicates that, although shown as a continuous function, percent same is a measure of errors for different pairs, but not when members of the pair are the same at the 100% communality level. Curves for the different body sites are indicated on the figure by the type of line drawn: solid lines are used for the whole body and fingers; dotted lines are used for the palm; dashed lines are used for the thigh.

ger to finger often cross neurologically distinct regions (see, e.g., the cortical mapping in Sur, Merzenich, & Kaas, 1980). Furthermore, the fingers of the hands are fairly disparate perceptually, and they may functionally resemble the numerous sites spread over the body (Craig, 1985; Craig, Green, & Rhodes, 1985).

Aston and Weed (1971) also presented patterns to the fingers, but their data are unlike those from Gilson's (1968) Experiment 3. They used a tactile Vocoder to study the effects of communality on the discrimination of actual speech sounds. The device analyzed the acoustic signals with eight filter channels and presented the resulting stimuli through bone oscillators to the fingers of the two hands (excluding the thumbs). The intensity of each vibrator varied with the energy of its corresponding filter channel. They analyzed the pattern communality between a pair as the percentage of channels in which the intensity of vibration changed less than a "just noticeable difference." Data of individual observers were fit well by exponential functions, and, although the general form of the functions was quite comparable to that found by Geldard and Sherrick (1965) and Gilson (1968, Experiment 3), the average error rate over communalities was considerably higher.

A reported difference between two of Gilson's (1968) experiments may shed light on the reason why Aston and Weed obtained higher error rates: the manner in which the vibrators drive the skin might affect discrimination performance. In the first experiment of Gilson's study, the fingers themselves were suspended by the stimulator assemblies, resulting in movement of an entire digit when

its vibrator was active. Indeed, he describes how another person could actually feel the wrist and arm vibrating when all of the fingers of a hand were activated. When the apparatus was modified for his third experiment in order to reduce propagation of vibration among the contactor sites, a distinct improvement in discrimination performance resulted. Gilson surmised that the high error rates for his Experiment 1 were probably due to spatial interactions that occurred among the vibrating fingers. The data from these two experiments can be compared in Figure 4 with an average calculated from individual data reported by Aston and Weed (1971). A stronger similarity in the functional relationships and absolute levels exists between Aston and Weed's (1971) data and Gilson's Experiment 1 than with Gilson's Experiment 3. It is likely that the strong sensation produced by 300-Hz vibration from the bone vibrators on the fingers of Aston and Weed's subjects' fingers produced sufficient interaction through the hand to significantly impair pattern discrimination.

The remaining functions in Figure 4 illustrate data from the present studies and Gottheil et al. (1978), who employed essentially the same paradigm as that above but used compact vibrotactile displays to provide a more coherent sensation to a restricted body area. As in Experiment 1, Gottheil et al. (1978) varied pattern communality and presented patterns for discrimination with a dense tactile array on the thigh. They explored the potential influences of symmetry and number of pattern cells with patterns consisting of a number of 2×2 -contactor cells distributed over the 8×8 -contactor array

in either symmetrical or random arrangements (the latter identical to the patterns used here in Experiment 1). In each of the studies, as shown in Figure 4, overall performance was poorer than when stimuli were well-distributed, indicating that discrimination performance may be affected by the amount of spatial interaction among cell sites, possibly as a result of vibration propagation. Supporting this view, overall levels of performance are quite comparable to those from the individual fingers when conduction of vibration is allowed to occur among them (Gilson, 1968, Experiment 1). As discussed earlier, it might have been predicted that overall performance would be better with the dense arrays than with vibrators on the separate fingers or distributed over the body because attention could be focused on a smaller area of skin. Conversely, performance was found to be poorer on

all three sites fit by the dense arrays than on either the whole body or fingers, as shown in the figure. It appears as though the vibrator spacing on the arrays, designed to match the spatial acuity of the sites to which they were applied, prevented resolution of separate pattern elements (cells). Thus, it appears as though any advantage that might accrue from presenting patterns on dense arrays, such as potentially being able to appreciate the whole pattern at a tactile glance, may be offset by a decreased awareness of distinguishing features if the stimuli are too similar.

