Skin and Touch
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Glossary

Active touch Mode of tactual perception in which the observer purposively controls the pickup of sensory information

Haptic Pertaining to sensory information derived from both cutaneous and kinesthetic receptors; typically involves purposive touch

Kinesthetic Pertaining to sensory information concerning limb movement that is derived from receptors in the muscles, tendons, and joints

Mechanoreceptors Receptors that respond to mechanical deformation

Microneurography Technique that involves the recording of neural responses in a single nerve fiber in awake, human subjects via the percutaneous insertion of a microelectrode into a peripheral nerve

Passive touch Mode of tactual perception in which the observer has no voluntary control over the receipt of sensory information

Psychophysics Study of the quantitative relations between physical events and the sensations evoked by those events. It is also used as a method for revealing the functional properties of perceptual stages of processing, both physiological and cognitive

Receptive field Area on the skin that, when stimulated, alters the response of a single neuron

Tactile Pertaining to sensory information derived from cutaneous inputs

Tactile unit Primary afferent neuron with its terminal sensory ending usually situated in the dermis; such a unit is primarily sensitive to deformation of the skin

Threshold of detection Minimum energy ("absolute threshold") or change in energy ("difference threshold") that is required to detect a stimulus or stimulus change, respectively

Weber fraction Measure of differential sensitivity for different stimulus dimensions; calculated as the ratio of the difference threshold to the initial stimulus value

MOST RESEARCH on human touch has focused on the hairless skin of the hand, particularly the palm and palmar aspects of the fingers. Four mechanoreceptor populations are found here. These differ in their structure and distribution within the skin and in their response to static and dynamic mechanical events. They are selectively sensitive to different stimulus properties and project such information to the central nervous system, where it is transformed by at least two neural networks before reaching the cerebral cortex. The filtering properties of skin that determine thresholds for intensive, spatial, and temporal aspects of stimulation have been considered using behavioral techniques, as has the relation between above-threshold mechanical events and the perceptual experiences evoked by those events. The limits imposed by the properties of the cutaneous filter will further affect the tactile perception of fingertip-size patterns, the perception of surface texture, and both real and illusory motion across the skin. These topics are considered along with the underlying neural coding mechanisms that
arise in the skin. More recently, the field has expanded its scope to include the study of the haptic system, a perceptual system that typically explores the world of objects purposively. Research indicates that humans often perform haptic tasks that involve two-dimensional objects or patterns larger than the fingertip rather poorly. In contrast, they can recognize three-dimensional common objects extremely well. The nature of haptic processing and reasons for this difference in performance are considered. Much of the laboratory research pertaining to human touch is potentially valuable in the development of sensory aids for the blind and deaf and in the design of flexible perceptual systems for sensate robots equipped with articulated hands.

I. Tactile Receptors in the Human Hand

A. Structure

Some 17,000 mechanoreceptive tactile units, all of them particularly sensitive to mechanical events, innervate the hairless skin of the human hand. These can be differentiated in terms of their structure and location within palmar skin (see Table 1). Figure 1 presents a vertical section through the hairless skin of the human hand, showing nerve terminals for each of four different types of tactile afferent units that send signals to the central nervous system: fast-adapting type I (FAI; sometimes called RA), slowly adapting type I (SAI), fast-adapting type II (FAII; sometimes called PC), and slowly adapting type II (SAII) (see Section I, B). Meissner corpuscles are ovoid-shaped capsules, located in the papillary ridges of the dermis, and typically associated with FAI units. Merkel cell neurite complexes surround the axons of SAI units and are located at the deep end of the epidermal pegs that project into the dermis. Pacinian corpuscles are relatively large onion-shaped structures located deep in the dermis and in subcutaneous tissue; they are the end-organs for FAII units. Ruffini endings are narrow, spindle-shaped capsules situated in the dermis, believed to be the terminals for SAI units. Throughout the foregoing discussion, the mechanoreceptor terms adopted in any animal or human research reported will be preserved.

