The Haptic Glance: A Route to Rapid Object Identification and Manipulation

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ABSTRACT What properties of objects are available from initial contact, and how useful are those properties for determining object identity and guiding manipulation? We begin with a brief review of the neurophysiology of touch, leading us to examine features that are extracted at the sensory periphery. We then consider haptically accessible properties of objects, some of which have counterparts in peripherally coded features. Data from a haptic search task indicate that object properties become accessible in an order proceeding from material, to abrupt surface discontinuities, to spatially coded attributes. An identification task confirms that properties of all three types can be encoded, at least at a coarse level, from a “haptic glance”—brief touch with minimal movement—and indicates the level of identification performance that such information supports. Applications to the design of freestanding objects for manipulation without vision, control panels, and haptic interfaces are described.

A chapter on touch may seem an odd candidate for a volume on “cognitive regulation” of performance. Touch is often discounted as a modality in object recognition, and its role in higher perceptual processes and cognitive function is not usually given much weight. We hope to change those attitudes with this chapter, which concerns the perception of objects and their properties from an initial brief contact. We use the term haptic glance for brief contact with an object involving minimal movement, as would occur when an object is first touched. The principal point of this chapter is that a haptic glance provides information about a substantial number of object properties and hence can support object identification and manipulation.

In everyday life, haptic perception contributes to identifying and manipulating objects more often than we may realize. While using vision for purposes such as viewing text or governing social exchanges, we may also be performing manipulations such as picking up a coffee cup, putting on our eyeglasses, or tying a shoe. While driving, we reach for control knobs or objects without taking our eyes from the road. These manipulatory acts are made possible by haptic processing, in combination with an internal model of the object to be manipulated and the environment in which it exists. In keeping with the theme of Attention and Performance XVI, top-down processing and cognitive regulation play important roles in haptic object recognition, particularly when incoming data are limited by brief contact and minimal exploration.
In our concluding remarks, which consider applications of the research to be described, we will suggest that designers of objects and instruments often fail to capitalize on the efficiency of the haptic system. One of us has a car, for example, with an air-conditioning control knob on which a small patch lights up when the unit is active. Checking on its status requires vision, and in sunlight, foveal vision is needed. The control could easily be designed so that haptic cues would be immediately sufficient to assess functional status, leaving the driver free to watch the road. Other applications of the research reported here can be found in the fields of teleoperation and robotics, as will be described below.

The organization of the chapter is as follows. First, because many cognitive psychologists are unfamiliar with the haptic system, we will first provide a tutorial on the underlying neurophysiology, from which we will draw inferences about features of objects and surfaces currently known to be initially coded in the sensory periphery. We distinguish between those “peripheral features” and various “object properties,” the latter being defined at a higher level of object description. We then describe the systematic movements that people use to extract object properties during extended, free exploration. The more constrained exploration of a haptic glance (i.e., brief contact with minimal movement) is next considered, and we describe property encoding and object identification via such exploration. Finally, we discuss applications of our work to haptic object perception and manipulation.

6.1 HAPTIC CODING AT THE SENSORY PERIPHERY

Haptic Receptors

The haptic system is actually a family of sensory subsystems, based on a variety of receptor populations. It comprises two broad classes of receptors, cutaneous and kinesthetic (Loomis and Lederman 1986). The cutaneous receptors, which reside beneath the surface of the skin, as shown in figure 6.1, include the following: (1) four distinct populations of mechanoreceptors, which have specialized endings and are sensitive to different aspects of mechanical stimulation of the skin; (2) two different classes of thermoreceptors, described as “warm” and “cold” fibers, which respond in a sustained fashion to specific temperature ranges, and in opposite dynamic patterns to changing temperature (see Keshalo 1984); and (3) unencapsulated (free) nerve endings, thought to play a role in pain. The kinesthetic receptors are mechanoreceptors that are found in muscles, tendons, and joints and provide information about the position of limbs and their movement in space. A variety of kinesthetic signals are known to be available, including stretch in ligaments, muscles, and joint capsules, muscle tension signaled by tendon organs, and muscle length signaled by spindles.
Cutaneous Mechanoreceptors

The functional characteristics of the four types of cutaneous mechanoreceptors in the skin of the hand have been characterized by a crossing of two binary-valued parameters: the size of the receptive fields (large or small), and whether the receptor slowly or rapidly adapts (slowly adapting, SA; fast adapting, FA) to continuous stimulation. Each class of receptor that is defined by this $2 \times 2$ classification has been associated (although not definitively) with a particular type of end unit, which can be identified by its gross anatomical structure and location within the skin. The classes are as follows:

