The perception of tactile distance: Influences of body site, space, and time

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Abstract. Vibrotactile prostheses for deaf or blind persons have been applied to any number of different locations on the body, including the finger, wrist, forearm, abdomen, back, and nape of the neck. The discriminability of patterns presented by such devices can be affected by the acuity of the site of application and the resolution of the display. In addition, the mutual influences among stimuli close together in both space and time can affect percepts within a broad range of parameters. For example, consideration must be given to a variety of tactile illusions often associated with the spatial separations and the range of temporal intervals typically used in cutaneous communication displays. Experiments are reported in which magnitude estimates and cross-modality matches of perceived extent produced by pairs of vibrotactile taps presented to separate loci were obtained on three different body sites. Perceived distance was directly related both to the timing between the taps and to their physical separation. The findings show a consistent relationship to cortical magnification across body sites.

1 Introduction

In the history of the study of tactile perception, a recurrent problem has been that of the relative influences of space and time on the localization of stimuli on the skin. With moving or changing stimuli, it is difficult to identify or define either a spatial or a temporal extent without acknowledging the influence of the other dimension in the judgment. For example, classical measurements of the two-point limen may be affected by whether the two points are presented simultaneously or successively (Dellon 1981; Johnson et al 1993; Jones 1956). The error of localization (measuring whether the *same* point was touched twice) may similarly be affected by the time between stimuli. In fact, in vision, audition, and the cutaneous senses, illusions of many types have their bases in such spatiotemporal interactions. The Phi phenomenon (or apparent movement, Graham 1965; Sherrick and Rogers 1966), the Tau effect (Helson and King 1931), and sensory saltation (Geldard 1975) are only three such illusions that have been studied in one or more sensory modalities (eg Collyer 1976; Shore et al 1998).

In this paper judgments of distance between two brief tactile stimuli are discussed, particularly as such judgments are influenced by space and time. The importance of the ability to make such distance judgments and discriminations can be seen in tasks ranging from the apprehension of objects in the everyday exploration of our environment, to the use of sophisticated aids that provide vibrotactile patterns to be read by blind persons in mechanized Braille or text devices, or tactile patterns of transformed speech signals to be decoded in aids to lipreading for deaf persons.

Although it may appear to be a relatively elementary task, the judgment of tactile distance has a long history of investigation. As long ago as 1826, Ernst Weber began his book, *De Subtilitate Tactus*, with a discussion of the differences in tactile sensitivity across different parts of the body (1826/1978, page 19). His first proposition was that not all parts of the body were "equally sensitive to the spatial separation of two simultaneous points of contact"—describing the variation in what has come to be known as the two-point threshold. There is an associated measure when the stimuli are separated by a much longer temporal interval: the error of localization. In this case,

rather than reporting whether one or two stimuli were felt, the observer is asked if the same or a different point was touched after the second of two presentations. Weinstein (1968) illustrates the variation in these measures at a number of body sites, as shown in figure 1.

Weber also described a distortion (specifically an asymmetry) of judgments of tactile extent in his second proposition. He said: "If two objects touch us simultaneously, we perceive their [suprathreshold] spatial separation and their arrangement more distinctly if they are oriented along the transverse rather than the longitudinal axis of the body" (1826/1978, page 25). Finally, in his third proposition, he related perceived distance to the two-point threshold of the area stimulated, describing the simple experiment of drawing a compass with separated legs "from the side of the face to the middle of the lips", noting how the points appear to draw apart as the more sensitive area is approached (page 38). These three observations imply that judgments of spatially extended patterns will depend not only on the physical extent but also on the site of stimulation and orientation of the pattern on the surface of the body (see also Goudge 1918).
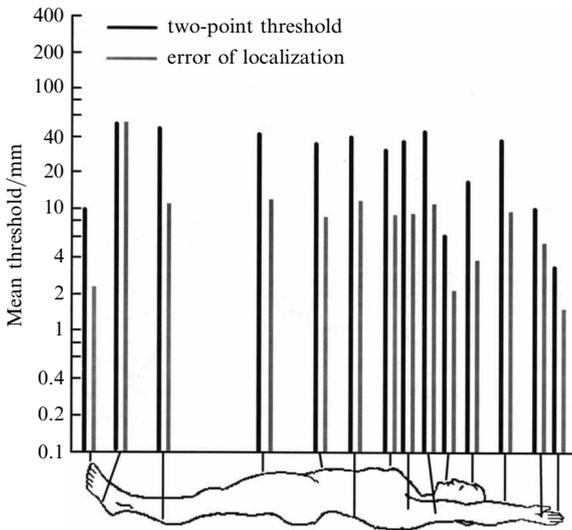
Figure 1. Two-point thresholds and errors of localization measured by Weinstein (1968). Note the similarity in the patterns of variation over the surface of the body. In every case, threshold for discriminating one point from two points when touched simultaneously (two-point threshold), is at least as great as that for determining whether the same location or two different loci were touched successively (error of localization). [After Weinstein (1968), figures 10-4 and 10-6.]

One hundred and forty years later, Green's (1982) review of the history of this research describes support for Weber's conclusions regarding the relationship between perceived distance and tactile acuity. Green then went on to quantify experimentally the functional relationships between perceived and physical distances for durative simultaneous pressure stimuli, confirming (i) that apparent distance varied with body site and orientation, and concluding (ii) that these misperceptions are compressive in nature, at least on the stomach, thigh, and forearm. That is, apparent distance, as estimated by visual comparison techniques, is less than actual distance. Furthermore, (iii) errors in perceiving distance correspond to errors in perceiving location.

Amplifying on the third point, Green (1982) referred to Boring's (1942) discussion of the threshold measures for absolute localization and two-point thresholds. Green argued that the localization of pairs of suprathreshold nearby tactile stimuli is only possible when they are referred to one another. At larger and larger separations, however, the body itself may provide more immediate "frames of reference" for localization. Such referents, first described by Henri (1895) and Parrish (1897), include anatomical features. For example, on the arm appropriate reference points might be the joints of the wrist and elbow. Because in Green's experiments the accuracy of localization appeared to improve at distances greater than 100 mm, while two-point localization errors ceased to increase

at the same distance, he thought it likely that "at these distances, localization may rely more heavily on the body as a referent" (page 321), than on the other stimulated point. He further suggests that, on a limb, the locus to which a stimulus refers would switch more readily from the second stimulated location to a distinctive body feature in the longitudinal direction than in the transverse direction. This would occur because of the ready availability of features, like joints, in a direction along the limb, and their absence across it. This difference in available referents might result in some asymmetry in judgments when distance estimates in the two orientations are compared. Furthermore, on a site such as the palm, where the area is surrounded by many such points of reference, it is likely that no asymmetry may be seen if the area were mapped.

Although Green (1982) examined the interrelations of these critical variables for static or durative simultaneous stimuli, another dimension—time—is often introduced into tactile displays, particularly those used to present analogs of visual or acoustic stimuli in alternative communication systems. In such a dynamic display, a complication might arise because "as the time between presentation of the two stimuli is progressively shortened to simultaneity, the expected result would be a perceptual migration of the two points towards one another [representing] spatial compression" (Green 1982, page 322; see also Kilgard and Merzenich 1995).

Indeed, over the years just these types of spatiotemporal interactions have been found within a number of different paradigms, as mentioned earlier. Often the primary interest in these studies was in the quality of movement that was produced by multiple presentations of stimuli across a space. Burtt (1917), for example, presented trains of pulses to the skin of the arm with two from a line of ten solenoids. As the stimulators were activated in series, the discrete taps generated what he called "the movement illusion" (page 374). His observers were simply instructed to introspect and describe what they felt. They typically reported their experiences in terms such as "flow", or "walk", or "skipping along" (page 375). The quality of the movement illusion was optimal with stimuli presented 30–75 ms apart and separated by fewer than 12 cm. These conditions, it is now known, can produce synthetic movement, or 'Phi', even with visual and auditory stimuli. Such illusory movement can be useful in displays to indicate real movement, or direction (see, eg, Alles 1970; Sparks et al 1978).

Several years later, Scholz (1924) conducted a series of studies aimed at examining visual, auditory, and tactile apparent distance, rather than movement, when the temporal separation between only two stimuli was varied. In the case of tactile stimuli, he used solenoid-held plungers that could only present durative pressure pulses. These stimuli have the disadvantage of having ill-defined onsets and offsets. Without precise control of pulse duration, temporal separations could only be roughly measured. In Scholz's experiments, after the stimuli were presented, observers were required to point the thumb of the free hand at one apparent locus on the forearm, and the index finger at the other. The hand was then brought up to a meter scale and distance read. As the interstimulus interval between stimuli decreased so did the apparent distance for the physical separations that ranged from 50 to 160 mm. This reduction in apparent distance usually (but not always) was accompanied by some degree of apparent movement. Scholz describes how the two phenomena can be separately observed, by appropriately focusing one's attention (see also Geldard 1982, page 160; Kilgard and Merzenich 1995).