The results from the majority of these studies can be described by similar communality functions taking the form of exponential curves with intercepts at about 10%–30% errors for pattern pairs with no common cells. Only in the cases of well-distributed stimuli like those in

Figure 5. Percent "same" responses in a discrimination task only for the "different" pattern pairs, as a function of the communality between the members of the pair. Data are replotted from Figures 3 and 4 on semilogarithmic coordinates in order to illustrate the underlying best-fit exponential functions. (Because the logarithmic scale does not have a zero point, zero scores were represented as 1% in this figure.) Panels A and B reproduce data from Figures 2 and 4; panels C and D show the data from Figures 3 and 4. Also included for comparison in panel A are four-cell data from Gottheil et al.'s (1968) thigh series.

Geldard and Sherrick (1965) or Gilson's (1968) third experiment do errors fall to zero at low communalities. The similarities and differences among these functions may be seen more readily if they are plotted on semilogarithmic coordinates. Because they are exponential functions, the graphs will show straight lines whose slopes are the exponents of the functions when the data are fitted by the method of least squares. The functional relationships between the communality of different patterns and error rate, as indicated by the percent of "same" responses, are shown in the panels of Figure 5. Different body sites appear to have different exponents, and studies performed years apart, or with different types of stimulators, have produced remarkably similar functions for a given locus. It is possible to test the significance of the differences among these functions by using methods described by Wiggans, Andrews, and Sahgal (1983).³ For example, the slopes of the three thigh functions in Figure 5A are not significantly different from one another [$F(2,13) = 0.229, p = .800$], nor are their intercepts [$F(2,15) = 0.636, p = .547$], so they may be represented by a single line (shown in Figure 6). Similarly, neither the slopes [$F(1,12) = 0.113, p = .741$] nor the intercepts of the two palm functions [$F(1,13) = 0.028, p = .864$] shown in Figure 5B are significantly different from one another (and the resulting common line is also shown in Figure 6). The finger functions in Figure 5C, however, are represented best by parallel lines with a common slope of 0.690, because, although the slopes of the lines

best fit to these data are not significantly different [$F(2,12) = 1.577, p = .246$], the intercepts are [$F(2,14) = 3.890, p < .05$]. In particular, the intercept of the three-cell function is smaller than that for either the six-cell or the nine-cell function. When the latter two are compared with Gilson's (1968, Experiment 1) and Aston and Weed's (1971) data (shown in Figure 5D), only the slope and intercept of Aston and Weed's function is significantly different from the others. The line common to the six-cell and nine-cell finger functions is plotted in Figure 6.

Figure 6 shows the generalized functions derived from the data plotted in Figure 5; also plotted are the data from the whole-body study (Geldard & Sherrick, 1965) and from Gilson's experiment on the independent fingers (1968, Experiment 3). The best-fit regression lines calculated for these data are also shown for the latter two studies. The dramatic difference that appears between the two families of functions owes primarily to the broad range in the logarithmic scale for values below 30%. Only performance from well-distributed displays is so good that it falls to "zero" errors (no "same" responses) when the patterns have very low levels of communality. The lowest error rates and thus the best resolution occur when patterns are presented over the whole body or the separated fingers of the hand. In these cases, the location or identity of pattern elements is readily detected because of the exceptional psychological distance between any pair of elements when the set is distributed over these surfaces. Examination of the slopes of the generalized and specific functions allows for a comparison of the effects of communality on each combination of site and array. The functions may be ordered in terms of increasing slopes as palm, thigh, finger, and, finally, whole body/five fingers. The dramatic change in performance with communality seen with the distributed functions in Figure 6 (the slopes for the whole body and five-finger data are three to six times steeper than those for the other sites) indicate that judgments made under these conditions are most affected by differences in pattern communality. Although the other three body sites described in the figure show higher error rates, particularly at low levels of communality, those rates change only slightly with increasing communality. Consequently, despite the fact that discrimination is generally poorer for these, they are much less susceptible to changes in communality. It appears that communality between pattern pairs has its greatest effect when the pattern elements are most distinct and other spatial interactions among elements play a smaller role.

The effects of communality for the data collected on the finger, palm, and thigh with the use of dense arrays appear quite similar to one another. Recall that the relationships between the underlying acuity of each of these three sites (as measured by the error of localization) and the resolution of the corresponding stimulus arrays were equivalent. That is, the ratio of the contactor spacing to the error of localization is approximately 1.3 at each site. Because the ratios among the arrays are virtually identical, comparisons among the finger, palm, and thigh

