THE HAND AS A PERCEPTUAL SYSTEM

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The hand is a truly marvellous organ. We use it to explore, perceive and recognize surfaces, objects, and their properties. We also use the hand—sometimes on its own, sometimes with tools—to stably grasp, transport and manipulate objects. The focus of the current chapter is on the sense of touch, with emphasis on the perceptual functions of the hand and the role that manual exploration serves in perception, rather than action per se.

The tactual system is usually divided into the cutaneous (or tactile) and haptic subsystems (Loomis and Lederman 1986). The cutaneous system uses sensory inputs obtained from receptors embedded in the skin. The haptic system uses not only cutaneous information, but also kinesthetic information from receptors in muscles, tendons and joints.

While kinesthesia is used to sense position and movement of our limbs in space and is an important sensing system in its own right, for present purposes we have chosen to focus on its role within haptic perception, particularly with respect to the hand. The interested reader may learn more about the kinesthetic system by reading the reviews by Clark and Horch (1986) and Jones (1986).

The cutaneous system

BEHAVIOURAL RESEARCH

Cutaneous sensitivity and resolving capacity

Many studies have measured the sensitivity of the human hand to variation in intensive, spatial and temporal stimulation.

- **Intensive.** The approximate minimum force that is required to detect the application of nylon monofilaments to the hand ranges from about 0.0037 N (distal phalanges of the thumb and fingertips) to about 0.008 N (centre of the palm) in young adult male and female subjects (Weinstein 1968).

- **Spatial and temporal.** It has been proposed (e.g. Lederman and Loomis 1986) 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 or all of its spatial and temporal information as a result of such filtering.

The spatial acuity of the skin (that is, its spatial resolving capacity) has been measured in a variety of ways. The classical two-point touch threshold (i.e. the minimum gap between two stimulus points that can be resolved as two separate sensations) is typically between
2 and 3mm on the distal volar portion of the fingers or thumbs (Weinstein 1968). With newer techniques, however, considerably smaller values have been obtained—about 1mm (Loomis 1979, Johnson and Phillips 1981, Sathian and Zangaladze 1996). There is little evidence of any strong lateral asymmetries in the skin’s resolving capacity, as is true of most other simple sensations (Summers and Lederman 1990).

The temporal acuity (or more formally, temporal resolving capacity) of the skin has also been measured in a variety of ways. One such measure, vibrotactile thresholds, indicates that adults are differentially sensitive to frequency, which is the inverse of cycle duration. The function relating absolute vibrotactile threshold to vibratory frequency is relatively flat between 0.4 and 3.0 Hz; it then declines slowly up to about 40 Hz at the rate of approximately −5 dB/octave; finally, it decreases more rapidly at the rate of −12 dB/octave until 200–300 Hz, at which point it begins to rise again up to around 500 Hz (Bolanowski et al. 1988).

The hand is poorer than the eye and better than the ear at resolving fine spatial details. In contrast, it is poorer than the ear and better than the eye at resolving small temporal differences. Measures of cutaneous sensitivity and acuity are important in setting norms for clinical assessment of hand function, and in designing tactile aids and prostheses as substitutes for a missing or deficient sensory system (Sherrick 1991).

Studies have also compared perception resulting from passive stimulation of the stationary hand with that effected by voluntary movement of the hand, to determine the contributions of cutaneous and/or kinesthetic inputs. Some percepts only require cutaneous inputs from receptors in the glabrous skin of the human hand—roughness (Lederman 1981, Johnson and Lamb 1981), softness of deformable surfaces (Srinivasan and LaMotte 1994; but note the special role for kinesthesia below), and the identification of 2D fingertip-size spatial patterns (Grunwald 1965).

• **Roughness/smoothness.** Investigators have used a wide variety of surfaces with raised elements to evaluate the relation between perceived and physical roughness (e.g. sandpapers—Stevens and Harris 1962; metal gratings—Lederman 1974; plastic 2D dot patterns—Lederman et al. 1986, Sathian et al. 1989, Connor and Johnson 1992). Perceived roughness generally tends to increase as a function of increasing inter-element spacing up to about 3.5 mm, although there is some debate as to whether the roughness of surfaces with larger inter-element spacings can be evaluated similarly, if at all, since some individuals seem uncomfortable judging roughness under such conditions. Perceived roughness tends to decrease as a function of increasing element width (Lederman 1974). Finally, it is independent of spatial period (for gratings, defined as the width of 1 groove + 1 ridge) and of hand speed during surface exploration (Lederman and Taylor 1972, Lederman 1983).

• **Hardness/softness.** Harper and Stevens (1964) showed that perceived hardness and softness increase and decrease as power functions of physical compliance (force/indentation), respectively, with exponents of +0.8 and −0.8, respectively. More recently, Srinivasan and LaMotte (1994) evaluated the perceived softness of two sets of stimuli. Subjects ranked one set of deformable rubber stimuli in terms of perceived softness using unconstrained
exploration; their judgments correlated perfectly with the objectively measured compliance of the rubber specimens, and proved to be based on cutaneous cues alone. Softness discrimination of these same deformable stimuli was also based solely on cutaneous cues. In contrast, the subjects used both cutaneous and kinesthetic cues to judge the relative softness of pairs of deformable objects with rigid surfaces.