In another attempt to quantify the relationships between space and time, Helson and King (1931) performed a series of studies describing a phenomenon they called the Tau effect. Tau was to be a statement of the interdependence of space and time, as implied by Einstein's theory of relativity which was receiving much attention at that time. Helson and King were determined to separate this effect from illusions, biases, or errors in judgment, primarily by using a comparative protocol. They also wanted to eliminate occurrences of apparent movement so as to avoid confusion with the

sensations produced by the 'gray ghost' of Phi, sweeping from one location to the other. Because Phi occurs with relatively short time intervals, these studies were conducted with interstimulus intervals greater than 100 ms with a device called the Harvard kinohapt. The comparative paradigm involved presenting tactile stimuli to three different skin loci on the forearm. Again, durative ($>$100 ms) pressure stimuli were generated because the kinohapt produced taps with electromagnetic solenoids. Observers had only to report "whether the spatial interval between the second and third stimuli was equal to, greater, or less than that between the first and second". The distances in these cases were 30 to 90 mm for the first separation (at a typical temporal interval of 500 ms). The temporal interval defined by the second and third taps was varied from 200 ms upwards, in 50 ms increments. The physical separation of these final two taps, when set to produce a sensation longer, shorter, or equal to that produced by the first two taps, was the dependent variable. Helson and King found that if the three loci define two distances of equal length, and if the times between the first pair and the second are unequal, judgments of the ratio of the first to the second separation will be in proportion to their respective temporal intervals. For example, when two 50-mm physical separations (S_1 and S_2) defined by three loci on the arm (L_1, L_2, and L_3) are stimulated by three taps (P_1, P_2, and P_3) that are 500 and 250 ms apart (T_1 and T_2, respectively), the ratio of the *apparent* separations between the loci will be in the same proportion as the times: S_1/S_2 will appear to be the same as T_1/T_2 or in this example, 2/1.

Helson and King were also able to demonstrate Tau when only two locations (L_1, L_2) were stimulated in a $L_1 - L_2 - L_1$ pattern, with different temporal intervals (1931, page 213). In this case, not only was the third tap felt to be in a different place from the first, but it had a different quality. They concluded that with short temporal intervals, where conditions for localization became labile, fixed local signs disappear and opportunities for mislocalization occur. Lechelt and his colleagues (Lechelt 1979; Lechelt and Borchert 1977) reexamined Tau, but with different procedures so as to: (i) dissociate the test and comparison stimulus locations (placing the test and comparison stimulus pairs on separate arms); (ii) retain a constant total presentation time; and (iii) vary the intensities of all or some of the stimuli. Furthermore, the electronically controlled stimuli were of a brief duration (2 ms). In general, Tau was obtained in all conditions, and the effects of varying intensity were minimal except when gross imbalances occurred. Even here, nevertheless, the general interdependence of space and time remained. Finally, there is an associated phenomenon, sometimes called the Kappa or S effect, in which estimates of time are also found, in the modalities of vision and touch, to be influenced by the physical separation between stimuli (eg Suto 1952).

While exploring Helson and King's Tau effect, Geldard and Sherrick (1972) discovered another form of the tactile spatiotemporal interaction that they named 'sensory saltation'. The essence of saltation is a mislocalization of the perceived location of the second of three tactile (or visual or auditory) stimuli. In their studies a brief tap at a single locus, which served as a spatial locator, was followed 700 ms later by a second tap at the same place. This tap was then followed by a third at a second locus within 20 – 250 ms. If the two loci were less than about 100 mm apart on the forearm, the sensation produced by the second tap was mislocalized towards the third, with the apparent separation between these two being a function of their interstimulus interval. It should also be noted that saltation has not only been observed in different sensory modalities (Geldard 1975), similar to Scholz's (1924) studies, but also has been tested over a number of body sites (Geldard 1982). The results across sites have shown not only that saltation demonstrates anisotropy (variation in the maximum extent of the effect along different radii from a central point) in a form consistent with Green's (1982) findings but that both the degree of anisotropy and the area so defined vary from body site to body site (Geldard and Sherrick 1983). Saltation differs from Tau in several respects. First, two

loci are typically used in saltation [although, as mentioned above, Helson and King (1931) did report the Tau effect with only two loci in one of their studies]. Second, in saltation the judgment is one of defining the apparent location of the second tap relative to the apparent loci of the first and third, rather than judging whether the separation between the first two is different from that between the second and third. Finally, the time intervals in the studies were somewhat different (Geldard 1975). Nonetheless, there exists a consistent functional relationship between the apparent separation of the test stimuli and their interstimulus interval that is remarkably similar for both effects (seen in figure 2).
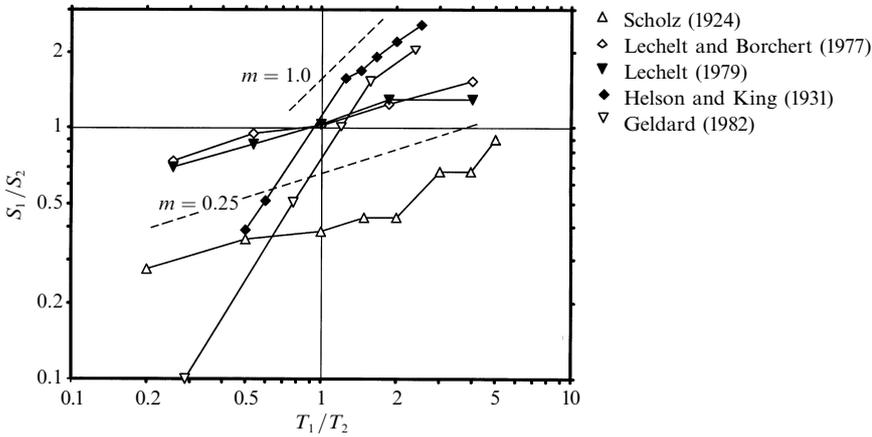
Figure 2. Tactile spatiotemporal points of equivalence as demonstrated in several different paradigms: magnitude matching (Scholz 1924), the Tau effect (Helson and King 1931; Lechelt 1979; Lechelt and Borchert 1977), and sensory saltation (Geldard 1982). In all cases, as the ratio of the times between stimuli fixed in location increases (to the right along the abscissa), so does the judgment of apparent spatial extent of the sensations produced by those stimuli (on the ordinate). For reference, dashed lines indicate slopes of 0.25 and 1.0.

A reanalysis of some of the data on cutaneous spatiotemporal interactions discloses some interesting similarities among these studies. In all of the experiments described above, observers were required to judge the apparent extent of space defined by two stimuli separated in time, either with or without comparison stimuli. One way to compare these findings is to plot the ratios of the spatial and temporal parameters over the ranges examined for these studies. In this way the reciprocity between space and time can be disclosed for points of subjective equality. The averages of values from the original data are plotted in figure 2, which summarizes the results of the five studies discussed above. [In some cases derived values had to be used.[1]] The ratios plotted are T_1/T_2 versus S_1/S_2; that is, the ratio of the time interval between the comparison and test pairs of taps versus the ratio of the two corresponding spatial separations (one veridical and one perceived). When the temporal separations are equal ($T_1 = T_2$) and the spatial separations are also equal ($S_1 = S_2$) then both ratios are 1 and presumably there is no differential influence of space or time on the other judgment. Because of the regular ordering of the data points, functional relationships between space and time exist among these ratios. Figure 2 demonstrates the similarity

[1] Scholz (1924) and Geldard (1982) did not use a comparative paradigm. Consequently, for this figure their ISIs were scaled to the data from Helson and King (1931) and from Lechelt and Borchert (1977) and Lechelt (1979) by plotting the data collected when the second temporal interval was set equal to 100 ms. The data plotted from Helson and King (1931) are the points at which the Tau effect is completely offset (that is, the ratios of the spatial separations required to offset the effect of a number of time differences).

in a number of these functions revealed by several different methods. Whether the task was to equate the apparent sizes of two tactually defined spans (Helson and King 1931; Lechelt 1979; Lechelt and Borchert 1977), or to produce or report a comparable visual or tactile span (Geldard 1982; Scholz 1924), the relativity of space and time is apparent by the linearity of the functional relationships shown in the figure. If the dimension of time had no effect on spatial judgments, then for all T_1/T_2 ratios every S_1 distance would be matched by a physically identical S_2 ($S_1/S_2 = 1$), so the slope of the function through the points of subjective equality on these coordinates would equal 0.0 with a y-intercept of 1.0. The same would be true if separation had no effect on temporal judgments except the slope would equal infinity. When the slope of these functions on the log–log coordinates is 1.0 (or close to it), there is a direct trading relationship between space and time. When the slope is less (for example 0.25), however, there is a 'compressive' relationship between space and time such that a given change in time results in a smaller change, proportionally, in distance. The differences in the slopes among the functions may be related to their methodologies or to their task demands. For example, in the case of Helson and King (1931), where the task was to match one spatiotemporal extent to another, the slope of the function is approximately 1, indicating the accuracy of the trading relationship between time and space. Helson and King (1931) and Geldard (1982) used what might be called a homogeneous method, in which the test and comparison stimuli shared common stimulus elements and skin loci. Scholz (1924), Lechelt and Borchert (1977), and Lechelt (1979), however, used heterogeneous sites; that is, the test and comparison stimuli were presented to different areas with separate tactor arrays. Whether these procedural factors alone account for the slope differences is unknown.

Similar interactions between space and time have also been seen with electrocutaneous stimuli. Jones (1956) examined these relationships while measuring the two-point limen in a 'same/different' paradigm. As the temporal separation increased from 2 ms to over 1000 ms, the minimal separation required for consistent 'different' responses decreased from about 1100 mm down to about 380 mm, on the average. He suggested that the data represented a spatiotemporal continuum, in which extremely short intervals represent the two-point threshold, while the longer intervals represent errors of localization.