$SAI$ receptors  slowly adapting, small receptive fields ($\sim 10 \text{ mm}^2$); associated end units are Merkel disks, which lie at the ends of folds that project deep into the dermis;

$SAII$ receptors  slowly adapting, large receptive fields; associated end units are Ruffini endings, which lie in the dermis;
FAI receptors rapidly adapting, small receptive fields; associated end units are presumed to be Meissner corpuscles, which lie between relatively deep and shallow epidermal pegs that project into the dermis;

FAII receptors (also called "PCs") rapidly adapting, large receptive fields; associated end units are Pacinian corpuscles (PCs) that lie deep within the dermis and subcutaneous tissue.

**Peripherally Coded Features**

We now consider what features, or distinctions in stimulus values, are coded by the peripheral receptors. These "peripheral features," we note, are not necessarily the same as the properties of objects that are used in identification. Early features may be used at initial stages in pattern recognition, for example, to segregate objects from supporting surfaces and one another, to extract edges and surface regions, and to bind those features into a common representation. They also presumably serve as input into higher-order processes that compute properties descriptive of objects; we believe that such higher-level properties are critical to haptic object identification (although peripherally coded features might also play a role).

Peripheral receptors within the haptic system can code stimulus distinctions in several ways. First, there may be different populations of peripheral units that respond maximally to different feature values. This occurs, for example, with the warm and cold thermoreceptors, and by means of differential tuning of the various types of cutaneous mechanoreceptors to stimulus frequency (see below). Second, within a single unit, the output can distinguish further among feature values. Such distinctions can be captured by various intensity codes (e.g., mean discharge per unit time) or by temporal codes (e.g., phase locking to vibratory stimulation, where individual units tend to fire at some multiple of the stimulus frequency). Whereas these first two mechanisms operate at the periphery, at subsequent stages, higher-level units can compute properties of entire populations from lower levels, constituting a higher-order type of feature encoding. We next consider a set of distinctions that are made at the periphery; coding at the population level, particularly for SA1 signals, is discussed subsequently.

All four mechanoreceptor populations respond to skin deformation. The FAIIs, with their short-term response and relatively good spatial resolution, appear to be highly useful in detecting microscopic variations in surfaces (LaMotte and Srinivasan 1991). One possible mechanism for this reflects the position of the FAI end units, which lie to either side of the deep folds that project into the dermis and correspond to inversions of fingertip whorls at the outer surface. LaMotte and Srinivasan (1991) have suggested that the whorls in fingertip skin catch on elevations in a touched surface, stimulating the protrusions into the underlying tissue, and thus activating the contiguous lying mechanoreceptors.
As was noted, the SAI units respond more steadily to sustained stimulation. Pressing an object into the skin induces SA firing, which increases with the amount the skin is indented (Srinivasan and LaMotte 1991). Surfaces of different curvature will deform the skin differentially and produce different peak pressure, holding total force applied to the surface constant (Srinivasan and LaMotte 1991). LaMotte and Srinivasan (1993) found, accordingly, that the SA responses of monkeys increased with the radius of curvature of a cylinder pressed into the skin, and Vierck (1979) found that SA responses in cats increased from flat surfaces to edges to punctate (point) stimulation. Thus the SAs can code presence of a shape gradient. Their response increases with movement of the stimulus across the skin; for example, the discharge rates evoked by a moving dot increase by approximately an order of magnitude relative to stationary indentation (Johnson and Lamb 1981).

Different mechanoreceptor populations are selectively sensitive to different portions of the frequency range (Johansson, Landstrom, and Lundstrom 1982) and may have a peak tuning within that range, providing mechanisms for coarse frequency coding at the periphery. FAI units respond at frequencies between 8 and 64 Hz, that is, to low-frequency stimulation. The FAII units respond best above that range and are maximally sensitive around 200–300 Hz, that is, to relatively high-frequency vibration, such as from vibratory stimulation or transient forces set off by initial contact with an object. The SAI units are most sensitive at very low frequencies (2–23 Hz).

The two types of thermoreceptors make a basic distinction between warm and cold surfaces. Warm receptors respond in a sustained fashion to a range of steady-state temperatures between 30° and 50°C. They increase their response to increasing temperatures and decrease their activity to decreasing temperatures. Cold receptors respond to steady-state temperatures between about 10° and 40°C, with a maximal response at about 29°C. These receptors increase their activity to decreasing temperatures and decrease it for increasing temperatures. The density of cold receptors is greater than that of warm, making us better able to detect cold surfaces. For surfaces that are at ambient temperature, that is, not artificially cooled or warmed, apparent temperature differences reflect the flow of heat from the body to the object (if ambient temperature is less than body temperature) or the reverse (if ambient temperature is greater than body temperature).