- **Temperature.** Thermal sensations can be considered as static or dynamic, depending on whether the skin temperature producing them is held constant or altered. In general, static responses to sustained skin temperatures can be divided into two categories: (1) when the skin temperature is maintained within the range of physiological zero (approx. 30–36°C for an area of stimulation of 15 cm²), the thermal sensation may completely adapt—the observer no longer experiences any thermal sensation; (2) with static temperatures above (up to about 45°C) or below (down to about 18°C) the zone of physiological zero, thermal sensations do not adapt—people continue to experience warm and cool sensations, respectively. Dynamic responses to rapid changes in skin temperature can be divided into two corresponding categories: (1) within the interval of physiological zero, a relatively quick increase or decrease in skin temperature results in the sensation of warm or cool, respectively; (2) when the adapting skin temperature is above the region of physiological zero, increasing or decreasing skin temperature will produce corresponding sensations of increasing or decreasing warmth (rather than coolness). Conversely, when the adapting skin temperature is below the region of physiological zero, decreasing or increasing skin temperature will produce corresponding sensations of increasing or decreasing coolness (rather than warmth). [For further details, see Kenshalo (1984) and Stevens (1991).] Thermal considerations are important, not only with respect to sensitivity, but also because of higher-level property information about object material (e.g. wood, metal) via differences in thermal conductivity.

- **Weight.** The perception of weight (or force) early on was regarded as the primary responsibility of the kinesthetic system (see below). In general, the magnitude of weight perceived tends to increase as a power function of the lifted mass, with an exponent of approximately 1–2 (Jones 1986). However, recent studies suggest an additional role for cutaneous processing. For example, Aniss et al. (1988) used cutaneous anesthesia to demonstrate an effect on perceived heaviness. More recent research by Flanagan et al. (1995) suggests that increasing slip between the fingertips (thumb, forefinger) results in an increased estimate of weight. Alterations in slip were produced by varying coefficient of friction between the fingertips and the contact surface (silk vs sandpaper). Ellis and Lederman (1998) have further implicated a role for cutaneous cues (slip and/or material) by showing a haptic material–weight illusion: observers tended to judge cubes made of aluminum, wood and styrofoam, constructed to have the same mass (about 60g), as increasing in perceived weight from aluminum to styrofoam. Finally, thermal influences on perceived weight have been shown by Stevens (1991). The importance of both cutaneous and kinesthetic cues suggest that the processing is more formally the domain of the haptic system, discussed below.
• **2D geometric pattern.** A number of studies have examined the accuracy of tactile pattern recognition when various 2D geometric patterns are applied to the distal fingertip (e.g. Loomis 1981, Phillips et al. 1983). A range of patterns has been presented, including braille, roman characters and abstract geometric forms. Further details of cutaneous performance are provided in a review of this work by Loomis and Lederman (1986), who argue that the spatial resolving capacity of the skin plays a large role in constraining the tactile recognition of fingertip-size patterns.

• **3D curvature.** Goodwin and Wheat (1992) showed that subjects are able to detect small differences in spherical curvature when objects are applied to the passive fingertip. Weber fractions (ratio of just noticeable difference in intensity to initial stimulus intensity) for curvature of about 15% were reported (see also Gordon and Morison 1982). LaMotte et al. (1994) have suggested that the characteristic geometric pattern of stresses and strains created by applying stimulus forms (e.g. spheres, ellipsoids) with different degrees of curvature to the fingertip is the proximal cutaneous stimulus to which the mecanoreceptors respond.

• **2D orientation.** In their 1994 study on curvature, LaMotte et al. also included some psychophysical data on the perception of orientation of ellipsoids applied to the fingertip. Their subjects were able to identify all six orientations of an ellipsoid with a vertical radius of 5mm along one axis, and 1mm along the orthogonal axis. Orientation varied from 0 to 150°, in 30° steps, with the 0° axis orthogonal to the longitudinal axis of the finger. Performance declined for a second ellipsoid with a larger radius along the orthogonal axis, which was therefore more spherical.

UNDERLYING NEURAL MECHANISMS AND CODES

In this section, we present a selected analysis of what is currently known about the cutaneous mechanisms and underlying codes used to represent the cutaneous percepts described above. The material is intended as a basic reference source with enough information for the reader to grasp key issues discussed in the primary sources referenced.

Most of the neurophysiological work has involved single-unit recordings in monkeys, whose nervous system strongly resembles that of humans in both structure and function. Most studies have focused on the first stage of processing by peripheral mecanoreceptor units (neurons with specialized end organs that respond to mechanical stimulation) in a single fingertip. Four populations of first-order afferents have been identified in humans, three in monkeys. Slowly adapting units are generally referred to as SA units in monkeys, where it is not possible to differentiate them any further. More recently, some cortical recording has also been carried out.

In the glabrous skin of the human hand, the four peripheral mecanoreceptor populations are known as FAI, FAII, SAI and SAII tactile units. FA and SA refer, respectively, to fast and slow adapting units. The relative speed describes the fact that when the receptive fields of these peripheral units are stimulated, the FA units respond only to transient changes in the stimulus (i.e. to onset and sometimes to offset, but not to sustained stimulation), whereas the SA units respond to stimulus onset and, uniquely, to sustained stimulation in proportion
to the stimulus intensity. The FA and SA units are each further differentiated in terms of the size of the receptive field. Type I units have small, well-defined receptive fields; type II units have very large, poorly differentiated fields (Valbo and Johansson 1984). It has been either directly demonstrated or presumed that each type of afferent unit terminates in a non-neural encapsulated ending, lying in specific locations within the dermal and subcutaneous layers of skin.