The findings of the studies discussed above are quite suggestive of a spatiotemporal continuum for tactile stimuli. However, in most cases, spatial or temporal parameters were not varied systematically over a large range. In addition, except in the case of saltation, only the forearm was tested. As mentioned earlier, body site is an important variable for a variety of reasons, especially since these findings have relevance to the use of tactile aids, which, as we have stated, are often applied to different body sites (see Cholewiak and Collins 1991; Cholewiak and Craig 1984; Sherrick 1984; Summers 1992). Another reason is that, because the physiological characteristics of the skin at different locations on the body vary (Greenspan and Bolanowski 1996; Johnson et al 1977; Verrillo 1966; Verrillo and Gescheider 1992), a survey of sites might disclose the relative influences of central versus peripheral encoding of spatiotemporal interactions in tactile perception of distance (eg Cholewiak and Craig 1984; Essick 1991). For example, represented in the present experiments are two glabrous skin sites (finger and palm) and one of hairy skin (the thigh). These sites also differ in terms of their level of involvement in the acquisition of spatial information. In the empirical portion of this paper several experiments are reported on time-dependent processing for vibrotactile spatial patterns presented to three different body sites: the thigh, the palm, and the fingertip.

2 General method

2.1 Apparatus

The vibrotactile systems used to generate patterns presented to the palm and thigh sites consisted of two square arrays of 64 piezoceramic benders controlled by computer, one designed for each location. The thigh matrix was made up of 5-mm diameter contactors on 16-mm centers in an 8 by 8 array. The matrix could be adjusted so that its surface would fit the contour of the left thigh of the seated observer, and rested with a static force of approximately 10 g per contactor. The smaller palm matrix was made up of 2-mm contactors on approximately 8-mm centers. The heights of these contactors were adjusted to approximate the contour of an 'average' left palm. The hand rested on the array, palm down, with a small sandbag placed over it for stability. The patterns of vibration on the matrixes were specified by computer commands controlling the locus, intensity, and duration for the active elements, vibrating at 230 Hz. With these systems, completely new spatial patterns could be presented with a temporal resolution of 1.00 ms. A more complete description of the apparatus (shown schematically in figure 3) may be found in Cholewiak and Sherrick (1981).

When the fingertip was the stimulus site, a computer-controlled interface drove the vibratory array from an R1D Optacon©, a text-reading machine used by blind persons (Craig and Sherrick 1982). The 144-element tactile array measures 12.7 mm by 25.4 mm, and is contoured and positioned to fit the distal portion of the observer's left index fingerpad. The vibrators are arranged in a rectangular matrix, 6 columns on 2.54 mm centers by 24 rows on 1.27 mm centers. In these studies, however, only the distal 21 rows were used, which excluded the less-sensitive crease at the base of the fingerpad. When energized, the elements are driven at 230 Hz, the same frequency used on the palm and thigh matrixes. However, because the Optacon's contactors touch the skin only during a brief portion of the cycle (see, eg, Bliss et al 1970, page 60), the stimulus would be best characterized as 230 pulses s^{-1}. With this system, a completely new spatial pattern could be presented to the skin once every 4.35 ms. Additional details of this apparatus (also shown schematically in figure 3) may be found in Cholewiak and Sherrick (1981).
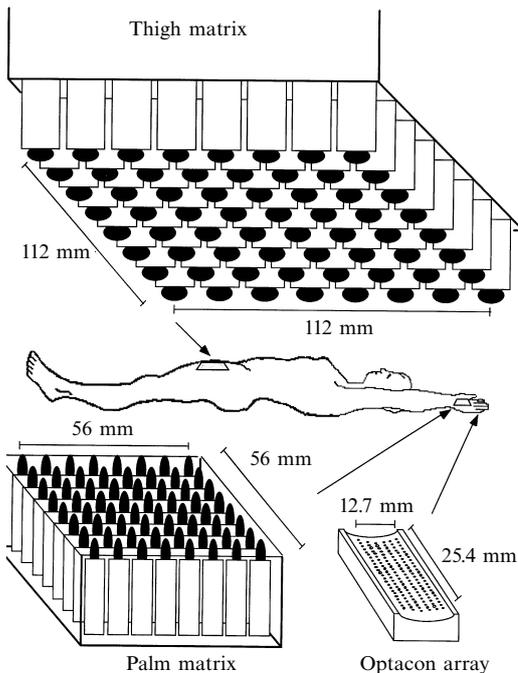
Figure 3. Representations of the three arrays used in these studies of tactile distance perception. The overall size of each display, and its relation to the size of the body site are also shown. Contactors are on 16-mm centers in the large thigh matrix, and on 8-mm centers on the palm matrix, while on the Optacon fingertip array, rows are separated by 1.27 mm while columns are separated by 2.54 mm.

2.2 Patterns

To facilitate the comparisons across body sites, the patterns were made as similar to one another as possible. In every case, the patterns used in these studies were active pairs of points or sets of points on the arrays, presented to the same location, loci adjacent to one another, or separated by one or more inactive elements. Patterns were presented in both longitudinal and transverse orientations on the arrays to permit examination of any asymmetries that might occur in the perception of distance along the axis of the limb versus perpendicular to it. The actual location on the array of the pair of active contactors in a given presentation was randomized over trials. Because of the physical differences in the construction of the thigh, palm, and fingertip matrixes, the distances available for testing varied from site to site and, on the fingertip, across orientations. For example, on the thigh or palm the active contactors were separated by as many as 6 inactive contactors in a row or column on the square 8×8 element arrays. The corresponding physical distances ranged from 16 mm to 112 mm on the thigh, and 8 mm through 56 mm on the palm. The patterns on the rectangular Optacon fingertip array consisted of one or two longitudinal or transverse lines made up of 6 adjacent contactors. It was not possible to use single points with the Optacon because the perceived intensity of individual vibrators was too weak. Furthermore, owing to the physical construction of this array, the actual distances possible between line patterns depended on the orientation being tested. In the longitudinal direction, rows are separated by 1.27 mm; while, transversely, columns are separated by twice that distance. Consequently, on the fingertip, pairs of stimuli were separated by 2.54 mm to 12.7 mm across the fingertip, and 1.27 to 25.4 mm along it. The actual distances, which increased in roughly logarithmic steps, are indicated in figure 3. In each of the three arrays, the resolution of the display was higher than the reported acuity of the body site to which it was applied, as defined by Weinstein's static two-point thresholds (1968; see also Daley and Singer 1975). In all cases, vibratory stimulus patterns were produced with individual 230-Hz haversine taps (4.35 ms period) presented with interstimulus intervals (ISIs) between the two ranging from 0 (temporally adjacent) to over 1000 ms, in roughly logarithmic steps. These ISIs were chosen to sample the range in which spatiotemporal illusions are most evident, including the intervals examined in the earlier studies described in the Introduction. The specific values for ISI, shown in the figures, depended on the characteristics of the array drivers described earlier: the Optacon had a period (and thus a resolution) of 4.35 ms, while the palm and thigh arrays had resolutions of 1 ms. Analyses of data over sites or orientations, to be described, used ANOVA, and included only those points that shared identical ISIs and physical separations.

2.3 Subjects

Subjects were naive to the psychophysical procedures and stimuli presented in these studies prior to testing. They were drawn from the population of male and female Princeton University students, aged 18 to 30 years, having good health with normal vision and hearing. In all cases, subjects signed informed consents, and were paid at the completion of each experimental session.

3 Experiment 1

In the first experiment, observers were presented with taps on the vibrotactile matrixes at either a single locus or two separate locations on the left thigh, palm, or index fingertip. The intensities of stimulation produced sensations characterized as distinct taps, not just a "recognition of a mechanical event" (Hämäläinen and Järvilehto 1981) with a perceived intensity well above threshold, ~ 14 dBSL. In this parametric design, all ISIs were combined with all possible physical separations. Each physical separation was presented twice in each block of trials. In trials in which the stimuli were asynchronous, the shift in location

from the first to the second occurred in both the proximo-distal and disto-proximal (longitudinal series) directions, or latero-medial and medio-lateral (transverse series) directions.

Depending on a number of factors, such presentations can produce sensations that may vary widely in character, ranging from a punctate tap at a single point, through a barbell-shaped sensation, to the feeling of two taps at separate locations (see Boring 1942; Dellon 1981; Essick 1992; Johnson et al 1993; Tawney 1895). In order to eliminate ambiguity, observers were required to estimate the apparent distance or extent defined by the two taps. If, however, observers had been asked to make a judgment of one versus two stimuli, an additional set of issues would have to be addressed. Specifically, with a sensitive enough procedure (eg two-alternative forced-choice procedures), it is always possible for observers to discriminate a spatially separated pair of touches to the skin (even if simultaneous) from either a single touch or even a pair apposed to one another. One powerful source for this discrimination is based in intensive cues. Over a hundred years ago Tawney (1895) claimed that "it seems that there is no such thing as a 'space-threshold' [the *Raumschwelle*] in the entire field of skin sensations, because there is no sensation of touch, not even that of a fine needle-point, which does not already possess a spatial quality" (page 592). Reviewing the history of attempts to measure two-point tactile acuity since then, Johnson et al reiterated that "a wide range of thresholds can be obtained, and ... there is no threshold separation beneath which two points cannot be separated from a single point" (1993, page 394). This critique can be applied to much of the classic literature in which two-point thresholds were measured (Johnson 1980; Johnson and Phillips 1981; J C Stevens et al 1996; J C Stevens and Patterson 1995). Consequently, in the studies to be described here, observers were specifically instructed to judge the apparent extent of the sensation rather than the distance between the taps, for, in certain cases, two separate events might never be felt. At the shortest of distances, below the point defined as the two-point limen, sensations of length are known to exist (see, eg, Friedline 1918), sensations to which observers were asked to attend in these studies.