Our brief review has isolated a number of stimulus discriminations that appear to be coded by first-order afferents. These constitute primitive features delivered by peripheral cutaneous (skin) receptors. We do not deal here with features that might be coded by receptors in muscles, tendons, and joints, as little is known about the contribution of these populations to the perception of limb position (see Clark and Horch 1986). To date, the following appear to be among peripherally coded stimulus features: (1) presence/absence of vibration; (2) coarse coding of vibrotactile frequency; (3) warm versus cool surface; (4) increasing/decreasing stimulus temperature; (5) net
force (stress) at a location; and (6) presence of a shape gradient, as one would find from a punctate feature, a curved surface, or a step edge.

We wish to stress that in referring to peripheral coding, we do not mean that the computation is completed at the periphery, but rather that a featural distinction can be made at that level. Considerable computation undoubtedly occurs between the peripheral responses of the sensory receptors and the point where an object property is input to an object classification system. Examination of peripheral coding tells us what properties of objects begin to be distinguished very early. Higher levels presumably combine the responses of peripheral units to reduce noise and increase the power of peripherally coded discriminations. For other features, those not distinguished at the periphery, higher-level analysis is needed to derive a code representing the population response as a whole. There has been particular attention to population-level coding of SAI responses, some examples of which we will briefly describe next.

**Coding from SAI Populations**

By virtue of their sustained response and relatively high degree of resolution (about 1 mm), a spatially distributed population of SAI receptors provides an isomorphic representation of the pressure gradient on the skin. This variation in response makes it possible for a population of SA receptors to code the pattern of surface points penetrating the fingertip (as one would find, for example, in a braille symbol) and the degree of curvature in a surface (LaMotte and Srinivasan 1993; Srinivasan and LaMotte 1991; Vierck 1979). The same map is apparently used to code surface roughness at a macro scale (see below). The map provided by the SAI population is passed on to the primary somatosensory cortex, where it is initially represented (area 3b) with sufficient resolution to account for form and roughness discriminations on about a 1 mm scale (Phillips, Johnson, and Hsiao 1988). The map becomes considerably degraded at later cortical stages. Thus, although an isomorphic pattern representation is provided at early stages, higher-order computation is necessary to produce a persisting code that can be passed further into the object recognition system.

**6.2 HAPTIC OBJECT PROPERTIES**

As we have noted and will expand on below, the features coded at early stages of haptic processing are not necessarily the same as the properties of objects. We next discuss what might be a fundamental set of properties at the level of objects. Such properties appear to constitute conscious perceptual representations of objects and to play an important role in haptic object identification (Klatzky, Lederman, and Metzger 1985).

We have approached classifying object properties in a variety of ways: by considering first principles of physics and the materials sciences (Klatzky and
Lederman 1993), by phenomenological reports of subjects who are identifying objects by touch (Klatzky, Lederman, and Metzger 1985), and by examining the variety of hand movements made during object exploration (e.g., Lederman and Klatzky 1987). These approaches converge on a classification that takes on a hierarchical form. We stress that this classification is coarse, such that even the most differentiated property classes incorporate multiple dimensions along which objects might be coded (e.g., surface texture might correspond to roughness, slipperiness, or spatial density).

We first distinguish between geometric properties of objects, which are specific to the particular object present, and material properties, which by definition are independent of any one sampled object. Broadly defined, the geometric properties pertain to size and shape. Object geometry appears to be treated quite differently, however, at two scales within the haptic system. Objects small enough to lie within a fingertip aperture can be apprehended cutaneously, whereas objects that extend beyond it require integration over multiple fingers, over time, or both, bringing in a greater contribution of kinesthesia. Thus we can refer to a macrogeometric and a microgeometric scale, with size and shape represented at each scale.

The material properties we have considered, stated in everyday terms, include texture, hardness (or compliance), and apparent temperature. Like geometric properties, texture can occur at both micro and macro scales. Microtextures are scaled on the order of microns, and macrotextures on the order of tenths of millimeters. Another property of objects is weight, a hybrid that results from both geometry and material density.

The relationships between the distinctions at the object level that constitute properties and the distinctions at the sensory level, which we have called “peripheral features,” are varied. Some object properties (e.g., apparent temperature) have direct counterparts at the level of peripheral sensory features, although they are presumably processed further beyond that level for signal/noise amplification. Other properties are represented only crudely by peripheral receptors (e.g., a geometric property might be peripherally coded as the presence or absence of a deformation gradient, based on peak deformation at a location). Still others require higher-order computations over populations of spatially distributed peripheral receptors at cortical levels (e.g., roughness).