B. Functional Properties of Tactile Units

Microneurographic techniques have been used to study the functional properties of peripheral tactile afferent units. This technique permits the recording of activity of single units in awake humans, as well as the direct relation of this neural activity to sensation (see Sections III and IV). The distinguishing functional properties of the four classes are also presented in Table 1. FAI units have relatively small receptive fields (with distinct borders); they respond primarily when deformation starts and, less consistently, when it ends. FAII units have relatively large, diffuse receptive fields; these respond to both onset and offset. SAI units have relatively small, precisely defined receptive fields; they respond both to the onset of indentation and, irregularly, to the sustained portion. SAII units have slightly larger receptive fields; they respond less vigorously to the dynamic aspects and more regularly to continuing indentation. These unit popula-

<table>
<thead>
<tr>
<th>Property</th>
<th>FAI</th>
<th>FAII</th>
<th>SAI</th>
<th>SAII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specialized ending for tactile unit</td>
<td>Meissner</td>
<td>Pacinian</td>
<td>Merkel</td>
<td>Ruffini</td>
</tr>
<tr>
<td>Relative depth of specialized endings from skin surface</td>
<td>Shallow</td>
<td>Deep</td>
<td>Shallow</td>
<td>Deep</td>
</tr>
<tr>
<td>Number of specialized endings per tactile unit</td>
<td>12-17</td>
<td>1</td>
<td>4-7</td>
<td>1</td>
</tr>
<tr>
<td>Clustered unit endings</td>
<td>No</td>
<td>—</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Mean receptive field area (mm²)</td>
<td>12.6</td>
<td>101.0</td>
<td>11.0</td>
<td>59.0</td>
</tr>
<tr>
<td>Adaptation to sustained stimulation</td>
<td>Fast</td>
<td>Fast</td>
<td>Slow</td>
<td>Slow</td>
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</tbody>
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b FAI, fast-adapting type I; FAII, fast-adapting type II; SAI, slowly adapting type I; SAII, slowly adapting type II.

c “Fast” describes units that respond only to the transient phase(s) of stimulation; “slow” describes units that show a sustained discharge.
FIGURE 1 A vertical section through human fingertips skin showing its basic structure and the specialized nerve endings for the four different types of tactile afferent units (see also Table 1). Meissner corpuscles (Mr), located in the papillary ridges of the dermis, are typically associated with fast-adapting type I (FAI) units. Merkel cell neurite complexes (MI) surround the axons of slowly adapting type I (SAI) units and are located at the deep end of the epidermal pegs that project into the dermis. Pacinian corpuscles (P), located deep in the dermis and in subcutaneous tissue, are the end-organs for FAII units. The spindle-shaped Ruffini endings (R), which are situated in the dermis, are believed to be the terminals for SAI units [From R. Johansson, and A. Vallbo (1983). Tactile sensory coding in the glabrous skin of the human hand. Trends Neurosci. 6, 27–32.]

II. Initial Distinctions

It has been strongly debated whether tactual performance is better when skin–object contact results from purposive manual exploration as opposed to passive stimulation of a stationary observer by an external agent. Unfortunately, this seemingly simple distinction confuses variation on two dimensions, either or both of which may have important consequences for human sensation and perception. These two dimensions are the degree of control exerted by the perceiver in the pickup of information and the type of sensory information available to the perceiver.

For purposes of clarification, therefore, the terms "active" and "passive" are reserved for conditions of touch in which the observer does or does not have control over the touching process, respectively. The terms "tactile" and "haptic" refer specifically to the type of sensory information that is used by the observer: "tactile" is used to describe conditions in which cutaneous inputs alone are used, whereas "haptic" is used to refer to conditions involving use of both cutaneous and kinesthetic inputs. "Kinesthetic perception" is based solely on sensory inputs from muscles, tendons, and joints.

III. Sensitivity

Noninvasive behavioral studies have used a variety of experimental techniques to consider the quantitative relation between the physical parameters of a mechanical stimulus and the resulting sensations and perceptions. Single-unit recording techniques have also been used to determine the underlying neurophysiological response to similar forms of stimulation. The monkey has typically been used in neurophysiological research because of the anatomical and functional similarities between monkey and human nervous systems.

A. Intensive

Traditional methods of assessing cutaneous sensitivity have involved the determination of thresholds of detection or their inverse (i.e., sensitivity). For example, force has been varied by applying calibrated nylon monofilaments to the skin until they just bend. The absolute force thresholds for detecting such step-function inputs differ considerably over the body surface. The most sensitive areas are the face and torso, followed by the fingers and the lower extremities. Sex and body side (left vs. right) also affect threshold. Across these factors, threshold values range from 5 to 355 g. Absolute sensitivity to repetitive forces (i.e., vibration) also varies across body locus, although the sensitivity pattern is not identical to that for static pressure. Differential cutaneous sensitivity has also been described in terms of the Weber fraction for different stimulus dimensions, where the smaller the value, the finer
the discrimination. For the finger, studies have obtained Weber fractions of about 0.14, 0.20, and 0.20 for static pressure, impulse (tap) stimuli (of sufficiently high signal/noise ratio), and 160-Hz vibratory bursts, respectively.