A question that might be raised is whether there might be changes in perceived intensity over the range of physical separations that could confound the data from the studies to be described. This issue was addressed in an earlier study in which the large vibrotactile array was applied to the thigh (Cholewiak 1979). In that experiment, observers judged the overall sensation magnitude of 250-Hz 200-ms bursts of vibration presented with 4 tactors at three different physical intensities when the 4 tactors were adjacent to one another or separated by 1 through 6 active elements. In these cases, physical separation had no influence on the overall perceived intensity of the patterns.

3.1 Study 1
3.1.1 *Procedure.* Observers judged the overall extent of the sensations produced by pairs of tactile events by the method of magnitude estimation. Neither a modulus nor a range was suggested (Gescheider 1985, 1993). Each of the observers was given a brief familiarization task with visual stimuli (judgments of line length) prior to the first session to acquaint them with the method of magnitude estimation and to stabilize magnitude scaling (S S Stevens 1975; Teghtsoonian and Teghtsoonian 1970; Zwislocki 1983; Zwislocki and Goodman 1980). The tactile stimuli were controlled and presented by the computer while the observer's verbal responses were recorded with pen and paper by the experimenter for later computer entry. Fifteen observers participated in both the thigh and palm series, while another group of twelve observers served in the Optacon study. Recall that, historically, apparent distance as a function of interstimulus interval was examined in comparative paradigms: comparison against an external visual standard (Scholz 1924); comparison against an external tactile standard (Lechelt 1979; Lechelt and Borchert 1977); comparison against a preceding internal standard (Helson and King 1931); and comparison against a surrounding internal standard (Geldard 1982).

3.1.2 *Results and discussion.* Geometric means of the magnitude estimates were calculated for analysis because such estimates tend to be logarithmically distributed. When these data were analyzed by repeated-measures ANOVA, there was no significant difference in estimates generated for the related directions of presentation (proximo-distal versus disto-proximal or latero-medial versus medio-lateral). Further examination of the effect of direction showed no interaction with orientation or body site, so the remaining analyses were collapsed over direction. The means for each spatiotemporal combination are shown in figure 4 for each site and orientation, plotted on logarithmic coordinates with ISI as the parameter. It is clear that both main effects of physical separation and interstimulus interval were highly significant (for separation, thigh-longitudinal: $F_{1, 14} = 44.33$; thigh-transverse: $F_{1, 14} = 45.91$; palm-longitudinal: $F_{1, 14} = 38.33$; palm-transverse: $F_{1, 14} = 36.53$; finger-longitudinal: $F_{1, 14} = 116.49$; finger-transverse: $F_{1, 14} = 217.58$; for ISI, thigh-longitudinal: $F_{1, 14} = 36.79$; thigh-transverse: $F_{1, 14} = 32.56$; palm-longitudinal: $F_{1, 14} = 26.12$; palm-transverse: $F_{1, 14} = 19.79$; finger-longitudinal: $F_{1, 14} = 19.17$; finger-transverse: $F_{1, 14} = 21.23$). So as not to obscure the figure, only representative standard errors are shown. Note that the coordinates are the same for the thigh and palm graphs, and in all cases the inter-contactor distances are represented by the point separations on the abscissa.

The functional relationships shown in figure 4 are identical for each body site. Perceived extent at a given ISI is constant for small physical separations between the two taps. However, for greater separations, the magnitude of apparent extent increases greatly. Furthermore, the magnitude of perceived extent is shown to be an increasing function of ISI, but in a complex way. The reported threshold for correctly distinguishing two separated points from one (the static two-point limen) as determined by Weinstein (1968) is also plotted for each site in figure 4. These thresholds, obtained with durative touches, were used because no other such normative data exist for taps or vibrotactile stimuli. These are marked on the abscissae of the corresponding graphs by solid black triangles. For the thigh, this threshold is approximately 40 mm, for the palm about 10 mm, and about 3 mm for the fingertip. The lower asymptotes in the individual functions reflect the fact that, below the reported static two-point threshold, two taps presented at the same or slightly disparate locations produce similar perceived extents at a given ISI. [See identical functions for electrocutaneous stimuli in Marks et al (1982, page 531).] At any physical separation, the differences in perceived extent over different ISIs likely reflect the error of localization for tactile taps. Even the estimates of extent for taps at the same locus (zero separation) are well ordered as a function of the time between them. On the other hand, for physical separations greater than the static two-point limen, estimates of extent increase precipitously. If functions are fitted to the data for these distances, power functions generally describe the data best, as shown in figure 4. The exponents of these power functions range slightly above and below the value of 1.0. For ease of comparison, a slope of 1.0 is drawn on each graph.

There is little support for the possibility of anisotropy in these judgments: The absolute levels of the estimates for the two orientations at a given site appear to be very similar. This apparent lack of an asymmetry in the perception of the transverse versus longitudinal stimuli is statistical: Analyses of variance also failed to find a significant effect of orientation at these sites. As mentioned earlier, asymmetries in spatial judgments have been reported for a number of body sites, though the absence of unambiguous referents [as discussed by Henri (1895) and Parrish (1897)] on the finger and palm could explain the failure to find such an effect here. Weber (1826/1978) reported two-point thresholds on the upper and forearms as being greater in the longitudinal direction than in the transverse direction, a finding mirrored by Green's (1982) exploration of distance perception on the forearm. Similarly, Fuchs and Brown (1984) found two-point thresholds to be greater along rather than across the calf of the leg, though on the lateral
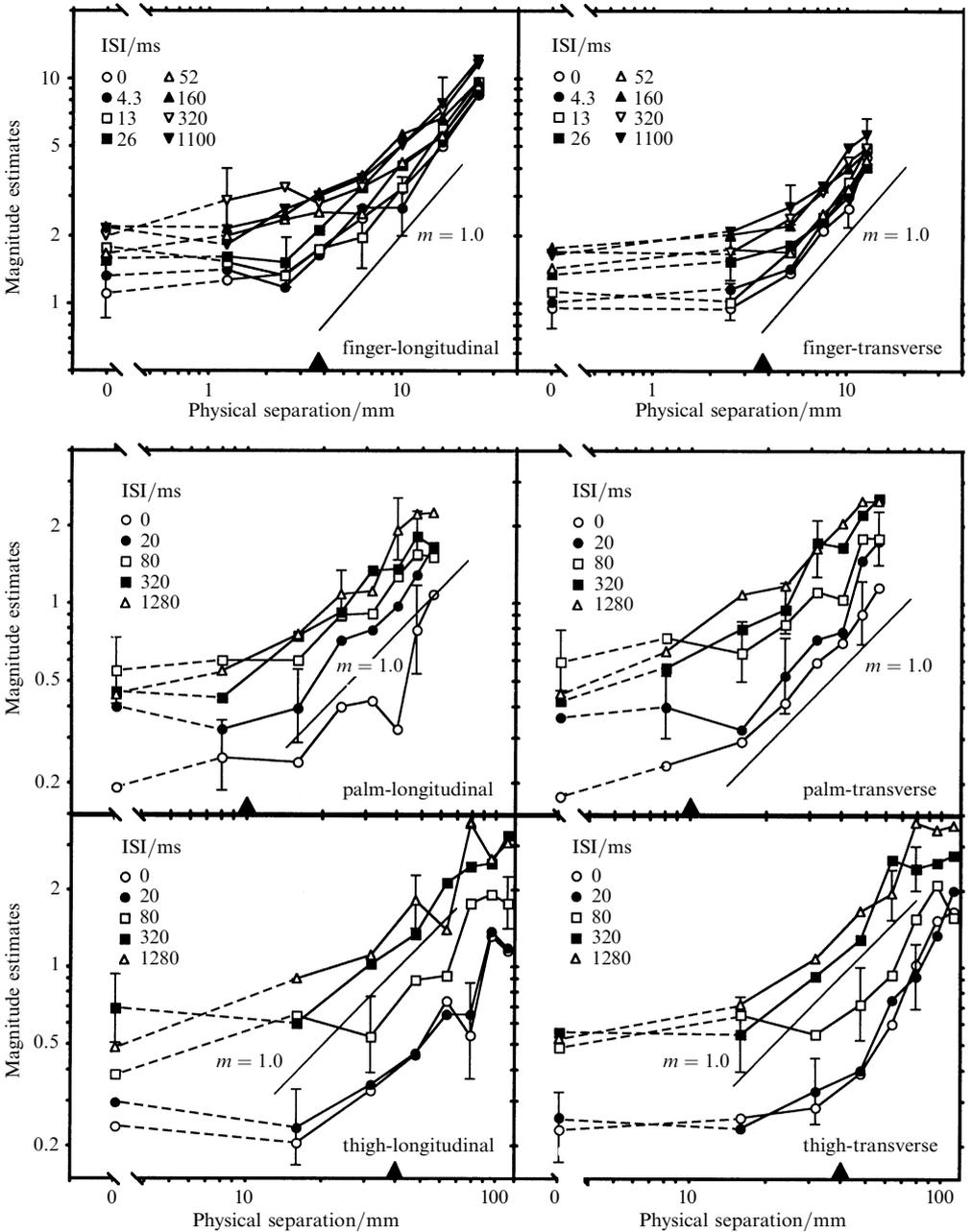
Figure 4. Magnitude estimates of the distance defined by a pair of vibrotactile taps on three sites and in two orientations with the interval between taps as the parameter. The top two panels show data for the finger, the middle two panels for the palm, and the lower two panels for the thigh. The left three panels are for points separated in the longitudinal orientation along the site, while the right three panels show the functions for points aligned transversely across the site. In each panel a line with a slope of 1.0 is shown, representing veridical ratio judgments. Filled triangles on the abscissa represent the two-point threshold, according to Weinstein (1968). Perceived distance grows with physical separation between stimuli as long as the separation is greater than the two-point limen for the site. Furthermore, the briefer the ISI, the smaller the perceived distance for a given physical separation between points. Representative standard errors are shown about several points.