6.3 HAPTIC EXPLORATORY PROCEDURES

The encoding of haptic object properties requires more than internal computation; it requires appropriate patterns of contact with the object. There are stereotypical hand movements, which we call “exploratory procedures,” associated with the extraction of haptic properties (Lederman and Klatzky 1987). For example, imagine how you would determine which of two surfaces was rougher, without the use of vision. You probably have a strong intuition that you would rub the surfaces with your fingertip, and indeed, you are
correct. This is what we term lateral motion, and it is used for the judgment of texture at both the micro and the macro scale. Lateral motion is an example of an exploratory procedure.

The principal exploratory procedures we have described are as follows:

Lateral motion associated with texture encoding; characterized by production of shearing forces between skin and object;

Static contact associated with temperature encoding; characterized by contact with maximum skin surface and without movement, also without effort to mold to the touched surface;

Enclosure associated with encoding of volume and coarse shape; characterized by molding to touched surface but without high force;

Pressure associated with encoding of compliance; characterized by application of forces to object (usually, normal to surface), while counterforces are exerted (by person or external support) to maintain its position;

Unsupported holding associated with encoding of weight; characterized by holding object away from supporting surface, often with arm movement (hefting);

Contour following associated with encoding of precise contour; characterized by movement of exploring effector (usually, one or more fingertips) along edge or surface contour.

How do we know which procedures are associated with which object properties? We have demonstrated this association through a number of tasks, including the following.

Free Exploration When Processing Objects on Experimenter-Designated Properties

In one paradigm, we required a match-to-sample task, using objects fabricated to differ with respect to particular properties. The blindfolded subject was asked to choose the test object (among three alternatives) that best matched a standard on the basis of a designated object property (e.g., roughness), and to ignore all other properties (Lederman and Klatzky 1987). We have also conducted several studies (Klatzky, Lederman, and Reed 1989; Reed, Lederman, and Klatzky 1990) in which blindfolded subjects were asked to speed-sort objects into categories, designated by a target property. The objects were fabricated to represent several levels on properties such as shape complexity, compliance, size, hardness, and surface roughness. In both paradigms, the exploratory procedure used for a given object was found to vary with the designated target property, with the observed relationships between procedures and properties following the pairings described above.

In a study where vision was present, Klatzky, Lederman, and Matula (1993) asked subjects which of two presented objects was greater with respect to a particular property—size, roughness, weight, and so on. In this
In Lederman and Klatzky 1990, we asked subjects to indicate whether an object was a member of a named class (e.g., "Is this writing implement a pencil?" "Is this pencil a used pencil"). A priori, we established which property or properties would be most diagnostic of that class, by asking another group of subjects to rate the diagnosticity of various properties in a list. After an initial grasp and lift, subjects tended to exhibit the exploratory procedure or procedures associated with the object's most diagnostic property.

## Constrained Exploration When Matching on Targeted Properties

In the examples given thus far, subjects were free to explore in whatever ways they wished, and the emergence of a particular exploratory procedure was used to assess the coupling of procedure to property. In a variant of the match-to-sample task, we constrained subjects to a particular pattern of exploration and designated a target property for matching. In this case, the optimum means of exploration could be determined, based on the accuracy of matching (and speed, in case of accuracy ties). The same exploratory procedure found to emerge during unconstrained exploration generally turned out to be the optimal one (Lederman and Klatzky 1987, experiment 2).

### 6.4 EXPLORATORY PROCEDURES AS OPTIMIZERS OF PROPERTY COMPUTATION

We can think of exploratory procedures as a means of optimizing the computation of a haptic object property. How the optimization works is more transparent for some procedures than others. Consider, for example, what happens when people want to judge the apparent warmth or coolness of a surface. They use the exploratory procedure we have termed static contact, which takes the form of holding a large skin surface (e.g., multiple fingers) against the object. How does this optimize? Potentially, in two ways—by reducing friction, which could artifactually warm the skin surface, and probably more importantly, by allowing the thermal system to summate over space (Kenshalo 1984). Other optimization routines are less well understood. Indeed, there is no computational model that encompasses processes from peripheral receptor activity to the percept of a property at the object level. Here we note research indicating how exploratory procedures might
influence the process of encoding an object property, to the extent that the process is understood.