- **Roughness/Smoothness.** Hsiao et al. (1993) have argued that roughness percepts are coded in the somatosensory system by SAI neurons. Their work (e.g. Connor et al. 1990, Connor and Johnson 1992) suggests that as the hand scans a surface, the SAI peripheral afferents produce an isomorphic representation of the textured surface in their firing pattern, which is passed to area 3b in SI somatosensory cortex. Cortical SA units with receptive fields having spatially separated regions of excitation and inhibition compute local spatial variation in the peripheral image over a range of about 2mm. Neurons in SII cortex then integrate the discharge rates in the relevant 3b neurons to produce the signal used for roughness discrimination. [See also work by Sinclair and Burton (1988, 1991), Sathian et al. (1989) and Goodwin and John (1991).]

- **Hardness/Softness.** To our knowledge, there is no published work on the neural processing of softness and hardness. As discussed above, research by Srinivasan and LaMotte (1994) implicates the need for cutaneous information in softness discrimination of deformable surfaces; both cutaneous and kinesthetic inputs appear necessary for discriminating compliant objects with rigid outer surfaces. Those authors speculate on the differential involvement of the various mechanoreceptor populations in coding softness (particularly the SAI units), although they come to no firm conclusions.

- **Temperature.** Two distinct classes of thermally sensitive peripheral afferent units in monkeys respond to graded thermal intensity. These are described as 'warm' and 'cold' fibres. [For details, see reviews by Sumino and Dubner (1981), Kenshalo (1984).] There are no known non-neural terminal structures that aid thermal transduction (cf. FAI, FAlI, SAI and SAlI mechanoreceptor units, whose encapsulated endings are involved in mechanical transduction). The response profiles of both populations to steady state and changing skin temperature have been determined for many of the same parameters examined in the study of human thermal sensations. Sumino and Dubner (1981) claim that the parallels observed between the response characteristics of the warm and cold peripheral afferent populations and human sensitivity to thermal stimulation are directly related to the physical characteristics of thermal primary receptors.

- **Weight.** Weight perception is generally attributed to information provided by kinesthetic inputs (Clark and Horch 1986, Jones 1986). However, the effects of slip and material on illusory weight perception (Flanagan et al. 1995) and skin temperature (Stevens 1991), and the effects of skin anesthesia (Aniss et al. 1988) further implicate roles for mechanoreceptor and possibly thermoreceptor populations in the hand.

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2D pattern. Johnson and his colleagues (e.g. Johnson and Lamb 1981) have demonstrated isomorphic representations of letter patterns scanned across the skin of monkeys’ fingertips in the peripheral SA response profiles; FAI units showed less distinct spatial representations, while FAII and SAI units are not feasible candidates because of their relatively low innervation densities. More recently, these investigators (Johnson et al. 1990) have studied the response of cortical units in areas 3b and 1; the responses of separate neurons were typified more by heterogeneity than homogeneity. By the time the information reaches the SA neurons in areas 3b and 1, it has undergone a series of spatial transformations such that the original isomorphic representation of the stimulus pattern is no longer available.

3D shape. On the basis of several studies (e.g. LaMotte and Srinivasan 1987, 1993; Srinivasan and LaMotte 1987; LaMotte et al. 1992, 1994), it was concluded that the spatial parameters of a population of peripheral SAI units determine the overall spatial information about object shape, defined as a spatial distribution of local curvatures. Intensive parameters of the SAI discharge to static or scanned objects and of the FAI discharge to scanned objects underlie fine discrimination of curvature differences for objects of the same shape class. In these studies, curvature was altered by applying half-sinusoidal steps of varying steepness and curvature, parallel cylindrical rods varying in spacing, and ellipsoidal objects to the finger. The stimuli were either vertically impressed into the fingertip or horizontally scanned across it.

2D orientation. In their 1992 study, LaMotte et al. also showed that the planar orientation of 3D ellipsoidal objects is coded by the peripheral SA units: the rate of SA firing increases with stimulus orientation.

The haptic system
In recent years, increasing attention has been devoted to the haptic system, a perceptual system that uses both cutaneous and kinesthetic inputs to derive information about the world of surfaces and objects and to interact with them. Because of space constraints, we will focus on selected aspects of our own research programme on manual exploration, haptic perception and haptic object recognition. This section is divided into three principal parts. The first part discusses the order in which perceptual object properties become available for further processing following only a brief contact. The second examines the consequences of such limited contact for haptic object identification. The final part considers the nature and perceptual consequences of more extended manual exploration. [For a contrasting dynamical approach to haptic perception, see Turvey (1996).]