mid-back the ratio was reversed. They suggested the possibility that the variation in the direction of the asymmetries over sites might be accounted for by dermatomal organization because dermatomes, which are areas of the skin innervated by the nerves within a single spinal dorsal root, are oriented along the length of the lower leg but across the width of the trunk. For the body sites examined here, the dermatomal organization is similar: commonly accepted maps indicate longitudinal orientations for dermatomes along the long axis of the thigh, hand (palm), and finger (see, eg, Keegan and Garrett 1948; Netter 1962, plate 32). The absence of an orientation effect found in the present data might better be explained, anatomically, by first-order afferent receptive field geometry. These areas of skin under which the receptors lie, can take various forms, including circles, ovals, points, and areas extended by sensitivity to stretch (Vallbo and Johansson 1984), and appear to underlie many aspects of tactile spatial sensitivity. For example, *perceptive* fields, defined by the area of skin from which a sensory experience results when single mechanoreceptor afferents are electrically stimulated, increase in size for some types of units on the skin in a distal to proximal direction (Schady and Torebjörk 1983), mirroring the increase that is found over those regions in error of localization for pressure touches (Weinstein 1968). Similarly, static spatial acuity at a location on the body has been shown to reflect the overall size, density, and the shape of the underlying mechanoreceptor afferent receptive fields (Vallbo and Johansson 1984). In the same manner, and a propos to this series of experiments, the physiological data indicate that over the body sites that asymmetries have been reported (eg arm and torso), receptive fields are typically oval, while on two of the sites studied here, the fingers and palm, they tend to be more circular (Johannson 1978, 1979; Knibestöl 1973; Knibestöl and Vallbo 1970; Sur et al 1980) as are the saltation fields on these sites (Geldard and Sherrick 1983). The picture is less clear on the volar thigh because at this site there is less consistency in field shape (Geldard and Sherrick 1983; Mountcastle 1961, figure 3). In the absence of any other explanation, it seems most reasonable that asymmetries in perceptual experiences on the skin are physiologically tied to underlying asymmetrical receptive fields, and psychologically related to the absence of distinct points of reference. [See Greenspan and Bolanowski (1996) for a more detailed discussion of the neural bases for anisotropies.]

   The present data begin to address one of the questions raised in the introductory discussion: How are tactile distances perceived over different body sites? One of the assumptions of the method of magnitude estimation is that observers can assign numbers to sensations that can accurately represent the perceived magnitude of the quality being judged—in this case, tactile extent. Because the same observers judged stimuli on both the palm and the thigh, a direct comparison can be made of the relative magnitudes on the two sites. Collapsing over direction and stimulus orientation for the shared physical separations, one finds a significant main effect of site ($F_{1, 14} = 27.361$). Specifically, for the same ISI and physical separation, observers perceive a greater apparent extent when the pattern is presented to the palm than when it is presented to the thigh. In addition, significant interactions were found between body site and ISI ($F_{1, 4} = 3.609$), and body site and separation ($F_{1, 3} = 10.535$), but the likely source of these interactions is the difference in the points of transition for the two sets of data—the curves become steeper at smaller physical separations on the palm than on the thigh. What about apparent extent on the finger? One must be more circumspect regarding comparisons among sites in this case because these data were generated by a different group of individuals. Nevertheless, as Zwislocki (1991) and others have shown, there is often consistency for identical sets of stimuli over different groups of persons. On assumption that the two groups of subjects used the same 'perceptual units' (Gescheider 1993), the pattern of these results indicates that the same stimulus is felt to produce the largest perceived extent on the finger, several times larger than that on the palm, which in turn is only slightly larger than that on the thigh.

Could these findings be related to the obvious differences in overall extent of the surfaces being stimulated? Proportionally, the Optacon array covers virtually the whole available surface of the fingerpad, the palm array covers about 75% of the surface of the hand, while the thigh array covers only some 35% of the available upper surface of the thigh. Areas for the three sites are approximately 3 cm^2, 41 cm^2, and 352 cm^2, with ratios of $1:14:123$, respectively, while areas for the arrays are 3 cm^2, 31 cm^2, and 125 cm^2, respectively. In terms of the maximum linear extent physically available on the finger, palm, and thigh, length ratios were $1:3:14$ over the three sites while the ratios of width were $1:5:9$, respectively. Attempts to match the ratios of the psychophysically obtained magnitude estimates with those obtained on the physical measures fail. For example, with 10-mm separations at 320 ms, estimates of extent on the finger were 6 to 10 times greater than for the same distances on the palm or thigh. These ratios do not match those calculated on the physical measures. So one might ask what features of the stimuli provide the scaling factor that subjects are actually responding to? These data cannot answer that query. This question will be addressed later and more directly with the method of cross-modality matching in experiment 2.

3.2 Study 2
Before leaving the paradigm of the first study, tactile extent on the thigh was reexamined in order to explore in more detail the temporal range over which changes in perceived spatial extent occurred, as well as to better examine the apparent convergence of the magnitude-estimation functions as physical separation increased. Fourteen additional observers judged the stimuli presented to the thigh using the same procedures and at the same ISIs as in study 1, as well as an additional two: 40 and 160 ms. Again, there was no effect of direction, nor was there a difference in perceived extent as a function of orientation. Consequently the results were collapsed over these parameters and are shown in figure 5, in which mean estimates of the separation between the two taps are
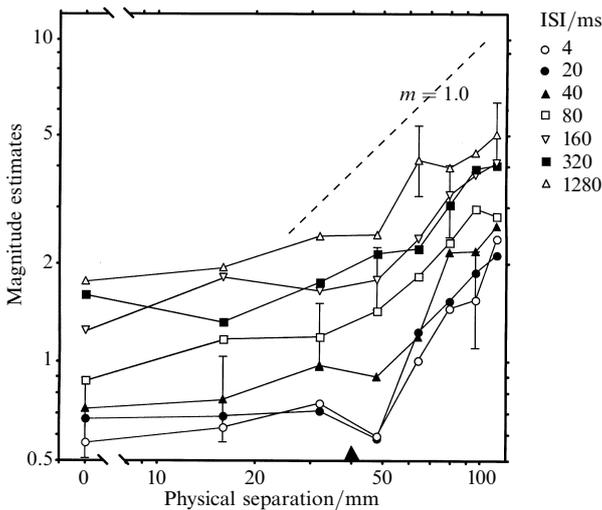
Figure 5. Estimates of the distance defined by a pair of taps on the thigh as a function of physical separation, with the temporal interval between taps as the parameter. Data from both the longitudinal and transverse orientations were combined. A line with a slope of 1.0 is shown and represents veridical ratio judgments. The triangle on the abscissa indicates the two-point threshold, according to Weinstein (1968). As before, perceived distance increases with physical separation between points for distances beyond the two-point limen. Furthermore, the briefer the ISI, the smaller the perceived distance for a given physical separation. Note the convergence (calculated to occur at about 300 mm) in the functions for physical separations beyond the two-point threshold. Representative standard errors are shown about several points.

plotted against the physical distances between them for each of the interstimulus intervals. Not only do these data show a clear main effect of physical separation ($F_{6,13} = 34.386$), and ISI ($F_{7,13} = 24.830$), there is also a clear convergence of the functions, supported by the significant interaction between ISI and separation ($F_{6,42} = 1.886$). The regular ordering of estimates with ISI indicates the presence of a strong spatiotemporal interaction in the perception of distance over a large range of separations.