Lateral Motion Procedure and Surface Texture

Lateral motion is associated with the extraction of surface texture at both macro and micro scales. For a clue to the phenomenological contrast between macrotexture and microtexture, rubbing one's hand on a macrotextured surface like sandpaper results in a feeling of roughness, whereas rubbing one's hand on a finely textured surface is described as producing a vibratory sensation (LaMotte and Srinivasan 1991).

There is a variety of evidence for the idea that macrotexture is coded by the spatial distribution of receptor responses and that microtexture is coded from temporal signals. Neurophysiological recordings show that the mechanoreceptor population producing the best correspondence between judgments of macrotexture and sensory output is that of the SAI receptor—which provides a temporally sustained rather than time-varying response. Johnson and associates have developed a model of macrotexture perception that computes what is essentially a measure of instantaneous variance in a spatial map of SAI intensity values (see Hsiao, Johnson, and Twombly 1993 for review). In contrast, the correlate of microtexture perception appears to be PC afferent responses (LaMotte and Srinivasan 1991). Further evidence against temporal coding at the macro scale comes from the fact that roughness judgments are largely unaffected by the speed at which the surface is rubbed (Lederman 1983) and by the spatial period of a grating (Lederman and Taylor 1972), and that these judgments are also unaffected by selective vibrotactile adaptation (Lederman, Loomis, and Williams 1982). The spatial-temporal distinction has also been supported by research with rats, in which the animals' ability to make texture discriminations at two scales was measured, after cutting their whiskers in order to constrain exploration. Two whiskers were needed to judge texture at the macro scale, whereas one whisker sufficed to judge texture at the micro scale, implicating spatial judgments in the former and temporal judgments in the latter (Carvell and Simons 1995).

Moving the hand laterally would create a vibratory signal that would enhance the response of the receptor population thought to be relevant to microtexture perception. But if macrotexture is computed from a spatial response pattern, it is less clear why people use motion to explore, and why, particularly, they use lateral motion. Motion is not needed, apparently, to produce a temporally coded signal. Nor is it needed simply to maintain stimulation to the mechanoreceptors, because (1) the receptors implicated in texture coding have sustained rather than transient responses, remaining active whether the stimulus is stationary or moving; and (2) other patterns of movement that would produce recurrent stimulation but that do not produce shear between skin and surface, as does lateral motion, are ineffective at enhancing roughness perception. (To judge this for yourself, try jittering
your fingers normal to a surface without breaking contact, and compare the feeling of roughness to one produced by lateral movement.)

That responses of SA receptors increase when the stimulus is scanned laterally (Johnson and Lamb 1981) provides a mechanism for enhanced roughness perception. Although these same receptors underlie the tactile perception of form and texture, the heightened response produced by lateral motion appears to produce only a modest improvement in form perception (Johnson 1983) and to be more critical to roughness.

Pressure Procedure and Compliance of Objects

When a finger is pressed against a surface, information about its compliance level is potentially available from both cutaneous and kinesthetic receptors. The cutaneous receptors respond to deformation of the fingerpad; the kinesthetic receptors provide information about the movement of the finger under a given motor command. Srinivasan and LaMotte (1995) investigated the relative contribution of cutaneous and kinesthetic signals with two types of compliant objects. One type had a deformable surface, as does a sponge. The other type had a rigid surface but was compliant, because underneath that surface was a spring. When the surface was nonrigid and conformed to the fingerpad, creating a pressure gradient, cutaneous inputs were sufficient to discriminate compliance levels. But if a rigid surface overlay a compliant medium, cutaneous cues were insufficient to make discriminations; input from kinesthesia, acquired during active touch, was also needed.

Unsupported Holding Procedure and Weight

Amazeen and Turvey (1996) suggested that holding and dynamically wielding an object allows one to determine the resistance to rotary acceleration (i.e., moments of inertia). They have formally modeled this as an inertia tensor in which the three moments of inertia lie along the diagonal (subsequent to appropriate normalization). Perceived weight increases as a function of the two principal moments and decreases as a function of the third, the moment of inertia about the longitudinal axis of the rod.