Relative Availability of Coarse Property Information from a Brief Contact
The work we report here derives from an experimental paradigm, first introduced by Anne Treisman (e.g. Treisman and Gormican 1988) to suggest candidates for early visual features ("primitives"), which are likely to be coded during very early stages of visual processing. Subjects are asked to search for a designated target (e.g. a dark patch) among varying
numbers of distractors (e.g. light patches). When the search function describing response time as a function of increasing display size is flat, the target feature is said to ‘pop out’, and visual processing of that feature across the entire display is said to be performed in parallel. In other words, the observer is able to process the entire display at once. Treisman suggested that such features might be considered reasonable candidates for visual primitives. In the haptics domain, we (Lederman and Klatzky 1997, Klatzky and Lederman 1998) have been interested in two related questions, namely: what object ‘properties’ (i.e. conscious perceptual representations of objects rather than features) are available from a very brief haptic glance, say, of the order of about 200ms, and, does such information become consciously accessible in any particular order?

Fig. 2.1. Schematic of the mechanical components contained within the wooden cabinet. (A) Enlarged view of hand/finger rest: (1) hand rest, (2) thumb switch, (3) finger-position marker, (4) finger rest, (5) finger-rest adjustor. (B) View of entire assembly: (6) stimulus drum, (7) facet (with stimulus), (8) indexing motor, (9) right auxiliary platform, (10) lift platform, (11) lift motor, (12) base plate, (13) left auxiliary platform, (14) slide plate, (15) hand-rest adjustment screw. (Reproduced by permission from Moore et al. 1991.)
TABLE 2.1
Search discriminations

<table>
<thead>
<tr>
<th>Material</th>
<th>Abrupt surface discontinuities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth vs Rough</td>
<td>Edge (Vertical vs No-edge bar)</td>
</tr>
<tr>
<td>Hard vs Soft</td>
<td>Edge (Horizontal vs No-edge bar)</td>
</tr>
<tr>
<td>Cool vs Warm</td>
<td>Hole (Cylindrical vs No hole)</td>
</tr>
<tr>
<td>Moderately smooth vs Rough</td>
<td>Shallow vs Deep (hole)</td>
</tr>
<tr>
<td></td>
<td>Moderately Shallow vs Deep (hole)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative orientation</th>
<th>Continuous 3D surface contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left vs Right (relative position)</td>
<td>Curved vs Flat</td>
</tr>
<tr>
<td>Horizontal vs Vertical (2D bar)</td>
<td>Slant (3D ramp) vs Flat</td>
</tr>
<tr>
<td>Left vs Right (2D bar)</td>
<td></td>
</tr>
<tr>
<td>Left vs Right (slanted 3D ramp)</td>
<td></td>
</tr>
</tbody>
</table>


distributed around its circumference to which various stimuli could be attached (e.g. rough or hard patches, raised bars, etc.). Two of the facets around each drum were removed to create a ‘blank’ (i.e. no stimulus), when required. To prepare each stimulus display, the drums were simultaneously rotated until the desired facets were facing upwards. The stimulus displays were prepared with the platform in its lowest position. At the appropriate time, the entire platform was raised by a stepper motor until the display contacted the outstretched fingers.

On each trial, a display consisted of from one to six stimulus items, presented to various finger combinations, with the remaining fingers contacting nothing at all (i.e. a blank). Subjects were informed that on half the trials a designated target (e.g. rough) would be present; on the other half of the trials, the target would be absent. Subjects had to indicate with thumb switches whether the target was present or not. Recorded response times were used to derive haptic search functions that reflected response times (averaged over all subjects) as a function of the number of items in the display.

The perceptual dimensions tested were organized into four categories, as shown in Table 2.1: material (rough/smooth, hard/soft, warm/cold), abrupt surface discontinuities (edge/no edge, hole/no hole), geometric relations (2D horizontal/vertical, 2D left/right orientations of a raised bar; 2D left/right position of a raised element relative to a central indentation; 3D right/left orientation of a ramp), and 3D continuous surfaces (curved/flat, ramp/no ramp). The target and distractor values were always selected to be as perceptually distinct as possible. Thus, the following results and interpretations refer specifically to the haptic discrimination of coarse differences in property values.