The convergence of the functions is a consequence of the fact that, for physical separations beyond 40 mm, distance estimates for the thigh increase for shorter ISIs at a greater rate than do those for longer ISIs. In addition, estimates for each separation increase with ISI. The converging family of curves is emphasized when the points beyond 40 mm are fitted by power functions. The slopes of the functions fitted to the last 5 data points, in order of ISI from 2 to 1280 ms, are 1.54, 1.00, 1.32, 0.78, 1.01, 0.58, and 0.50, with an approximate point of convergence of 300 mm, as calculated by the method outlined by J C Stevens (1974). Such families of converging functions are not at all uncommon in the psychophysical literature, as Stevens illustrates in his review. He suggests that the point of convergence may represent some perceptual upper limit for the system (eg, for estimates of perceived intensity, the limit might be a level that could produce pain or injury). In this case where extent is being judged, the separation at the convergence point might represent the limiting distance for the spatiotemporal interaction; that is, beyond this distance, time no longer influences judgments of extent and the interaction collapses. Stimuli presented beyond these ISIs and separations may be judged veridically. This distance also approximates the limits of the saltatory area on the thigh, discussed by Geldard (1982), and may represent the maximum extent of physiological receptive fields at some level of cortical processing (Geldard and Sherrick 1983). When stimuli were presented on the thigh and on the palm at distances beyond those described here, Geldard and Sherrick found that the mutual interaction between sites broke down and only veridically located taps were felt (1983).

In summary, the magnitude estimates of extent over different body sites showed very similar functional relationships between interstimulus interval and physical separation when punctate stimuli were presented to the skin by tactile arrays. Nevertheless, observers judged a given distance at a given ISI on the thigh as covering a shorter extent than the same stimulus on the palm, and apparently, even less so than on the finger. On some body sites judgments typically involve *under*estimation of the distance. Green (1982) has called this phenomenon 'spatial compression', an effect he detected with a method that involves reproduction of the stimulus by the observer. It is not clear if spatial compression occurred at the thigh in the present studies because these judgments were made by the modulus-free method of magnitude estimation. In this paradigm, it is not possible to determine whether the observer felt the stimuli to be shorter than, as long as, or longer than the actual distances covered. To answer more directly the question whether the judgments reported here are greater or smaller than veridical, the next experiment employs a cross-modal matching paradigm similar to that used by Green.

4 Experiment 2

In this cross-modality matching study, the accuracy of the relationship between judged extent and veridical distance was to be determined on the different body sites. Using a variety of visual matching methods, Teghtsoonian and Teghtsoonian (1970) demonstrated (i) that a linear relationship exists when individuals judge perceived line length (visually), and (ii) that the estimates of perceived visual length are accurate. By using visually defined length as one of the two stimuli in a cross-modality matching paradigm, the tactile judgments could be considered accurate if the visual distances matched to them coincided with true distances (Fitt 1917; Gogel et al 1985).

4.1 Procedure

When the finger was the test site, thirteen observers were presented with pairs of stimuli on the Optacon at interstimulus intervals that ranged from 4 ms to over 1000 ms in roughly equivalent logarithmic steps. As before, the selection of physical separations in the longitudinal and transverse directions differed because of the inherent asymmetry in the rectangular array. The Optacon patterns were identical to those used in the magnitude estimation studies in experiment 1. In this case, the task involved simply drawing two lines (or one, if appropriate) on a piece of paper, separated by a distance that represented the apparent extent of the sensation produced by the vibrotactile stimulus. Even if only a single line or some variant was felt, observers were always free to draw illustrations that characterized their experience. The extents drawn for the fingertip study were measured with a computer-interfaced digitizing tablet having a resolution better than 0.5 mm over the maximum distance of 105 mm. Occasionally when the largest physical separations were presented, observers did not feel one or the other stimulus in the pair. In those cases, aberrantly small matches were generated. In these few instances, the data points were excluded from the analysis.

Cross-modality matches to visual extents were also made to tactile stimuli presented to the thigh and palm in a reduced design. Eight observers matched the apparent extent defined by a pair of taps on both sites. Unlike the case when the fingertip sensations were matched, these taps were separated by only a single interstimulus interval (320 ms). This temporal separation was chosen because the spatiotemporal interactions established in experiment 1 appear to have reached an asymptote: Apparent extent does not increase appreciably for longer ISIs. As before, stimuli were presented at a number of physical separations on the vibrotactile matrix appropriate to each site. Because of the larger physical distances involved on the thigh and palm, these matches were made by adjusting the distance between two 8-mm diameter white dots viewed on a linear potentiometer. One of the dots was fixed in place at one end of the track, and the other was on a slider that could be moved away to produce a separation of as much as 250 mm. This distance was more than twice the physical extent of the largest available vibrotactile stimulus separation. The separation between the dots was directly measured by the computer during the course of the experiment as a variable voltage across the potentiometer. With the visual slide system, distances could be measured with a resolution of 1 mm.

4.2 Results and discussion

The geometric means of the visual matches for judgments of extent on the fingertip were plotted as a function of the actual separation between the two loci for each orientation, with ISI as the parameter. These data are shown in figure 6. The curves look remarkably similar to those from the magnitude-estimation experiment (figure 4). As in that case, there was no significant effect of orientation for the physical distances tested in both directions on the rectangular array. The sizes of the visual matches appear to be proportional to the ISI when the two events occurred at the same location (0 mm physical separation), but at different points in time. This finding can likely be explained in terms of the error of localization for successively presented stimuli as discussed by Marks et al (1982), and was obtained with the magnitude-estimation procedure described in experiment 1 as well. Another point of similarity between the data from the two procedures is that a plateau is seen for a short range of the smallest physical separations at all ISIs. That is, apparent extent for short separations, as reflected in the cross-modality matches, is generally constant for a given ISI and independent of physical separation. Even though there is little or no physical separation between the stimulated points, the matches reflect a minimal yet stable sensation of extent that increases with the time between the presentation of the two taps (ISI). Thus it seems that increasing the time between two tactile events occurring at the same
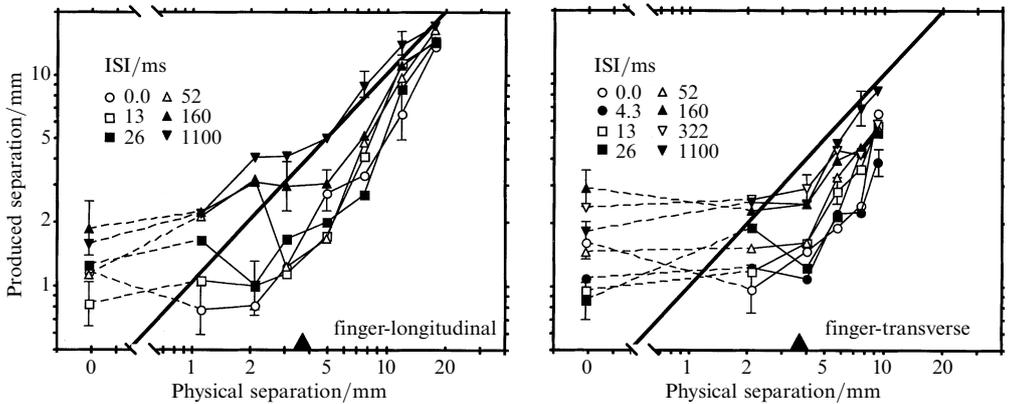
Figure 6. Geometric means of the cross-modality matches between perceived tactile extent and visual distance. Functions are shown for stimuli presented in both the transverse and longitudinal orientations on the finger. Note that apparent extent increases only for physical distances greater than the two-point threshold (filled triangles on the abscissa). Representative standard errors are shown about several points.

or almost the same place on the skin produces a sensation with an extent that is proportional to the temporal separation between the events. However, for larger distances between stimuli, matches become dependent on both temporal and spatial separations. They increase with separation producing a function with a slope close to 1.0 (shown on the graphs). The transitional regions between the horizontal and rising portions of these functions exist at the point at which separations become greater than Weinstein's (1968) two-point limen (indicated by the triangular marker on the abscissa). Examination of the upper limb of these functions reveals curves well-ordered by ISI in the same manner as were those in the magnitude-estimation functions from experiment 1. These functions also converge in much the same way.

The ordering of estimates both within and across ISI shows the presence of strong spatiotemporal interactions. For most separations greater than Weinstein's (1968) two-point limen, physical separations are generally underestimated, and that underestimation is a function of interstimulus interval. The shorter the ISI, the further the data points fall below the heavy diagonal line that represents an accurate 1 : 1 relationship between matched extent and stimulus. Only for the longest ISIs do the responses approach the veridical line.

In figure 7 the geometric means of the cross-modality matches for the thigh and palm are plotted along with some of the finger data from figure 6. There were no significant differences between the longitudinal and transverse functions at these sites. These additional data indicate that, in judging distance on the finger, on the palm, and on the thigh, the common finding is that observers showed a regular increase in their produced settings as stimulus distances increased above Weinstein's (1968) two-point threshold. On the thigh, as on the fingertip, matches fell somewhat below the veridical (45°, $m = 1.0$) line, suggesting the presence of perceptual compression. That is, observers underestimated the actual extent of the stimulus at the longer distances. When the palm was the stimulus site, however, the whole function is raised slightly above the veridical, suggesting some small degree of constant spatial expansion. In this case, distances were judged to be slightly greater than their actual physical extent. The thigh and palm functions are converging towards the veridical line (the slope for the palm, combining orientations, is 0.826, while that for the thigh is 1.027). Nevertheless, considering the variability in the data from both the thigh and the palm, lines with a slope of 1.0
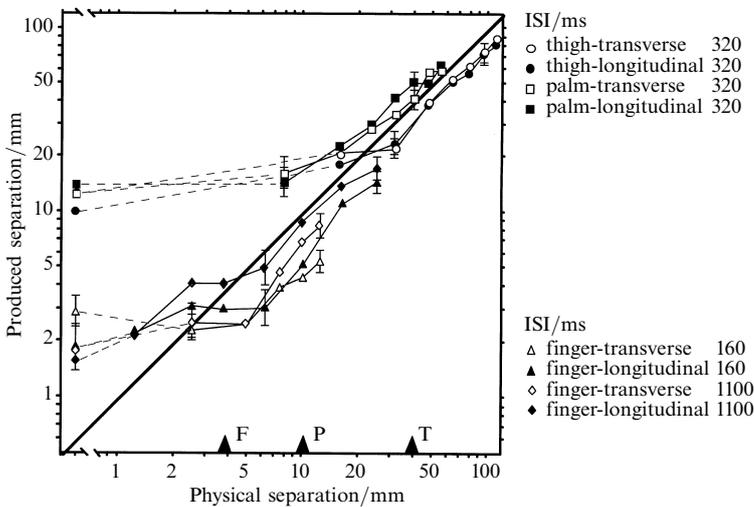
Figure 7. Geometric means of the visual productions of tactile distance on three different body sites: thigh, palm, and fingertip. Stimuli were presented in two different orientations on the sites: transverse or longitudinal at the indicated interstimulus intervals. Veridical or accurate judgments would fall along the diagonal line marked with a slope of 1.0. Thigh and fingertip data are suggestive of spatial compression for distances greater than their two-point thresholds (falling below the 1.0 line), while judgments of stimuli on the palm tend towards spatial expansion. Representative standard errors are shown about several points.