B. Spatial and Temporal Sensitivity

It has been proposed that the early stages of cutaneous processing filter the stimulus contacting the skin, both spatially and temporally. According to this approach, the stimulus that is available for later stages of processing will have lost some of or all its spatial and temporal information as a result of such filtering. More recently, the use of linear systems (in which the response is directly proportional to the stimulus) analysis has been advocated, as it permits us to predict the response to any arbitrary stimulus, provided that the system is linear and that the filter function is known. Although strict linearity is unlikely, linear systems analysis can provide an approximation of the cutaneous system's performance.

There are two ways in which the stimulus, the spatiotemporal filter, and the filter output (constituting the input or stimulus for the higher level stages of perceptual processing) may be represented mathematically. It is possible to represent each of these either as a function of three orthogonal dimensions (two spatial dimensions on the skin plane, and time), or as the Fourier transforms of these three functions in terms of three dimensions: two for spatial frequency and a third for temporal frequency. Knowledge of the spatial and temporal filtering properties of the cutaneous system is critical for a complete understanding of tactile pattern perception. What is needed is a systematic evaluation of the spatial and temporal sensitivities across the body surface. Unfortunately, current psychophysical and neurophysiological data on this point contribute only isolated fragments to the overall picture. In accord with tradition, the topics of spatial and temporal sensitivity will be treated separately but with caution, as the two may be interdependent.

1. Spatial

Traditionally, spatial sensitivity has been evaluated using aperiodic stimuli. The most common of these continues to be the “two-point touch” test applied to the skin. The task requires the observer to indicate whether a single or two separate points are experienced. The resulting estimates of spatial acuity vary considerably as a function of body site (Fig. 2). The smallest two-point separation that can be detected as such is approximately 2 mm on the fingertips; however, more refined psychophysical tasks have obtained considerably finer estimates. The “point localization task,” which assesses the accuracy with which a point applied to the skin may be localized, has also been used as an indicator of relative spatial acuity at various body loci. It varies in the same way as the two-point touch threshold, but it is more sensitive. Errors of localization range from about 1.5 mm on the fingertips to about 12.5 mm on the back. More refined techniques have demonstrated that subjects may detect a shift in location as small as 0.1 mm on the fingertips (Fig. 2).

To specify completely the properties of the cutaneous spatial filter as a function of body locus, it would be necessary to use periodic sine-wave gratings with independent control of the depth of skin penetration. Unfortunately, considerable technical difficulties have made it impossible. Two techniques, however, have been used to obtain limited approximations of the spatial filtering properties of the skin. One involves the use of square-wave gratings with separations (defined by the width of one element plus the width between the elements) close to the limit of cutaneous resolution. The sensitivity of the fingertips to square-wave gratings varying in separation has been assessed by requiring subjects to discriminate the orientation of pairs of them (aligned along or across the axis of the finger). The depth of skin penetration was also independently manipulated. Below a separation of 1 mm, no information about grating orientation was available. Above that level, sensitivity increased in an approximately linear fashion as a function of increasing separation. Seventy-five percent correct discrimination performance was obtained with separations of 2.25, 1.84, and 1.68 mm for the 500-, 900-, and 1,200-μm indentation levels, respectively. Note that this approach yields only the high-frequency cut-off (i.e., small separations); there are no sensitivity estimates at the higher separations.

A different approach involves the single-unit recording of various mechanoreceptor populations in humans or monkeys, the functional properties of which have been described in Section 1, B. The recording of responses of different types of tactile units to braille-like patterns moved across the surface of fingertip skin in monkey suggests an important role for receptive fields in transmitting precise...
Spatial information. In accord with their relative size, an array of SA units could transmit the most precise spatial details, followed by RA units, and least precisely by PC units (Fig. 3). Note that this research deals specifically with the spatial filtering characteristics of the peripheral stage of cutaneous processing.