The slopes of the regression lines fit to the linear search functions are presented in Table 2.2. The slopes indicate how much additional processing time was required for each additional finger stimulated. A flat function indicates that subjects processed all items in parallel. We interpret such low slopes as indicating relatively early property accessibility. In contrast, a non-flat function indicates that an additional processing load, measured by the slope, was added for each finger, indicating processing at a finger-by-finger level. An examination of Table 2.2 reveals that processing time was relatively short for all material
<table>
<thead>
<tr>
<th>Target/Distractor</th>
<th>Mean slope (ms)</th>
<th>Target/Distractor</th>
<th>Mean slope (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td>Abrupt surface discontinuities</td>
<td></td>
</tr>
<tr>
<td>Rough vs Smooth(^1)</td>
<td>3.7</td>
<td>Cylindrical hole vs No hole(^1)</td>
<td>-1.8</td>
</tr>
<tr>
<td>Hard vs Soft</td>
<td>8.3</td>
<td>Edge (horiz.) vs No edge</td>
<td>4.3</td>
</tr>
<tr>
<td>Soft vs Hard</td>
<td>10.4</td>
<td>Edge (horiz.) vs No edge</td>
<td>11.5</td>
</tr>
<tr>
<td>Cool vs Warm(^1,2)</td>
<td>30.2</td>
<td>Edge (vert.) vs No edge</td>
<td>17.2</td>
</tr>
<tr>
<td>Smooth vs Rough</td>
<td>36.1</td>
<td>No edge vs Edge (horiz.)</td>
<td>17.3</td>
</tr>
<tr>
<td>Relative orientation</td>
<td></td>
<td>Deep (hole) vs Shallow</td>
<td>22.6</td>
</tr>
<tr>
<td>Horizontal vs Vertical (planar orientation)</td>
<td>57.2</td>
<td>No hole vs Cylindrical hole</td>
<td>56.3</td>
</tr>
<tr>
<td>Vertical vs Horizontal (planar orientation)</td>
<td>90.8</td>
<td>Shallow (hole) vs Deep(^1)</td>
<td>63.0</td>
</tr>
<tr>
<td>Right (2D) slant vs Left (2D) slant</td>
<td>101.4</td>
<td>3D continuous surface</td>
<td></td>
</tr>
<tr>
<td>Left (2D) slant vs Right (2D) slant</td>
<td>116.8</td>
<td>Curved vs Flat</td>
<td>42.1</td>
</tr>
<tr>
<td>Left (3D) slant vs Right (3D) slant</td>
<td>182.5</td>
<td>Flat vs Curved</td>
<td>44.6</td>
</tr>
<tr>
<td>Right (3D) slant vs Left (3D) slant</td>
<td>189.5</td>
<td>Flat vs Slanted (3D)</td>
<td>57.6</td>
</tr>
<tr>
<td>Right vs Left (position relative to a central indentation)</td>
<td>439.4</td>
<td></td>
<td>289.1</td>
</tr>
<tr>
<td>Left vs Right (position relative to a central indentation)</td>
<td>463.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Reproduced by permission from Lederman and Klatzky (1997).

\(^1\)Indicates evidence of a perceptual asymmetry.

\(^2\)Indicates that ‘Warm’ was not used as a target.

and most abrupt surface discontinuity tasks, regardless of the number of fingers stimulated. In contrast, it took increasingly longer, sometimes quite substantially so, to process geometric relations as the number of items in the display increased. The extremes are presented in Figure 2.2, which shows the combined slopes for the target-present and target-absent conditions for the rough vs smooth and right vs left relative-position tasks. The slopes for the continuous 3D surface discriminations fell somewhere in between.

We suggested that dimensions that can be performed in parallel, or at least nearly so, are processed ‘intensively’. By intensive, we mean that the stimulus is encoded solely in terms of its relative magnitude along the relevant perceptual dimension with no additional reference to any spatial coordinate system, whether egocentrically or exocentrically defined. We consider both the material and edge-discontinuity dimensions to be intensively coded dimensions. In contrast, we propose that properties that are encoded ‘spatially’ do require some spatial coordinate system, and consider the geometric relations tasks as examples of spatial dimensions. The status of the continuous 3D surface dimensions remains uncertain.

In conclusion, we propose that when only a brief contact interval is permitted, properties that are encoded intensively (such as material properties and the presence vs absence of edges) are accessible for further processing relatively earlier than those that are encoded spatially.
Fig. 2.2. Mean response time as a function of display size for both target-present and target-absent conditions. (Top) Rough vs smooth; (bottom) right vs left position relative to a central indentation. $T =$ target; $D =$ distractor. (Reproduced by permission from Lederman and Klatzky 1995.)

**RECOGNIZING COMMON OBJECTS FROM A BRIEF CONTACT**

We also wished to determine the level of object recognition possible with brief contact, that is, with just a brief haptic 'glance'. From the findings reported above, we might expect that with only coarsely coded intensive variations and coarsely distinguished local edge orientations, no recognition would be possible, particularly with objects larger than finger span that do not permit a full volumetric representation. Moreover, our previous research (Klatzky et al. 1985) indicated that subjects most frequently took about 2–3 seconds to successfully identify common objects in unconstrained search.
To address this issue, we (Klatzky and Lederman 1995) required subjects to identify a series of common objects with a very brief presentation. The objects were differentiated by two levels of size (horizontal axis within or beyond the width of the middle fingers) and two of diagnostic property (texture, shape), which had been obtained from a rating of the informativeness of various properties when identifying an object by touch (Lederman and Klatzky 1990). The amount of object information provided at the beginning of the trial was also varied. In the low-information condition, no advance cue was used. An example of the question asked in this condition is: “What is it?”. The intermediate-information condition provided a superordinate-level cue prior to the object’s presentation. Superordinate-level classification is the most inclusive level at which objects are classified (Rosch 1978). An example of the experimental question is: “It’s a container top: what is it?”. The highest-information condition used an advance cue in the form of a possible basic-level name. People most typically classify objects at this level (e.g. pen, pencil). An example of this type of question is: “Is this container a glass—yes or no?”. After receiving the cue, if any, the subject followed a vertical guide to the object and touched it without movement until an auditory signal indicated that the hand should be withdrawn. A force-sensitive board beneath the object allowed the time from initial contact to the auditory signal to be controlled. In two different conditions, times of 200 ms and 3000 ms were used. Objects were placed on the board so that contact would be made with their most informative feature(s). After withdrawing the hand, the subjects attempted to name the object (or, in the basic-level cue condition, said yes or no) and gave a rating of their confidence.