would fit the last 6 points as well as those fit by regression analysis.[2] These data bring back the question posed at the end of experiment 1: Are the same physical separations felt as identical on the two skin sites? Although ANOVAs of these data indicate the absence of statistically significant differences in the palm and thigh matches over all common separations (0, 16, 32, and 48 mm), COMPREG analysis of the lines fitted to the last 6 points (in the steeply rising portion of the thigh and palm curves) finds that they are neither parallel ($F_{1,572} = 4.361$), nor do they have the same intercepts ($F_{1,573} = 52.701$). That is, stimuli are felt to be longer when presented to the palm compared to the thigh. Therefore, in this direct comparison for longer separations, data from these two sites are found to be different, which was also found with the magnitude-estimation procedure. The question remains whether there is a reasonable ordering of the sensations produced over the three sites for equivalent stimuli. Examination of these functions indicates that two taps presented at a physical separation of 25 mm and at an ISI of about 160–320 ms would be matched by visual stimuli in the following order: finger matched at 15 mm, thigh matched at 22 mm, and palm matched at 30 mm. One-factor ANOVAs support these differences. For example, the longitudinal finger match at 16 mm is significantly smaller than that for the palm ($F_{1,19} = 17.683$) as well as being smaller than that for the thigh ($F_{1,19} = 4.498$). In contrast to what was suggested by the magnitude-estimation data, when the same tactile stimulus is presented to the finger, it is matched with a visual extent that is smaller than that from either other site. The most parsimonious explanation is that the two groups of observers in experiment 1 generated magnitude estimates based on different perceptual 'units', so they might not be comparable. It has been suggested that this might occur if the *absolute* magnitude-estimation procedure is not used, as was the case here (Gescheider 1993).

[2] The curves were analyzed with the COMPREG program developed by Wiggans et al (1983). COMPREG is comprised of a set of statistical tests taken from Woodward (1972) that assess the differences among a number of regression lines based on combined analyses of variance and covariance (regression) techniques.

5 General discussion

In these experiments, the presence of a strong spatiotemporal interaction in the perception of distance over a large range of physical separations over three body sites is revealed by the generally regular ordering of estimates over distance with ISI. This range of spatial and temporal intervals was of particular interest in that the large body of research on spatiotemporal illusions described earlier shows major effects within the parameters examined here. The effects that Scholz (1924) observed occurred for distances on the arm up to 16 cm and temporal intervals up to about 400 ms. Helson and King's (1931) Tau effect was demonstrated for distances of 30 to 85 mm on the forearm for ISIs ranging from about 200 ms to over 500 ms. On the thigh, saltation is known to occur over distances that are represented in these studies, and over times ranging from about 25 ms to more than 200 ms.

Reaffirmed by the present findings is what appears to be a general principle of operation of the nervous system underlying spatiotemporal illusions, including cutaneous saltation and the Tau effect. That is, if two events occur on the skin within certain spatial and temporal bounds, the localization of one element, as reflected in the estimates of extent, will be influenced by the presence of another. In these data, however, it is impossible to indicate whether the perceptual displacements found with brief ISIs are caused by a symmetrical displacement of the two stimulated loci towards one another or are the consequence of an apparent shift in location of only one of the taps [see, eg, Geldard's discussion of the saltatory 'attractant' (1975, pages 43 – 50) versus Kilgard and Merzenich's (1995) symmetrical localization]. Nevertheless, the magnitude of the influence of time on distance judgments can be as great as 3 : 1, as is shown by the range of estimates or matches for a given physical separation in figures 4, 5, and 6. Such a temporally determined interaction might underlie specific illusions such as saltation. A possible mechanism for saltation, for example, can be generated by incorporating some of these findings. It could be that the first tap (P_1) in saltation, at locus 1, is required to establish a point of reference (Geldard's 'locator' tap). Because the second (P_2, also at locus 1) and the third (P_3, at locus 2) occur at least 700 – 1000 ms later, these data suggest that the locator P_1 will not influence their apparent location (Geldard 1982). However, in the saltation paradigm, because P_2 and P_3 are presented within 300 ms of one another, their apparent physical separation would be a direct function of the time interval between them according to the present data. Since the question asked in saltation ("Where does P_2 occur?") focuses the observer's attention on location, the pulse P_2 is reported to shift its location away from its locus of origin (Kilgard and Merzenich 1995), with the resulting illusion of displacement (see, eg, Sherrick 1991, page 198). This scenario is akin to the Tau effect (relatively shorter times result in relatively smaller perceived extents), except for the change in attentional focus. In the case of saltation the question is "where", in the case of Tau it is "how far". It may be—to paraphrase Dennett—that these discriminations "are a matter of logic based on the brain's capacity to make a temporal order discrimination of a particular acuity", a discrimination in which location is recovered later, when there is time available to draw inferences about location (Dennett 1991, pages 150 – 151).

Let us return to the more general question of how characteristic such spatiotemporal interactions are of the operation of the nervous system. Functions similar to those shown in figures 4 – 6 have been reported in the literature when the apparent locations of sensory events were studied in other sensory systems. As mentioned above, Marks et al (1982) described a similar ordering of estimates of the distance between electrocutaneous stimuli presented to the abdomen and to the forehead. As can be seen in figure 8a, the variation in the temporal relationship between stimuli in their study had systematic effects on perceived distance, again with perceptual compression apparently occurring at temporal intervals ranging from 2 to 960 ms (page 535). Loomis (1983) also described
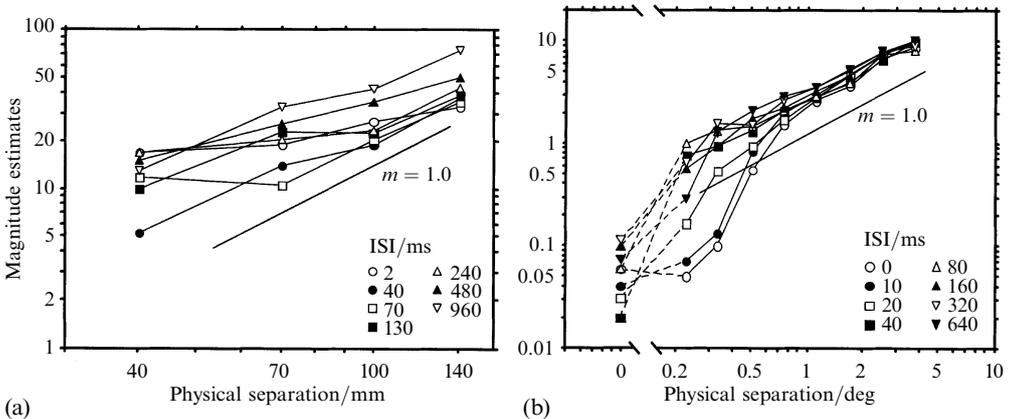
Figure 8. Functions, similar to those in figures 2 and 3, illustrating spatiotemporal interactions with two other types of sensory stimulation (procedures detailed in text). (a) Electrocutaneous stimuli on the abdomen (Marks et al 1982), and (b) visual stimuli (Loomis 1983)—both demonstrate changes in estimates of stimulus extent as a function of both physical separation (on the abscissa) and interstimulus interval (the parameter), with a particularly strong pattern of convergence in the visual data.

the same type of interaction, this time occurring with visual stimuli presented with temporal intervals ranging from 0 to 640 ms. A pair of 0.85 deg stimuli were viewed binocularly 2.2 deg to the left of fixation, separated by distances ranging from 0 to 3.75 deg of visual angle. Although noisy, the data from Loomis's three subjects (shown in figure 8b) are functionally similar to those obtained here with tactile stimuli presented to the thigh, palm, and finger, and to those collected by Marks et al.