Enclosure Procedure and Microgeometric Properties

To perceive a pattern on the scale of the fingertip, a version of what we term enclosure is used; in this case the fingerpad deforms to surround the pattern elements or edges as much as possible. The perception of shape and size by this mechanism appears, like macrotexture, to be based on SA1 receptor activity. The isomorphic map provided by the mechanoreceptors is thought to provide input to a spatial pattern computation, although inputs from FA1 receptors may also play a role. Loomis (1990) has proposed a model of the computations used to recognize characters pressed into the skin that begins
with a map of binary intensity values, representing the inputs from high-contrast character stimuli, and proceeds with two computational processes: (1) stimulus transformation, including both linear low-pass filtering and a nonlinear (square root) transformation, and (2) a process of matching to an internal template. The first process produces a nonbinary intensity map that was assumed to represent the degradation of the stimulus representation as it is transferred from skin receptors to cortical sites. The second process, template matching, deals with the decision as to the symbol’s identity. A process of template matching was also invoked in a model by Vega-Bermudez, Johnson, and Hsaio (1991). Both these models attempted to account for confusion errors. The reliance of these models on matching to an isomorphic stimulus representation, which is known to be lost at later cortical levels (see above), is bypassed by a model of Bankman, Johnson, and Hsaio (1991), which describes the neural responses of cortical units as a distributed network.

Enclosure Procedure and Macrogemetric Properties

Presumably, kinesthetic information about the relative positions of fingers and palm when the hand molds to an object is useful in determining its external envelope. A simple version of enclosure is to pinch an object to determine the length of the axis between opposing fingers. Accordingly, it has been found that finger span (across two hands) is a cue to object extent (Teghtsoonian and Teghtsoonian 1965). A study by Chan, Carello, and Turvey (1990) questioned the utility of this cue, but those experiments used attachments to the fingers, breaking the natural correlation between interfinger distance and object size.

Contour-Following Procedure and Geometric Properties at Micro and Macro Scales

As we have noted, the same SAI population that apparently underlies roughness perception appears to be important in the perception of patterns scaled to the fingertip, and actively scanning a pattern at this scale enhances character recognition to some extent. We consider such scanning to be a form of the exploratory procedure we term contour following.

To compute geometric properties on a larger scale than the fingertip requires moving the limbs while contacting object contours and constructing a representation on the basis of limb positions at points of contact. This map is likely to be subject to anisotropies and systematic distortions. For an example of one type of distortion, we have shown that judgments of the distance between two touched points on a tabletop are inflated when irrelevant hand movements are made in traversing between the points (Lederman, Klatzky, and Barber 1985). The increase in error with irrelevant movement appears to reflect the use of a heuristic in which movement time is translated into distance (Lederman et al. 1987).
Reliance on this heuristic may occur because more direct coding of the exocentric distance between stationary limbs is relatively poor. Other data from Klatsky, Lederman, and Barber 1985 show that people err considerably in perceiving the distance or direction between the index fingers of two hands when they are placed simultaneously on the tabletop. We found, whether or not subjects were allowed to hold one finger in the starting position while the second one moved into the terminal position by a circuitous route, the distortion of judgments of interfinger distance, caused by the irrelevant movement, was approximately the same. When the first finger remained in situ, the subject should have been able to ignore the movement and simply judge the distance or direction from the terminal finger positions—but the distortion remained virtually intact.

6.5 HAPTIC ENCODING OF OBJECT PROPERTIES OVER BRIEF DURATIONS

Haptic exploratory procedures generally are extended in time. For example, the durations we observed in our initial match-to-sample task averaged about 3.5 sec. However, in highly constrained and repetitive tasks, such as speeded sorting into categories, exploration became more efficient. The total response time (RT) for that task, including response generation and vocal output, averaged about 750 msec. This suggests that we can learn a considerable amount about an object’s properties during brief, initial contact. It is this sort of contact we term a haptic glance.

What information might be conveyed by a haptic glance? Because exploratory procedures deliver information about particular properties, we first consider what exploratory procedures the glance instantiates, and therefore what associated properties it is likely to convey. There are four exploratory procedures that can be incorporated, at least to some degree, in the haptic glance. One is static contact, associated with thermal sensing. A second is enclosure, but only as it is executed on the highly local level of the fingertip—by deformation of the finger pad to accommodate surface discontinuities. The pressure gradient from even such limited enclosure could provide information about the size and orientation of edges and surface curvature relative to the plane of the finger. A third exploratory procedure is pressure, generally applied normal to the surface with enough force to maintain contact, if not to overly deform the surface or finger pad. This could give rise to information about the compliance of the touched surface. Fourth, any tangential movement of the skin across the object surface during the glance—as is likely to occur during the earliest stages of contact—would constitute both lateral motion, associated with texture encoding, and contour following at a micro scale, delivering local geometric information. To summarize, then, consideration of the exploratory procedures that a haptic glance would instantiate leads to the hypothesis that it would provide at least coarse coding of thermal properties, local shape and size, compliance.
and texture. Obviously, the haptic glance would not directly provide information about an object's geometry outside the scale of the fingertip, nor would it convey distribution of mass, which may tell the haptic system a great deal about an object's part structure (Solomon, Turvey, and Burton 1989).