2. Temporal
The absolute vibrotactile threshold has been measured as a function of temporal frequency. The results vary with many factors [e.g., contactor size, presence or absence of a contactor surround, body locus (although few sites have been tested), stimulus duration, skin temperature, and previous exposure to intense vibration of selected frequencies]. The duplex model proposes that the observed variations may be accounted for by the temporal filtering properties of two different channels, as described in Fig. 4, which shows the specific effect of contactor area when a rigid surround is used.

Additional information about temporal sensitivity comes from neurophysiological recordings of activity in the different mechanoreceptor populations of humans and monkeys. In monkey, responses of three different types of peripheral mechanoreceptor units to a broad range of frequencies and amplitudes show responses around three different frequencies: 20 Hz, 40 Hz, and 250 Hz for SA, RA, and PC units, respectively. In humans, FAI units responded at frequencies between 8 and 64 Hz, whereas the FAII units responded best above that range; however, at high stimulus amplitudes there was considerable overlap. The SA units were most sensitive at very low frequencies (about 2–32 Hz), although they responded across a broad range of test frequencies (0.5–400 Hz).

Weber fractions for resolving vibrotactile frequency typically range between 0.20 and 0.25 over the frequency range of 20–300 Hz. Such findings have important consequences for using frequency as a stimulus dimension in artificial displays to make the skin "hear" (see Section VIII, B).

Other methods have been used to assess cutaneous temporal resolution as well. For example, the separation time between two 1-msec pulse stimuli that is required for an observer to perceive them as successive is 5.5 msec. And cutaneous numerosness, measured as the number of events accurately perceived to have occurred within a given period of time, is a little less than 9 when events occur at a
single site at the rate of 5/sec. Because these measures used aperiodic stimuli, they do not provide complete information about the cutaneous temporal filter. However, they do permit us to compare the extent to which various sensory systems can resolve temporal details. Touch usually proves to be better than vision and poorer than audition.

IV. Quantitative Assessment of the Perceived Magnitude of Suprathreshold Mechanical Events

Psychophysical techniques have also been used to assess the nature of the mathematical function relating the magnitude of sensation to the magnitude of the physical stimulus. In these behavioral tasks, subjects must quantitatively judge the magnitude of their suprathreshold sensations. The obtained psychophysical functions, which are usually best described mathematically by a power function, have been used to uncover the way in which the sensory channel processes the incoming information. However, where different sections of a psychophysical function are better described by separate power functions with different exponents, the simultaneous contribution of as many neural mechanisms or subchannels has been postulated to account for the overall growth in sensation.

V. Recognition of Spatial Micropatterns and Texture Perception

The perception of small, raised micropatterns and surface textures appears to be mainly determined by cutaneous inputs (i.e., kinesthetic inputs are not required): Provided there is relative motion between skin and stimulus, it makes no difference whether the observer moves his or her fingers across the stimulus or the stimulus is moved across the observer’s stationary fingers. These patterns and textures are considered two-dimensional inasmuch as there is no variation in the third dimension.

A. Tactile Character Recognition

1. Spatial Resolution of Micropatterns

Research on the tactile recognition of raised characters has dealt with a variety of different character
FIGURE 4 The duplex model of vibrotactile sensitivity proposes that two systems mediate the effects of many stimulus parameters (see text) on the function relating absolute threshold to vibrotactile frequency. The NP (non-Pacinian) system is not affected by frequency and does not summate energy over space or time. The P (Pacinian) system shows a U-shaped response to frequency (with a minimum at about 300 Hz) and is capable of summing energy over both space and time. It is assumed that whichever system is the more sensitive will determine the threshold response. In the current figure, the effect of contactor area is shown when a rigid surround is used to prevent the spread of traveling waves. Thresholds obtained with a small contactor are independent of frequency, whereas those obtained with the large contactor show both a flat portion below about 40 Hz and a U-shaped function above. It has been suggested that the NP system determines the flat threshold response as a function of frequency when the small contactor is used. It may also determine the flat portion below about 40 Hz for the large contactor condition, because the sensitivity of the P system in this part of the frequency range (indicated by the dashed segment that represents data from other studies) is lower than that of the NP system. The P system is believed to mediate the U-shaped, frequency-dependent portion obtained with the larger contactor. The extent to which it is uniformly lower than the corresponding portion for the small contactor condition indicates the greater sensitivity that is due to spatial summation. [Adapted from R. T. Verrillo (1963). Effect of contactor area on the vibrotactile threshold. J. Acoustical Soc. Am. 35(12), 1962–1966.]

formats: braille, Roman letters, Japanese characters, and graphics symbols. Although the goal of most early work was to determine the legibility of different tactile codes for use in communication with the blind, more recent work has been concerned with understanding the mechanisms that underlie tactile recognition.