The most important finding of this experiment was that people could identify objects from a single haptic glance. With no advance cue and only 200 ms exposure duration, accuracy varied from 5 per cent (large objects with shape most diagnostic) to 25 per cent (large objects with texture most diagnostic), for an average accuracy of 15 per cent. We expected poor performance for the large/shape objects, as the diagnostic shape cues extended beyond the contact area. But clearly, the haptic system capitalizes on fairly accurate perception of intensively coded properties and local shape as input to data-driven processing. However, advance cueing further improved performance. While it was not possible to compare the effects of advance cueing on accuracy, given differential guessing rates in the three cue conditions, confidence increased significantly with cue informativeness. Moreover, an analysis of confusion errors (i.e. misnaming responses) indicated greater structural and material similarity to the target item when the superordinate cue was given than with no cue. The improved performance with advance cueing suggests that we use top-down processing to compensate for impoverished inputs.

**PROCESSING PRECISE INFORMATION FROM EXTENDED MANUAL EXPLORATION**

*Exploratory procedures*

In the speeded haptic search tasks described in the previous section, the intensively coded coarse property information could often be extracted without extended hand movements; the coarse geometric relations features in the pop-out tasks required brief sequential motions. Additional research results indicate, however, that extended hand movements of the order of seconds, as opposed to milliseconds, are necessary when more precise property information
Fig. 2.3. Exploratory procedures (EPs) and associated object properties. (Adapted by permission from Lederman and Klatzky 1987.)

is required. Accordingly, in this section we emphasize how critical manual exploration is for haptic perception and object recognition.

We became interested in manual exploration when we demonstrated (Klatzky et al. 1985) that adults could recognize a large number of common objects both highly accurately (close to 100 per cent) and quickly (most often in 2–3 s) using only touch. We began to suspect that what people did with their hands might account for such good performance.

Accordingly, we (Lederman and Klatzky 1987) had subjects perform a task in which they were first presented with a multidimensional object, the standard, and told to explore it to learn about a designated property (e.g. hardness). Next they were presented with a set of three comparison objects, and asked to explore each in turn and to decide which of the three best matched the standard in terms of the property to which they were attending. On each trial, the hand movements were videotaped.

The properties considered are shown in Figure 2.3. We found that subjects were highly systematic in their manual exploration strategies. They performed a variety of different stereotypical hand movement patterns, which we have called ‘exploratory procedures’ or EPs. Each procedure can be described by its necessary and typical features, and in addition, is selected on the basis of a particular object property that is desired. Caricatures of the six exploratory procedures we have studied in greatest detail to date are depicted in Figure 2.3,
TABLE 2.3
EP-to-property weightings, generality, and average duration for each EP*

<table>
<thead>
<tr>
<th>Property</th>
<th>Lateral Motion</th>
<th>Pressure</th>
<th>Static Contact</th>
<th>Unsupported Holding</th>
<th>Enclosure</th>
<th>Contour Following</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hardness</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Temperature</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Weight</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Volume</td>
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<td>0</td>
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<td>1</td>
<td>2</td>
<td>1</td>
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<tr>
<td>Global Shape</td>
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<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Exact Shape</td>
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<td>0</td>
<td>0</td>
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<td>3</td>
</tr>
<tr>
<td>Generality</td>
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<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Duration (s)</td>
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<td>2.24</td>
<td>0.06</td>
<td>2.12</td>
<td>1.81</td>
<td>11.20</td>
</tr>
</tbody>
</table>

*Reproduced by permission from Lederman and Klitzky (1990).

along with the properties each most commonly extracts (for additional details, see Lederman and Klitzky 1987). The set of EPs shown include: Lateral Motion, Pressure, Static Contact, Unsupported Holding, Enclosure and Contour Following.

In a version of the match-to-sample task above, we next constrained our observers to use a designated EP in conjunction with a particular property-matching instruction, such as: match for texture using Unsupported Holding. Across the entire experiment, we paired each of the six EPs with each of the texture, hardness, thermal, weight, size and shape instructions, and recorded accuracy and response times. For each property, relative EP performance was ordered in terms of accuracy (and in the case of a tie, response times). The results are presented in Table 2.3. A ‘0’ indicates that for a given property, the EP only performed at chance level; a ‘1’ indicates the EP was sufficient for the task; a ‘2’ connotes that the EP was not only sufficient, but also optimal for extracting that property; and a ‘3’ indicates that the EP was sufficient, optimal and also necessary, as is Contour Following for precise shape. We now see that the EPs that were freely selected in the unconstrained match-to-sample task were in fact those that were found to be either optimal or necessary in the constrained manual exploration experiment. The optimal/necessary EPs provide the most precise information about property variation.