Figure 6. Percent "same" responses in a discrimination task only for the "different" pattern pairs, as a function of the communality between the members of the pair. Data from the whole-body study (Geldard & Sherrick, 1965) and from Gilson's (1968) Experiment 3 (separated fingers) are plotted on semilogarithmic coordinates as in Figure 5, with zero scores plotted at 1%. Also included are generalized functions for finger, palm, and thigh derived from Figure 5 as described in the text. Curves for the different body sites are indicated on the figure by the type of line drawn: solid lines are used for the whole body and fingers; dotted lines are used for the palm; dashed lines are used for thigh.

functions described in Figure 6 were expected to reveal site differences if they exist. An analysis of these three functions revealed that indeed the finger and thigh functions were not significantly different from one another in slope or intercept [$F(1,54) = 0.261, p > .05$; $F(1,55) = 0.304, p > .05$]. The palm curve, however, was significantly different from the finger and thigh functions [$F(1,51) = 13.375, p < .01$; $F(1,31) = 11.009, p < .01$, respectively] (see note 3). In comparison with the finger and thigh data, those for the palm had slightly higher error rates and a more shallow slope. Although these differences were statistically significant, they are small in size, and thus the similarity between the curves for these sites and their associated arrays seems more remarkable than their differences. The equality between the finger and thigh functions is particularly noteworthy, considering the dramatic differences between these sites in receptor components and structure (given that the former skin type is glabrous and the latter is hairy). The correspondence suggests that if patterns are presented through arrays that are designed with cell spacing close to the error of localization for that site, discrimination performance will also be comparable.

Finally, an alternative explanation for the present results must be considered. It is possible that the measured effects of communality are actually the consequence of pattern "goodness." Typically "better" patterns have global characteristics, such as symmetry, that make them more readily distinguishable than patterns composed of randomly placed elements (Garner, 1974, 1978). Gottheil et al. (1978) did examine the influence of pattern symmetry on discrimination by using a tactile matrix and found that errors were primarily related to communality, with symmetry having no effect on performance. It could be that the psychological similarity between the two members of the pair as opposed to their communality, a measure of physical similarity, plays the significant role in the decision-making process.

To examine this possibility, an additional experiment was conducted that was identical to Experiment 2 except for the task demands. Instead of discriminating between members of pattern pairs, observers judged the overall similarity of the pairs. Similarity judgments were made by 10 observers from our general subject pool (including 2 naive observers and 8 who had some experience with vibrotactile pattern perception, one of whom participated in Experiment 2). On the rating scale used for the judgments, 1 meant that the patterns were one and the same or identical, whereas a rating of 10 indicated that the members of the pattern pair were completely different; the ratings were indicated by keystrokes on a numeric keypad. All presentation conditions, including stimulus parameters, patterns, number of trials within a block, and number of sessions, were identical to those used in Experiment 2, except that feedback was not provided. After completing the five tactile sessions, observers judged the same patterns visually in one additional session, using the identical procedures. In this case, however, rather than being presented to the fingertip by the

Optacon display, the patterns were presented graphically on a computer monitor at a size and viewing distance such that the rectangular array was approximately $2^\circ \times 5^\circ$ of visual angle. Ratings for tactile stimuli were performed first, to minimize visual imagery cues that might occur if observers knew what the stimuli looked like.

On the rating scale, the correlation between tactual and visual similarity was very high over all levels of numerosity ($N = 3, r^2 = .857$; $N = 6, r^2 = .835$; $N = 9, r^2 = .763$). Interestingly, although ratings extended over the range of 1–9 for all visual stimuli, the range of tactual ratings became smaller as numerosity increased (for $N = 3$, the range of the average ratings was c. 1–9, whereas for $N = 9$, the range was about 2–6). These data suggest that the members of the pattern pairs felt more alike with increasing numerosity. As might be expected, correlations were similarly high between the tactual similarity and the communality of pattern pairs ($N = 3, r^2 = .821$; $N = 6, r^2 = .818$; $N = 9, r^2 = .742$). This is not a surprising finding, because pattern pairs with high levels of communality are constructed by reproducing locations of pattern elements in the two, so some degree of spatial similarity is essentially built into each pair. Consequently, the overall correlations between both of these measures and discrimination performance are high. However, there were a number of isolated cases in which the communality level and similarity rating for a pattern pair opposed one another. In these cases, tactual discrimination performance was predicted better by communality than by tactual similarity, regardless of numerosity. Thus similarity, a potential process limitation (Garner, 1978, pp. 114–115), does not provide a more compelling explanation of the present data.