Because any circumscribed region of the skin (e.g., the fingerpad, forehead, or forearm) is severely limited in the number of spatially resolvable points, especially when compared with the retina of a normal observer, it has been suggested that were vision to be similarly “blurred” (i.e., limited in its ability to resolve spatial detail to the same extent as the skin), it ought to show a functional similarity with tactile pattern perception; this has been confirmed in a number of experiments. When the effective spatial resolution of vision was matched to that of touch by optical blurring, it was found that the variation in legibility among a variety of character sets was remarkably similar for blurred vision and touch; for example, for both senses, braille was found to be a more legible character set than the Roman alphabet. These and related studies show
that many of the facts about tactile character recognition are traceable to the limited spatial resolution of cutaneous sensing, which more than any other factor sets tactile pattern perception apart from visual pattern perception. Stemming from this experimental work is a mathematical model that accounts quite well for the relative legibility of character sets presented either visually or tactually.

As mentioned in Section III, B, spatial pattern is likely coded peripherally by SA and FAI units, with the limits of fine-pattern discrimination being set by the innervation density of SA and perhaps FAI units. Research on the coding of object shape in anesthetized monkeys indicates that the SAs signal vertical displacement, vertical velocity, and the extent and rate of change of curvature of the skin. Rates of FAI response are in proportion to vertical velocity and rate of change of skin curvature. Thus both peripheral mechanisms code the positions of maximal change in curvature (object boundaries); however, only the SAs code absolute skin curvature. The distinction in function of these two populations of mechanoreceptors thus resembles that between the X and Y cells of the visual system.

At the cortical level, cutaneous neurons positioned anteriorly in somatosensory cortex (cytoarchitectural area 3B) have small receptive fields, allowing many of the fine spatial details coded by the mechanoreceptors to be preserved. However, in more posterior cortical areas (cytoarchitectural areas 1 and higher), the neurons have larger receptive fields that frequently span several fingers. Here, the spatial details of the object are lost, being replaced by the selective coding of edge orientation and direction of motion (see Section VI). To date, there has been very little systematic investigation of cortical mechanisms that code curvature, pattern, or shape. [See Somatosensory System.]

2. Temporal Resolution of Spatial Micropatterns

There is evidence that the temporal resolving power of the cutaneous pathway also restricts tactile character recognition. Much of the relevant research has used a modified version of the Optacon, a reading device for the blind, which is described in detail in Section VIII, A. As a research tool, it permits control of spatial and temporal parameters of vibrotactile patterns presented to the fingertip. The results of such research indicate that the tactile system is somewhat temporally sluggish in processing spatial patterns. Consider the results of a study in which a stimulus pattern (i.e., a letter) and its spatial complement (i.e., the spatial distribution of light energy in the original letter is reversed), each lasting 26 msec, was presented as follows: The start of the letter stimulus was preceded by or preceded the start of the complement by varying intervals. Although subjects could partially resolve the two patterns, full resolution did not occur until the complement preceded the letter stimulus by at least 30 msec and until the complement followed the letter by at least 104 msec.

Other research has investigated the effectiveness of different modes of presenting spatial patterns to the skin. Although this work has important implications for the design of communication systems that substitute visual for cutaneous information (Section VIII, B), it also addresses how the tactile system processes spatiotemporal information. The modes of presentation have included a "static" mode in which the entire pattern is presented at once to the skin without any lateral displacement, a "scan" mode in which the entire pattern is moved across the skin, and various "sequential" modes, in which the elements are presented separately over time. In general, the static mode has proved superior to various other modes when experimental conditions (size of stimuli; body locus) were such that cutaneous spatial resolution was unlikely to limit recognition performance. In contrast, when spatial resolution was limiting, sequential modes tended to result in better pattern recognition performance.

Still other investigations have more specifically focused on the reduction of a person’s ability to detect or identify a tactile pattern as a result of the presence of another pattern that is contiguous (or overlapping) in space or time. To date, there are no definitive theoretical accounts of these findings.