The data in Table 2.3 also indicate the extent to which each EP provides information about more than just the property that it extracts most precisely. Counting the number of non-zero cells in a row indicates the total number of properties for which that EP is sufficient. Thus, Lateral Motion and Pressure are narrowly sufficient, inasmuch as they both provide sufficient information about three properties in all. Contrast them with Enclosure and Contour Following, which are very broadly sufficient since they provide information about almost all of the properties in question. However, there is a cost to executing a Contour Following procedure, as is evident in Table 2.3, which also shows the mean durations (across all subjects and a variety of object sets) used in the unconstrained exploration experiment first described.
In addition to learning about the relative efficiency and breadth of sufficiency of each EP as just described, we have also considered the extent to which pairs of EPs are compatible (i.e. can be executed at the same time). Each EP was initially profiled in terms of the values pertaining to four relevant EP parameters determined to differentiate the set of EPs from one another. These four parameters include type of force (static vs dynamic), direction of force (normal vs tangential), primary area of contact (edges vs interior surface vs both), and finally, whether or not a supporting surface is required. EP compatibility was determined by comparing the extent to which the EP profiles matched. When the set of parameter values matched, or more commonly, if some form of manual exploration could be performed that overcame any discrepancy across the parameter constraints, the pair of EPs were considered compatible. For example, although Static Contact usually requires a steady or static force and Enclosure a dynamic force, the constraints of both EPs may be achieved by performing an Enclosure. [Details of our EP compatibility analysis are available in Klatzky and Lederman (1993).]

**Perceptual Consequences of Manual Exploration**

*Haptics without vision*

The EP characteristics that we have just discussed can be thought of as constraints that people consider in choosing how to explore manually, given a specific circumstance. For example, a person's immediate goal(s) may dictate how s/he haptically explores the environment. Already, we have shown that if fairly detailed information about a particular property is desired, then a person will select the EP that provides the most precise information about that property (e.g. Lateral Motion for texture). We have already described how this happens when a person is specifically instructed to look for a particular property (e.g. Lederman and Klatzky 1987).

We also thought it might happen when a person seeks to identify an object by focusing on the dimension known to be most diagnostic of that object class. For example, in a cued-identification task (Lederman and Klatzky 1990), we asked subjects to decide whether an object that was a member of a given object class, X (e.g. an abrasive surface), was also a member of a less-inclusive subclass, Y (e.g. sandpaper). In only one-half of the trials was the X placed in their hands also a Y. We analyzed the patterns of manual exploration by examining the sequence in which our subjects executed various EPs. We discovered that they explored in a manner that involved a two-stage sequence of exploratory procedures.

Regardless of the object class named, Stage 1 involved subjects executing some version of a grasp-and-lift routine (i.e. Enclosure, Unsupported Holding). Both of these EPs are fairly broadly sufficient and relatively quick (see Table 2.3). We suspect that Stage 1 is probably performed irrespective of whether or not the subject is cued as to the object's possible identity, because it provides a considerable amount of information in a relatively brief time. In Stage 2, subjects subsequently executed one or more EPs (e.g. Lateral Motion) that provided the most precise information about the property that was most diagnostic of the designated subclass, Y. Additional research allowed us to determine which EP was most diagnostic of each object class in our experiment. Accordingly in our example, since roughness proved to be most diagnostic of sandpaper, we also predicted that our subjects were
likely to perform a Lateral Motion EP, which has been shown to be the best method for obtaining precise information about roughness (see Table 2.3).

**Haptics with vision**

Thus far, we have only considered manual exploration, haptic perception and identification when vision is not available. However, frequently both modalities are accessible simultaneously. Studies by Klatzky et al. (1987) and Lederman et al. (1996) have shown that vision and haptics tend to complement one another in the property information that is emphasized and used to represent the object. In the 1987 study, subjects were asked to sort planar objects that varied in perceptually equivalent intervals across four dimensions: roughness, hardness, shape and size. Groups of subjects manually sorted objects into three piles according to one of the four following instructions. The ‘unbiased haptics’ group was simply told to sort objects that were most similar into the same pile. The ‘biased haptics’ group was told to sort objects that felt most similar into the same pile. The ‘visual imagery’ group was told to sort on the basis of the similarity of their visual images. Like the unbiased haptics group, the ‘haptics + vision’ group was told to sort only on the basis of how similar the objects seemed. The results of the three-pile sorts revealed which dimensions subjects were using to make their judgements, since for each of the four dimensions, a given stimulus object had one of three values on each of the four dimensions. Thus, choosing to sort objects solely by one dimension meant that they could not be sorting by any of the others. The results indicated that when vision was available (either real or imagery-based), subjects chose to sort primarily by shape; the haptically biased and unbiased subjects, however, emphasized the objects’ material properties—hardness and texture.

This finding was replicated and extended in the 1996 study to include other material variations—thermal cues and weight—by altering the material used to construct the objects. This study further demonstrated that the tendency to base haptic similarity judgments on material was a general bias that did not require specialized exploration for material properties in order to occur. In this case, the discriminations were so simple that optimal EPs were not required, nor were they performed; yet the haptically biased and unbiased subjects still emphasized material properties when sorting the objects.

Therefore, when subjects are free to use variation on any property to sort objects by perceived similarity, they choose to sort by variations in material properties. Apparently, this bias reflects general experience in which the optimal EPs for extracting material information are more accurate and rapid than those used to extract geometric information. The results thus complement our earlier findings concerning the earlier availability of material, as opposed to geometric, properties.

**EP compatibility and perceptual gating**

EP selection is also critical in that, once chosen, the given EP(s) determine which properties and what level of precision are available for further processing. In other words, the EPs serve as ‘perceptual gatekeepers’. A given EP will provide some information about those dimensions for which it has been shown to be sufficient (Lederman and Klatzky 1987), and even more information about the dimension(s) for which it is either optimal or necessary.
For example, Lateral Motion provides the most precise information about texture, and also some about both hardness and thermal properties.