The correspondence among these functions suggests a general underlying set of processes that serve to limit the ability of the tactile sense to discriminate among patterns composed of common sets of elements. These restrictive processes operate regardless of whether the pattern set is presented in a coherent display like a vibrotactile matrix, or one that limits the spatial integration of the patterns, as occurs on the separate fingers of the hand or over the body (see, e.g., Craig, 1984; Craig et al., 1985). It is also possible that such limitations may play a role in the discrimination of letter-like patterns (Craig, 1984; Evans, 1987; Horner, 1991, 1992). Such factors may be central to why most users of tactile aids report slow rates in processing of tactile information. For example, most users of the Optacon report reading rates of only 50–60 words per minute (Goldish & Taylor, 1974), whereas normal visual reading rates have been reported to be as high as 500–800 words per minute (Moore & Bliss, 1975). Only two general methods have been found to reduce error rates at high levels of communality: either one must limit the number of pattern cells (Gottheil et al., 1978), or one must distribute the loci of non-common elements to functionally disparate body sites (Geldard & Sherrick, 1965; Gilson, 1968). With the ever-increasing use of matrices in which many stimulators are often simultaneously activated, the gen-

eral functions described here may typify the limits of this type of pattern discriminability.

REFERENCES

- ANDRES, K. H., & VON DÜRING, M. (1973). Morphology of cutaneous receptors. In A. Iggo (Ed.), *Handbook of sensory physiology: Somatosensory system* (Vol. 2, pp. 3-28). New York: Springer-Verlag.
- ASTON, R., & WEED, H. R. (1971). A man-machine model for evaluation of the tactile Vocoder. *Journal of the Association for the Advancement of Medical Instrumentation*, **5**, 19-25.
- BIEDERMAN, I. (1985). Human image understanding: Recent research and a theory. *Computer Vision, Graphics, & Image Processing*, **32**, 29-73.
- CHASE, W. G. (1986). Visual information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 28/1-28/71). New York: Wiley.
- CHOLEWIAK, R. W. (1977, March). P-32. Computer generation of vibrotactile patterns. In F. A. Geldard & C. E. Sherrick (Eds.), *Princeton Cutaneous Research Project* (Report No. 29, pp. 8-15). Princeton, NJ: Princeton University, Department of Psychology.
- CHOLEWIAK, R. W. (1979). Spatial factors in the perceived intensity of vibrotactile patterns. *Sensory Processes*, **3**, 141-156.
- CHOLEWIAK, R. W., & COLLINS, A. A. (1988, June). P-32. Computer generation of vibrotactile patterns: (A) Vibrotactile pattern learning and transfer. In C. E. Sherrick & R. W. Cholewiak (Eds.), *Princeton Cutaneous Research Project* (Report No. 51, pp. 4-5). Princeton, NJ: Princeton University, Department of Psychology.
- CHOLEWIAK, R. W., & COLLINS, A. A. (1990). The effects of a plastic-film covering on vibrotactile pattern perception with the Optacon. *Behavior Research Methods, Instruments, & Computers*, **22**, 21-26.
- CHOLEWIAK, R. W., & COLLINS, A. A. (1991). Sensory and physiological bases of touch. In M. A. Heller & W. Schiff (Eds.), *The psychology of touch* (pp. 23-60). Hillsdale, NJ: Erlbaum.
- CHOLEWIAK, R. W., & CRAIG, J. C. (1984). Vibrotactile pattern recognition and discrimination at several body sites. *Perception & Psychophysics*, **35**, 503-514.
- CHOLEWIAK, R. W., & SHERRICK, C. E. (1981). A computer-controlled matrix system for presentation to the skin of complex spatiotemporal patterns. *Behavior Research Methods & Instrumentation*, **13**, 667-673.
- CHOLEWIAK, R. W., & WOLLWITZ, M. (1992). The design of vibrotactile transducers. In I. R. Summers (Ed.), *Tactile aids for the hearing impaired* (pp. 57-82). London: Whurr Publishers.
- CRAIG, J. C. (1980). Modes of vibrotactile pattern generation. *Journal of Experimental Psychology: Human Perception & Performance*, **6**, 151-166.
- CRAIG, J. C. (1984). Vibratory temporal integration as a function of pattern discriminability. *Perception & Psychophysics*, **35**, 579-582.
- CRAIG, J. C. (1985). Attending to two fingers: Two hands are better than one. *Perception & Psychophysics*, **38**, 496-511.
- CRAIG, J. C., GREEN, B. G., & RHODES, R. P. (1985). Ipsilateral versus bilateral placement of a tactile vocoder display. *Journal of the Acoustical Society of America*, **77**, 1266-1268.
- CRAIG, J. C., & SHERRICK, C. E. (1982). Dynamic tactile displays. In W. Schiff & E. Foulke (Eds.), *Tactual perception: A sourcebook* (pp. 209-233). Cambridge: Cambridge University Press.
- DALEY, M. L., & SINGER, M. (1975). A spatial resolution measure of cutaneous vision. *IEEE Transactions on Systems, Man, & Cybernetics*, **16**, 124-125.