To test these hypotheses and to directly investigate the information available from initial contact with an object, we have used two experimental paradigms. The first (Lederman and Klatzky 1997) uses a variation on the well-known visual search paradigm, in which subjects search for a target object in a display of distractors that varies in size. Our paradigm is similar to that used by Treisman (e.g., Treisman and Gormican 1988), in that the target and nontargets have differing values with respect to some perceptual dimension. Ours is explicitly a nonvisual search task, however, in that it involves a search across the fingertips for haptically defined properties, and vision is denied. In our second paradigm (Klatzky and Lederman 1995), we assess object identification performance under circumstances of brief contact without overt exploration.

6.6 HAPTIC SEARCH TASK

In each of a series of fifteen experiments, as shown in figure 6.2, the subject searched for a target defined by a haptic property, among distractors that had a different value on the same dimension. For example, the subject might search for a rough surface among smooth surfaces. We used this task to investigate the relative availability of haptically perceptible properties. Relative availability can be defined in two ways, corresponding to different parameters of the function relating response time to the number of fingers stimulated, which varied from 1 to 6 (presented over the three middle fingers of each hand).

The first parameter, and that usually considered in search tasks, is the slope of the function. If the function is flat, this is taken to indicate parallel search across the fingers. If the function is increasing, a limited-capacity search (which may or may not be serial) is indicated. In our case, we wish to go beyond a simple dichotomy between flat and increasing search functions because our interest is in the relative availability of properties and not just the nature of search. Thus the value of the slope is important, with greater slopes indicating properties that are less available.

The second parameter of the search function that addresses relative availability is the \( y_0 \) intercept. Although Treisman and Gormican (1988), using a variety of visual search tasks, found that the \( y_0 \) intercept was unrelated to the slope and varied relatively little, we found a significant correlation between slope and intercept. This implicates some stimulus processing within the intercept value. The intercept includes both processes that occur one time, regardless of the number of fingers stimulated, and processes that occur in parallel across the fingers. Examples of one-time processes are generating the
Figure 6.2  Stimuli used in haptic search tasks in Lederman and Klatzky 1997. Each experiment required discriminations between the two stimuli shown, one serving as target and the other as distractor for a series of search trials.
response output and executing it motorically. In our task, one-time processes may also include processes that vary with the property being encoded. These could include hand positioning or exploratory movements occur across all fingers simultaneously. The intercept may also include the time to process—presumably, in parallel with unlimited capacity—information about the surfaces touching the individual fingertips. If the search function is flat, then the intercept incorporates all of the stimulus computation. If the search function is increasing, the intercept may still include some parallel computation across the fingertips, but in this case, the computation is only part of stimulus processing, the rest requiring capacity use that shows up in the slope.

The properties tested in the thirteen experiments of interest here (see figure 6.2) were intended to cover a broad range, with respect to the broad property classes we have identified and the level of processing at which the distinction was likely to be first coded. There were (1) material discriminations, such as a rough surface among smooth surfaces (experiments 1–3); (2) abrupt surface discontinuities, such as a surface with a raised bar among flat surfaces (experiments 4–7); (3) planar or 3-D spatial position, such as a surface with a raised dot to the right of an indentation among surfaces with a dot to the left of an indentation (experiments 8–11) and (4) continuous 3-D contours, such as a curved surface among flat surfaces (experiments 12–13). Generally, searches were evaluated in both directions, for example, smooth targets in rough distractors on some trials and rough in smooth on others.

Precise control over stimulus presentation and measurement of response time (RT) was made possible by a special apparatus (Moore et al. 1991), consisting of a set of six rotating drums, each having a set of planar facets slightly larger than the fingertip. Each drum contacted a finger. A stimulus surface could be mounted on five of the facets of each drum; the sixth facet was cut out to allow for the absence of any contact whatsoever. Each drum was controlled by a stepping motor, and the entire set was mounted on a motorized platform. On each trial, the drums were rotated under computer control so that from one to six planar facets faced upward, to produce the desired stimulus configuration (e.g., 1 rough surface, 3 smooth, and 2 cutouts, for a rough-in-smooth positive trial). When the display was prepared, the platform supporting the drums lifted upward to contact the fleshy portion of the subject's fingertips, which extended horizontally beyond finger supports. The subject indicated the binary response by pressing one of two thumb switches.