What is the source of these effects? Because such spatiotemporal interactions can be found in several sensory systems and over many body sites, it is likely that they are central in origin. Wiemer et al (1998) suggest that there are processes in our nervous system that transform temporal distances into spatial distances, and these temporal differences may be used to organize the formation and alteration of cortical representations. A contrary option was discussed by Jones (1956) in his examination of spatiotemporal influences on the two-point limen, who proposed the possible "translation of spatial patterns in primary somatosensory cortex into temporal patterns in cortical association areas" as being the basis of tactile space perception. Regardless of the direction of the transformation, these central notions are supported by the current data because they show a strong similarity in the functional relationships between spatial and temporal parameters across the sites tested, despite important differences in their receptor complement and density. Consequently, peripheral factors probably play a minimal role in the interaction between space and time.

Libet (1982, 1993) provides further evidence to suggest that cortical spatiotemporal interactions might affect perception. He has described clinical evidence obtained by direct stimulation of human somatosensory cortex in which the perceived location of the sensation produced by cortical stimulation may be shifted to that of a sensation produced by a prior stimulus at a nearby point on the cortex. Furthermore, the durations of many of the effects described in the data from the present psychophysical studies agree with his proposal that neuronal adequacy for the production of a given sensory response might reach into the hundreds of milliseconds (Libet 1977, 1982, 1993). Similarly, Amassian's (1954) physiological data illustrate how, in cat somatic association areas, responses to electrocutaneous or tactile stimuli regularly block one another when interstimulus intervals fall between 150 and 600 ms. Such interactions also occurred with volleys of visual and auditory stimulation, and over extraordinary

durations. Amassian concluded that "temporal factors are important in the cortical representation of space in the periphery" (page 56). The implications are that even the stimulus quality of location may take time to develop, and the presence of stimuli nearby may perturb the accurate localization of these events.

Other correlational evidence to suggest involvement of cortical mechanisms in the determination of the extent of spatiotemporal interactions comes from the work of a number of neurophysiologists. When representative primate somatosensory cortex is mapped by determining the locations of the peripheral skin sites that drive the cells in the cortex, as is shown in figure 9, what has become evident is that certain large regions of cortex appear to receive information from relatively small areas of the body surface. Note particularly the discrepancy between the cortical areas devoted to the thigh versus digit 2. When these areas are mapped onto a body surface, they produce the distorted homunculus figure well known to students in introductory psychology. The ratio of the area of cortical representation of a site, divided by the surface area of the skin it represents has been defined as 'cortical magnification' (Sur et al 1980). The larger the area of cortex devoted to a skin site, presumably the higher the density of innervation of that site. Note, in figure 10, how magnification changes from less to more densely innervated areas —with an ordering of arm to hand. We can assume that the thigh and fingertips fall at either extreme. Geldard and Sherrick (1983) showed that the sizes of the skin areas over which spatiotemporal interactions occur appear to be ordered much like the ordering of degree of cortical magnification over sites, implying that it is within these cortical regions that spatiotemporal interactions can occur. More recent data indicate that spatial stimuli not only are encoded by cortical cells spatially proximate to one another, but that the dynamic relations between such groups of cells change to a remarkable extent with temporally contiguous stimuli (Clark et al 1988; Recanzone et al 1990; Spengler et al 1996; Wang et al 1995; Whitsel et al 1989; Wiemer et al 1998). The correlations between the physiological and psychophysical results are tenuous, at best, because the results from these studies indicate that such alterations in cortical receptive field characteristics occur only after thousands of stimulus presentations. In the phenomena we have discussed in this paper, the perceptual experiences involving spatiotemporal interactions are immediate, typically apparent on the first exposure to the pairing of stimuli within the physical
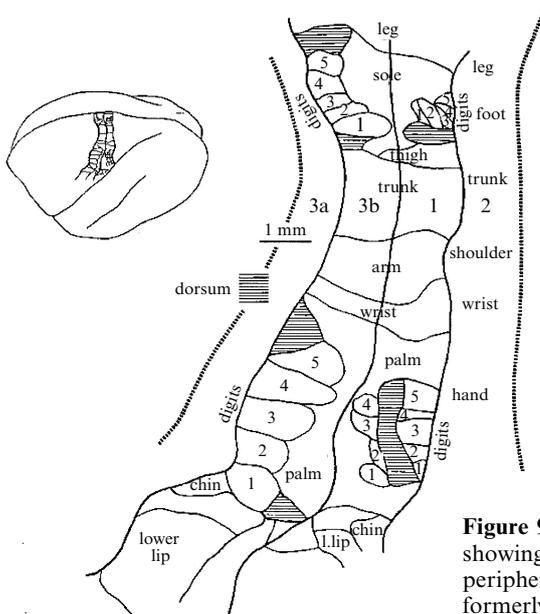
Figure 9. The mapping of *Aotis* somatosensory cortex showing multiple representations of a number of peripheral body sites in areas 3b and 1 of the region formerly known as SI. After Kaas et al (1979), figure 1.
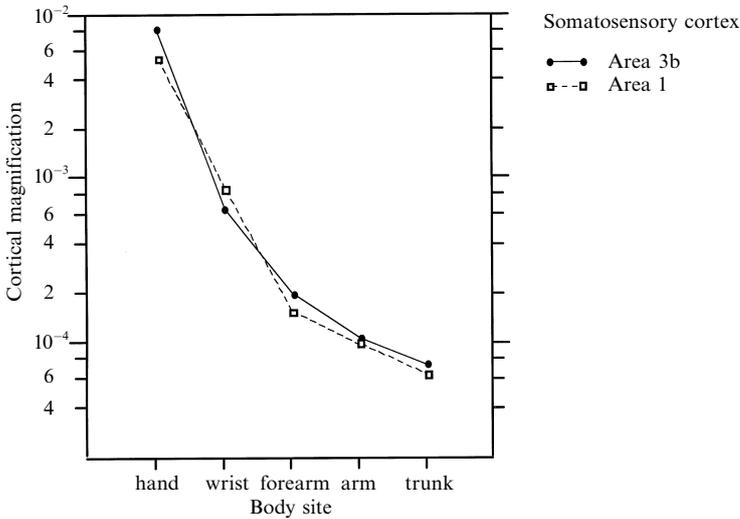
Figure 10. Cortical magnification factors for a number of skin sites calculated as the ratio between the cortical representational area and the peripheral skin area innervated by that portion of the cortex with the resulting unit of cortical area per unit body-surface area. Magnification is indicated by the high ratio for the most sensitive sites. [After Sur et al (1980), figure 2.]

distances and interstimulus intervals described above. Nevertheless, it is possible that these immediate experiences likely indicate a built-in propensity at some level in the nervous system for complex interactions between adjacent cortical fields activated by spatially and temporally contiguous events. As with so many perceptual phenomena, these may be inborn and emergent like the Gestalt principles of perceptual organization. However, the single-unit physiological data cited above may indicate that, through repeated experiences, the physical connections and interactions can be strengthened to reflect the more general processes involved with any type of learning in an area of cortex (SI) not usually associated with pattern learning.

These data have several implications for both basic and applied research on tactile-pattern processing. First of all, because given physical distances appear to have different extents that depend to some degree on the location to which they are applied on the body, identical displays and pattern sets cannot be applied haphazardly. Rather, more work should be done to investigate the relationships among the resolutions of displays, the associated spatial characteristics of the patterns to be presented, and the display modes (Horner 1991; Loomis 1980), all as a function of body site. Some work has already been done along these lines. Cholewiak and Craig (1984) examined pattern identification, discrimination, and masking at a number of body sites. Their findings, for example, indicated that the rank ordering of recognition performance followed the order of measures of tactile sensitivity such as spatial acuity or innervation density: performance on the finger was better than on the palm, which, in turn, was better than on the thigh (see also Scadden 1973). Similarly, Cholewiak and Collins (1995b) also examined pattern discrimination and communality on these same sites, finding comparable functional relationships over sites between accuracy and number of common elements in the patterns being compared. Nevertheless, some interesting differences remain. For example, although normalized masking curves for tactile patterns are identical for the finger and thigh, overall levels of recognition performance for the same patterns differ considerably at these sites (Cholewiak and Collins 1988).

From the present experiments, it is clear that the functional resolution of a tactile array can depend greatly on how patterns are presented on that display. These data indicate that brief presentation intervals will tend to produce spatially attenuated patterns

that, for some observers, may be difficult to use in vibrotactile communication systems such as the Optacon or Tactaid, assistance devices for blind or deaf individuals, respectively. Those who might be most affected by such a reduction in display acuity would likely be elderly persons who now comprise the largest segment of the population suffering from visual and auditory disability. Cholewiak and Collins (1995a), Gill (1993), J C Stevens (1992), J C Stevens and Patterson (1995), and J C Stevens et al (1996) all present compelling data indicating that the tactile acuity of the sensory systems in the elderly is compromised compared with that of young persons. On the other hand, it is also clear that, in order to be useful, communication systems must be rapid and accurate, having brief presentation times for individual patterns. In order to match the hundreds of words per minute that are processed either in normal speech or in reading, tactile communication systems must be able to compress or to present data in manners or at rates that tax the trade-off between speed and precision. That this can be done is obvious with 'natural' communication systems such as Tadoma (Reed et al 1982, 1983), but mechanical systems have yet to be developed to provide for such rapid information transmission, yet to be resistant to the deleterious effects of the spatiotemporal interactions described here. Finally, it is clear that certain effects, such as the spatial asymmetries described earlier, deserve greater study over a wider range of body sites. This effect alone, if present, could impede the learning process for tactile patterns by imposing unexpected spatial distortions.

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