- ESSICK, G. K. (1991). Human capacity to process directional information provided by tactile stimuli which move across the skin: Characterization and potential neural mechanisms. In O. Franzen & J. Westman (Eds.), *Information processing in the somatosensory system* (Wenner-Gren Center International Symposium Series, Vol. 57, pp. 329-339). New York: Macmillan Press.
- EVANS, P. M. (1987). Vibrotactile masking: Temporal integration, persistence, and strengths of representations. *Perception & Psychophysics*, **42**, 515-525.
- GARDNER, E. P., & PALMER, C. I. (1989). Simulation of motion on the skin: II. Cutaneous mechanoreceptor coding of the width and texture of bar patterns displaced across the OPTACON. *Journal of Neurophysiology*, **62**, 1437-1460.
- GARNER, W. R. (1974). *The processing of information and structure*. Hillsdale, NJ: Erlbaum.
- GARNER, W. R. (1978). Aspects of a stimulus: Features, dimensions, and configurations. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 99-133). Hillsdale, NJ: Erlbaum.
- GELDARD, F. A. (1961). Cutaneous channels of communication. In W. A. Rosenblith (Ed.), *Sensory communication* (pp. 73-87). Cambridge, MA: MIT Press.
- GELDARD, F. A., & SHERRICK, C. E. (1965). Multiple cutaneous stimulation: The discrimination of vibratory patterns. *Journal of the Acoustical Society of America*, **37**, 797-801.
- GILSON, R. D. (1968). Some factors affecting the spatial discrimination of vibrotactile patterns. *Perception & Psychophysics*, **3**, 131-136.
- GINSBURG, A. P. (1986). Spatial filtering and visual form perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 34/1-34/41). New York: Wiley.
- GOLDISH, L. H., & TAYLOR, H. E. (1974). The Optacon: A valuable device for blind persons. *The New Outlook for the Blind*, **68**, 49-56.
- GOTTHEIL, E. F., CHOLEWIAK, R. W., & SHERRICK, C. E. (1978). The discrimination of vibratory patterns on a tactile matrix. *Bulletin of the Psychonomic Society*, **11**, 21-24.
- HORNER, D. T. (1991). The effects of complexity on the perception of vibrotactile patterns. *Perception & Psychophysics*, **49**, 551-562.
- HORNER, D. T. (1992). The effects of complexity on the perception of vibrotactile patterns presented to separate fingers. *Perception & Psychophysics*, **52**, 201-210.
- HORNER, D. T., & CRAIG, J. C. (1989). A comparison of discrimination and identification of vibrotactile patterns. *Perception & Psychophysics*, **45**, 21-30.
- JOHNSON, K. O., & HSIAO, S. S. (1992). Neural mechanisms of tactual form and texture perception. *Annual Review of Neuroscience*, **15**, 227-250.
- LOOMIS, J. M. (1974). Tactile letter recognition under different modes of stimulus presentation. *Perception & Psychophysics*, **16**, 401-408.
- LOOMIS, J. M. (1982). Analysis of tactile and visual confusion matrices. *Perception & Psychophysics*, **31**, 41-52.
- LOOMIS, J. M. (1990). A model of character recognition and legibility. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 106-120.
- LOOMIS, J. M. (1993). Counterexample to the hypothesis of functional similarity between tactile and visual pattern perception. *Perception & Psychophysics*, **54**, 179-184.
- LOOMIS, J. M., & LEDERMAN, S. J. (1986). Tactual perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 31/1-31/40). New York: Wiley.
- MARKS, L. E. (1978). *The unity of the senses*. New York: Academic Press.
- MOORE, M. W., & BLISS, J. C. (1975). The Optacon reading system. *Education of the Visually Handicapped*, **7**, 15-21.
- PHILLIPS, J. R., JOHNSON, K. O., & BROWNE, H. M. (1983). A comparison of visual and two modes of tactual letter resolution. *Perception & Psychophysics*, **34**, 243-249.
- PIÉRON, H. (1952). *The sensations: Their functions, processes, and mechanisms* (M. H. Pirenne & B. C. Abbott, Trans.). London: Muller.
- SHERRICK, C. E., & CHOLEWIAK, R. W. (1977, May). *Matching speech to vision and touch*. Paper presented at the Conference for Speech Analyzing Aids for the Deaf, Gallaudet College.
- SHERRICK, C. E., & CHOLEWIAK, R. W. (1986). Cutaneous sensitivity. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 12/1-12/58). New York: Wiley.
- STEVENS, J. C. (1991). Thermal sensibility. In M. A. Heller & W. Schiff (Eds.), *The psychology of touch* (pp. 61-90). Hillsdale, NJ: Erlbaum.
- SUMMERS, I. R. (ED.) (1992). *Tactile aids for the hearing impaired*. London: Whurr Publishers.
- SUR, M., MERZENICH, M. M., & KAAS, J. H. (1980). Magnification, receptive-field area, and "hypercolumn" size in Areas 3b and 1 of somatosensory cortex in owl monkeys. *Journal of Neurophysiology*, **44**, 295-311.
- TREGGAR, R. T. (1966). *Physical functions of skin*. New York: Academic Press.
- UTTAL, W. R. (1973). *The psychobiology of sensory coding*. New York: Harper & Row.
- VALLBO, Å. B., & JOHANSSON, R. S. (1978). The tactile sensory inner-