B. Texture Perception

The term “texture” is rarely well-defined. In this article, it will refer to all the physical properties of objects, liquids, and materials, except macroshape. Thus, it can include roughness, hardness, slipperiness, stickiness, element density or cluster, and elasticity. To date, the most systematic behavioral research has involved the perception of roughness. The studies have employed stimuli such as fabrics, abrasive surfaces, and more precisely controlled, unidimensional rectangular gratings, as well as regular and jittered two-dimensional spatial arrays of raised dots. The work reported here will
deal primarily with the gratings and raised-dot arrays.

With static touch, only crude roughness discriminations can be made. Relative motion between skin and hand, whether produced by active or passive touch, is necessary for fine-texture perception. It has been suggested that such motion serves to prevent cessation of mechanoreceptor activity resulting from fast adaptation or, alternatively, that it causes all mechanoreceptor populations to be activated. Whether it is the hand or texture that moves seems to have no effect on either roughness discrimination or the magnitude of roughness perceived. Consequently, it has been concluded that only cutaneous (not kinesthetic) inputs are required for perceiving roughness.

Roughness perception of gratings appears to increase primarily with the width of the grooves and, to a lesser extent, with the fingertip force applied; it remains unaffected or decreases slightly with the width of the ridges. The spatial period (i.e., the sum of the widths of one groove and one ridge) has little influence on perceived roughness. Finally, the speed of the relative motion between hand and surface has little effect on the magnitude of roughness perceived, whether the surface is moved across the observer's stationary hand or the hand is moved across the surface in a similar manner. Given the relative unimportance of speed of motion, the perception of roughness has been described on the basis of a quasi-static model of the instantaneous deformation of the skin. This model rejects the contribution of temporal factors resulting from the vibratory impulses produced by relative skin-surface motion.

Results related to many aspects of the human psychophysical work on perceived roughness have been obtained in the corresponding neural response of anesthetized and alert monkeys at peripheral and cortical levels. The growth in the human perception of roughness magnitude with increasing groove width of linear gratings may be coded by activity in all mechanoreceptor populations, as may the observed force effect and a relatively small effect of increasing ridge width. Moreover, recent cortical work in area 3b of alert monkeys has found FAI cells that increase rate of firing as a function of groove width (rather than spatial period) when the hand is actively moved across a grating. In general, this work tends to support an intensity, as opposed to temporal, code for roughness.

Differences in the spatial separation of gratings of about 5% may be discriminated by humans with 75% accuracy. This value approaches 2% for discrimination of rectangular arrays of raised dots, with spatial separation increasing in only one of the two possible (X, Y) dimensions of the dot array. The rate of firing by peripheral FAI units can serve as an underlying neural code (based on intensity) for discrimination of such dot arrays. More generally, it has been suggested that the successful discrimination of very fine textures (i.e., those with element separations less than the innervation density of the spatially sensitive SA and FAI units) may be coded nonspatially by the relative firing rates of all mechanoreceptor populations.

VI. Object Motion Across the Skin

When a probe is moved across the skin, smooth continuous motion is perceived. However, similar sensations can result from the application of discrete stimuli to the skin, provided that the duration and the spatial and temporal parameters for stimulus separation are appropriately chosen. This is similar to the illusory movement perceived visually on a movie marquee, where two or more spatially separated lights are sequentially illuminated so as to produce the appearance of smooth motion. A second form of cutaneous apparent motion has been documented, also with parallels in other modalities. Apparent motion is felt in discrete jumps when a succession of taps is applied to the skin in an orderly spatial progression at several different skin sites, with several taps delivered at each site. It has been humorously equated to a rabbit hopping along the skin, landing not only at the sites of contact, but in the intervening spaces as well.

Both SA and FAI mechanoreceptors, which detect change of skin curvature, are involved in coding object motion on the skin. Both types respond at higher rates when an edge is moved laterally across the skin than when the stimulus is stationary, their firing rates reflecting the speed of motion. The response of FAII units also varies with speed but is independent of the spatial properties of the moving stimulus. In the monkey somatosensory cortex, cortical neurons in the more anterior portion are selectively sensitive to continuous motion through the cell's receptive field. Other cells more posteriorly situated in the cortex are also selective to the direction of stimulus motion. Motion need not be continuous to trigger these two types of motion-
selective cells, suggesting they are responsible for the human perception of continuous apparent motion.