In a series of studies (Klatzky et al. 1989, Reed et al. 1990, Lederman et al. 1993), we explicitly explored the consequences of EP compatibility and incompatibility on speed of object classification. The stimulus objects varied in roughness, hardness, shape and size, and were drawn from the same overall set of planar objects used in the Klatzky et al. (1987) study described above. Subjects learned to classify selected object sets into one of three groups on a dimension named by the experimenter (e.g. texture). Across the entire experiment, different redundancy-variation classification rules were used. For a given rule, the set of objects could vary redundantly with 0, 1 or 2 other properties. For example, a two-dimensional redundancy rule involving texture and hardness might be as follows: very smooth objects were also very hard, objects with an intermediate level of roughness were of an intermediate level of hardness, and all very rough objects were very soft.

We found that when two redundant dimensions defined the object sets, if the associated EPs were compatible (e.g. texture and hardness), classification response times were faster than when no redundancy was available. For example, variation in either texture or hardness alone (but not in both) produced faster classification times.

Additional experiments further confirmed our interpretation. For example, in one experiment subjects were initially taught to classify objects on a single, experimenter-defined dimension (texture), when the objects actually varied redundantly on two dimensions (e.g. texture and hardness). After this task was learned, and unbeknownst to the subject, information about the non-targeted, second dimension (hardness) was ‘withdrawn’ by holding the value of that dimension constant across a new set of objects. The result was that performance was impaired—apparently, subjects had been using the implicitly redundant information made available via compatible EPs. However, performance was less impaired for both texture/shape and hardness/shape redundancies. The reason is that the primary area of contact during exploration of these planar stimuli differs for shape and material. While EPs for texture (Lateral Motion) and hardness (Pressure) are both performed on homogeneous object surfaces, those for shape (Contour Following and Enclosure) are typically performed along the edges. When the incompatibility was eliminated by using three-dimensional ellipsoids for which shape could be accessed locally at any point on the object, withdrawing redundant shape information impaired performance, as did adding non-redundant shape variation on a second dimension.

Collectively, the research reported in this section emphasizes how manual exploration (i.e. EP selection) determines not only the quality of the information available for further perceptual processing, but also what information is or is not available.

Some developmental issues
While our research has dealt primarily with adults, developmental work by Bushnell and Boudreau (1991) has shown that exploratory procedures are actually first used to haptically access various kinds of object properties during infancy. More specifically, they suggest that the timetable for the development of haptic perception appears to be dictated at its lower bound by the order in which the motoric capabilities needed to perform EPs develop,
followed by cognitive considerations pertaining to what infants want or need to know about an object. The consequence is that infants can haptically perceive thermal and size changes during their first three months of life. Differentiation of texture and hardness appears by about 6 months of age, followed somewhat later by weight perception at around 9–12 months, and finally by shape perception as late as 12–15 months. (For additional information on infant manual exploration and haptic object recognition, see Ruff 1989.)

Recent work by Klatzky et al. (unpublished results) has extended the study of manual exploration and exploratory procedures to preschool children when examining how they assess tool function. In this study, children aged 4 years 7 months were required to judge verbally whether a spoon would serve to carry a target object (small vs large candy) and whether a stick could be used to stir a target substance (sugar vs gravel). As expected, children chose to use vision alone when assessing spoon function; in contrast, they selected an appropriate form of haptic exploration (Pressure EP) when assessing stick function. Presumably, vision is more efficient than touch with regard to estimating the size of the spoon, while touch is more efficient than vision in evaluating the stick’s rigidity. In addition, direct assessment of the children’s perceptual exploration when making comparisons of weight, hardness, roughness, shape and size, confirmed adult patterns. The children used appropriate haptic EPs for the material properties and confined their exploration to vision when judging size and shape, as has been found with adults (Klatzky et al. 1993). Clearly, manual exploration serves an important role for children as well as adults.

Summary and applications
In this chapter, we have focused on the sense of touch, with particular emphasis on the role the hand plays as a perceptual agent. When the hand is stationary and a surface or object is moved across the skin, we will experience a number of subjective sensations. We have concentrated primarily on the hand’s sensitivity, and on the extent to which it can resolve fine spatial and temporal details in stimulation. In addition, we have considered the cutaneous system’s ability to perceive various external object attributes. These experiences derive from particular neural codes, beginning with specific activity in various mechanoreceptor and thermoreceptor populations in the glabrous skin of the hand. While coarse property variation (especially those properties that are intensively encoded) and object identity (to a degree) are available from a single brief contact, more precise information and complex object identification requires the voluntary execution of specific patterns of haptic exploration (exploratory procedures), the selection of which is determined by the observer’s perceptual goals. Thus, actions are performed in the service of perception, and depend upon the haptic system’s processing both cutaneous and kinesthetic inputs. The EPs for extracting intensively coded information, e.g. variations in material properties and presence/absence of edges, are more efficient in both speed and precision than those required to extract spatially encoded information. Presumably this is why we typically prefer to use vision to judge geometric properties, when available.

The data concerning cutaneous sensitivity and the resolving capacity of the hand provide adult norms to clinically assess the extent to which sensory capacity is diminished (e.g. owing to peripheral nerve damage to the hand) and to evaluate the extent of subsequent recovery.
REFERENCES