- vation of the glabrous skin of the human hand. In G. Gordon (Ed.), *Active touch: The mechanisms of recognition of objects by manipulation. A multidisciplinary approach* (pp. 29-54). Oxford, U.K.: Pergamon Press.
- VAN BOVEN, R. W., & JOHNSON, K. O. (1994). A psychophysical study of the mechanisms of sensory recovery following nerve injury in humans. *Brain*, **117**, 149-167.
- VERRILLO, R. T. (1966). Vibrotactile thresholds for hairy skin. *Journal of Experimental Psychology*, **72**, 47-50.
- VERRILLO, R. T., & GESCHIEDER, G. A. (1992). Perception via the sense of touch. In I. R. Summers (Ed.), *Tactile aids for the hearing impaired* (pp. 1-36). London: Whurr Publishers.
- WEINSTEIN, S. (1968). Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. R. Kenshalo (Ed.), *The skin senses* (pp. 195-222). Springfield, IL: Thomas.
- WIGGANS, G. N., ANDREWS, J. S., & SAHGAL, A. (1983). COMPREG: A BASIC program to test for differences between several linear regression lines. *Behavior Research Methods & Instrumentation*, **15**, 609-610.
- WOODWARD, R. H. (1972). Linear relationship between two variables. In O. L. Davies & P. L. Goldsmith (Eds.), *Statistical methods in research and production* (pp. 178-236). New York: Hafner.

NOTES

1. Alternative techniques in which a single site might be used while varying the density of contactors in the tactile display, or in which the same display might be used on different body sites, address different

issues. These approaches test the utility of a device, rather than the pattern processing capability of the skin, evaluating the appropriateness of the match between the spatial resolution of a device and the spatial acuity of a site. In both of these cases, the confounding variable of spatial acuity would complicate an analysis of performance across sites.

2. Acuity is defined here as error of localization, because it best characterizes the perceptual demands of the present task. The pattern pairs differ from one another in the spatial locations of their cells, and as the level of communality increases, the discrimination judgment depends on the ability to localize positions of single cells or to tell whether different cell positions have been stimulated. Thus, the task is similar to that used to determine error of localization in which two taps occur and the observer must determine whether they were at the same or at two different locations. It should also be noted that the error of localization is typically measured with transient pressure stimuli, whereas the communality patterns were generated with vibrotactile stimulation.

3. The curves were analyzed with the COMPREG BASIC program developed by Wiggans et al. (1983). COMPREG consists of a set of statistical tests taken from Woodward (1972) that assess the differences among a number of regression lines on the basis of combined analyses of variance and covariance (regression) techniques. COMPREG was used for all comparisons among regression lines in the present paper.

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Erratum

Cohen, M. M., Ebenholtz, S. M., & Linder, B. J. Effects of optical pitch on oculomotor control and the perception of target elevation. *Perception & Psychophysics*, 1995, **47** (4), 433-440. On page 438, in the Results and Discussion section, under "Measures of eye position and target position" (column 1), the first sentence should read as follows:

Mean settings of eye position and target position as a function of the orientation of the pitchbox are illustrated in Figure 5.