VII. Haptics

The haptic system is usually described as a perceptual system that uses inputs from both cutaneous and kinesthetic receptors to derive information about objects, their identities, properties, and spatial layout. Haptic perception and recognition typically involve purposive exploration of the concrete world. Performance can vary markedly with the type of task and stimulus object.

A. Two-Dimensional Raised Patterns and Planar Objects Larger Than the Fingertip

Unfamiliar raised line patterns of various lengths and orientations, solid planar shapes made of some homogeneous material, and outline drawings of common objects have all been used to investigate haptic performance of tasks involving two-dimensional stimuli that are larger than the fingertip. With certain exceptions, the research indicates that the haptic system performs relatively poorly—it is slow and/or inaccurate and highly susceptible to distortion.

For example, with simple line displays, perceived length is distorted by the direction of manual exploration: it is overestimated when movements are radial (toward or away from the body) rather than tangential to the body. Length perception is also affected by the extent of the path traversed by the hand, as when the subject must infer the direct (“as the crow flies”) distance between the ends of a pathway: The distance tends to be increasingly overestimated as pathway length increases. Matching solid planar objects by shape is also slow and prone to error, as is the recognition of common objects depicted as raised outlines, unless the number of possible objects is small and the identities of all such objects known a priori.

For all these tasks, observers must extract contour information by performing a relatively slow form of manual exploration (i.e., contour following), which places a considerable memory load on haptic processing. It has been suggested that under such circumstances, those with some visual experience may transform the initial haptic inputs into a visual image, which is then interpreted using visual processors for purposes of perception and recognition. However, even this image-mediation process does not guarantee efficient performance.

B. Three-Dimensional Objects

In contrast, people are remarkably good at recognizing common objects, such as a spoon. It typically takes only 1–2 seconds to identify most of these objects correctly. Common objects are easier to recognize because they are three-dimensional and have other characteristics such as surface texture, hardness, thermal properties, and weight. All these different sources of information redundantly specify the object’s identity. It appears that the anatomical, sensory, and motor characteristics of the human hand lend themselves admirably well to the extraction of these different types of information. It has been suggested that in processing multidimensional objects, the haptic system functions independently of other perceptual systems (such as vision), with its own specific ways of selecting and processing information about objects, and of representing them in memory (e.g., it may choose to weight material properties of objects more strongly than vision). Sensory integration of vision and haptics likely occurs during the later stages of processing.

1. Role of Purposive Manual Exploration

It has been observed that people move their hands purposively when freely exploring objects. They execute a number of highly stereotypical hand movement patterns (i.e., “exploratory procedures”), each associated with the goal of extracting a particular object property. For example, when determining an object’s weight, a lifting motion is performed. Figure 5 presents caricatures of typical movement patterns, together with the attribute(s) that each extracts best. The exploratory procedures also vary in terms of how many different kinds of information they provide. For example, the Pressure procedure primarily provides information about hardness, whereas the Enclosure procedure is highly general, providing coarse information about a number of attributes. These procedures are also influenced by factors resulting from the dynamics of the hand–object interaction (Section VII, B, b).
2. Constraints on Manual Exploration and Their Consequences

Variation in the degree of specialization of the information obtained may account for the finding that when people were required to answer whether an object in the hand was a member of a certain
class (e.g., "Is this abrasive paper sandpaper?")
they explored in a specific two-stage sequence.
During stage 1, they executed a "grasp-and-lift"
routine; during stage 2, they adopted a set of more
specialized patterns, most diagnostic of the class of
objects named in the task (e.g., for sandpaper, its
texture).

Another constraint derives from differences in
ease of movement and in the possibility of carrying
out different exploratory procedures at the same
time. Manual exploration is also constrained by the
location of different attributes on an object (e.g.,
edge versus center) because this influences the ex-
tent to which people can integrate information
about more than one attribute at the same time. It
has been argued that as manual exploration is fur-
ther constrained by hypotheses generated by the
explorer's knowledge of the world, the study of
hand movements may serve as a window through
which it is possible to reveal the nature of the cog-
nitive representations of multidimensional objects in
memory, as well as the processes by which these
are achieved.

C. Spatial Frames of Reference for Organizing
Tactual Pattern Perception

When an asymmetric pattern, such as the letter
"d", is drawn on the back of the head, it is recog-
nized. However, when the same pattern is drawn on
the forehead, people usually report perceiving its
mirror image, the letter "b." Such mirror reversals
have been observed in other passive-touch condi-
tions (e.g., when patterns are traced on the forward-
facing palm and on back of the hand) and when
people actively explore a forward-facing surface in
front of them. In general, it seems that patterns ap-
plicated to the front and back of the head are judged
relative to a local frame of reference located behind
the head. Patterns delivered to other head and body
surfaces are organized in a considerably more com-
plex manner, with frames of reference selected in a
complicated way (i.e., on the basis of the position
and orientation of the stimulated surface). These
results appear to be fairly general, inasmuch as they
have also been found with young children and con-
genitally blind adults and in studies involving active
touch and motor production tasks. Such work is
fundamental to our understanding of the ways in
which people represent spatial knowledge about
stimuli contacting the body and for the design of
sensory prosthetic devices.

VIII. Applications

A. Tactile Sensory Prostheses and Aids for the
Sensory Handicapped

Several attempts have been made to permit the skin
to "see" or "hear." The most common noninva-
sive sensory aids include devices that address only
one area of deficiency (i.e., reading or mobility and
navigation by the blind or speech comprehension
by the deaf). In all cases, it is important to match the
capabilities and limitations of the substitute system
to the processing requirements of the task that is
performed with the designated aid. Below are some
eamples.

1. Visual Substitution

The Optacon (which stands for OPTical-to-TAc-
tile CONverter) is an aid that is used by the blind for
reading print text. It provides a direct translation
by quantizing an area roughly the size of a letter-
space into 144 black-white points (24 rows and 6
columns) and displays these points on a corre-
spounding array of 144 vibrators. The person directs
the small camera with the right hand and receives
the equivalent vibratory picture on the index finger
of the left hand. With training, average reading rates
of 30 words per minute have been achieved. Al-
though this rate may be relatively slow (i.e., the
comparable visual reading rate is about 250 words/
minute), it succeeds in making all print materials
accessible to the blind.

Another common form of educational and naviga-
tion aid for the blind is the tangible graphic display,
which uses raised symbols (i.e., points, lines, and
surface areas) to represent spatial information in the
form of pie-charts, maps, graphs, pictures, and so
forth. These displays vary in effectiveness for rea-
sons that relate to the specific limitations and capa-
bilities of the system used to process the informa-

2. Auditory Substitution

The usefulness of the Tadoma method of tactual
communication by the deaf-blind serves as proof
that touch can be used successfully to understand
running speech. The deaf-blind individual places
the fingers of one hand over the lips and sides of
the speaker's face, thereby making available a rich set
of dynamic cues that relate to the natural articula-
tory movements of the speaker. Artificial displays
have been based on this articulatory information. In
another system, spectral displays of the acoustic speech signal are presented to the skin. The acoustic vibrations of speech are passed through filters tuned to different frequency bands, the output of each being delivered to a separate site on the skin, with the sites arranged either uni- or two-dimensionally. These displays are usually intended for deaf individuals who can see, so that the resulting tactile information may be augmented by lip reading.

B. Touch by Sensate Robots

Efforts are being made to design flexible robotic systems capable of intelligently perceiving, recognizing, grasping, and manipulating objects. One approach attempts to solve these problems by applying knowledge concerning biological systems, because they demonstrate that machines are indeed capable of performing the tasks.

Feedback from a variety of sensory receptors provides an important source of information that contributes to the considerable flexibility and intelligence with which biological systems perceive and act on the world. In keeping with this fact, a variety of sensors are being designed for the current generation of robots to provide different forms of sensory feedback (e.g., visual, tactile, kinesthetic). With respect to touch, contact sensors or sensors that pick up force information distributed over an array of sensing elements may be mounted on a standard two-fingered gripper of a robot; articulated hand(s) with three or four fingers have also been designed to provide kinesthetic information from position and force sensors at the joints, as well as contact or array forces, vibration, and thermal information from additional sensors mounted on the hand.

These attempts must address enormously challenging and complex issues, such as the specifics of hardware implementation, sensor performance, the integration of multiple and varying sensor inputs, the selection and sequencing of exploratory movements, and the nature of object representations and their underlying processes.

Acknowledgments

The author would like to thank Jack Loomis and Chuck Vierck for their helpful comments and suggestions on an earlier draft. This work was supported by a grant awarded by the Natural Sciences and Engineering Research Council of Canada.

Bibliography