It is obviously important, when attempting to compare properties with respect to relative perceptual availability, not to have availability be an artifact of task difficulty. As discriminations are made more difficult, one would expect the slopes and intercepts of the search functions to increase, indicating decreasing availability. Ideally, one would equate all the discriminations in difficulty. This, however, is not possible. Instead, our approach was to make each of the basic experiments involve a very coarse discrimination. The differences between targets and distractors were often as large as was possible
within the modality (e.g., left versus right spatial position). In cases where an easier discrimination was possible, our results would have favored material properties even more than would be reported (e.g., if we had compared a rough surface to a featureless surface, instead of to the densely dotted one that was used for the smooth alternative). In this way, we accepted the inherent differences in baseline discriminability as part of the dimensions we were testing; it is in this context that our ordering of feature availability stands. (Effects of discrimination difficulty were also tested explicitly in additional experiments illustrated in figure 6.2.)

Initially, we hypothesized that two of the classes of properties—material and abrupt surface discontinuity—would be more perceptually available than a third—spatial relations. Discriminations of the first two types can be based on what we call an “intensive” representation, in which the property is coded—for purposes of the required discrimination, at least—unidimensionally. For example, discriminating a surface with a deep hole from one with a shallow hole could be based on relative deformation of the skin, which would be greater if the finger “bottomed out” in the shallow hole. Intensive discriminations directly contrast with spatial discriminations, which are defined here as requiring at least 2-D pattern information. Consider, for example, how one might discriminate a left oblique raised bar from a right oblique raised bar in the plane presented to the fingertip. The extent of skin deformation produced by the two stimuli is identical; what differs is how the pressure gradient is oriented in the fingertip plane. Thus the problem cannot be solved intensively, and a spatial representation is required.

Our prediction that spatially coded properties would be available later than intensively coded properties is based on three considerations. First, there is a substantial behavioral literature suggesting that the haptic system is relatively inefficient and inaccurate at spatial coding, in comparison both to spatial coding by the visual system and to haptic coding of nonspatial properties (e.g., Cashdan 1968; Johnson and Phillips 1981; Lederman et al. 1990). Second, at least some intensive properties begin being discriminated at the periphery, whereas spatial judgments require examining population-level responses. And third, relative spatial discriminations logically include intensive processing as a component because they require extraction of pattern from skin deformation and, possibly, kinesthesia.

We turn now to the results of these experiments. There were twenty-five search tasks in all in experiments 1–13, each producing a function for target and nontarget trials, and each function having a slope and intercept. In general, the search functions were substantially accounted for by a linear component. Figure 6.3 shows an example function that is nearly flat (roughness judgment), and another that is clearly increasing (relative position of indentation and raised element); these functions represent averages of target and nontarget trials.

The correlation between slopes and intercepts across individual tasks was significant ($r = .48$), and the slopes and intercepts tell a similar story about
relative property availability. Figures 6.4 and 6.5 show how those parameters were distributed for three different classes of discrimination—material, abrupt surface discontinuities, and spatial relations. The figure was devised by first ordering the 25 slopes and 25 intercepts obtained from the search functions, then dividing each ordered series into quintiles. (Parameters from target and nontarget functions were averaged.) The proportion of values within each quintile that came from a particular class of discrimination was then computed and is shown on the y-axis, as a function of the quintile value. Below the quintile number is shown the corresponding numerical range of slope or intercept values.

Figures 6.4 and 6.5 indicate that there is a progression in availability from material properties, to surface discontinuities, to spatial relations. None of the slopes for material properties was greater than 36 msec, and several were close to zero. Similarly, the intercepts of material property search functions tended to fall into the first two quintiles, with one notable exception—the intercept for detection of cool surfaces in warm (copper target in pine distractors) was relatively high, which reflects the slow transduction of heat flow by the thermoreceptors. In contrast, the slopes and intercepts for spatially defined properties tended to fall into the upper quintiles.

The differentiation among classes of properties was also seen when the subjects’ exploratory movements were considered. Although the instructions did not constrain movement, active exploration takes time, and the task was
Figure 6.4 Proportion of discriminations falling within quintiles defined by slope of the search function for each of three types of search: material properties, surface discontinuities, and spatial properties. The range of slopes within each quintile is shown below the abscissa. From Lederman and Klatzky 1997.
speeded, discouraging extensive exploration. Exploration tended to be least with intensively processed properties and greatest with spatial discriminations. Several of the search tasks involving material properties or surface discontinuities yielded few or no overt hand movements, once subjects were practiced.

From these data, it appears that the properties computed early after contact are primarily properties that can be coded unidimensionally, which char-
acterizes material and coarse geometric discriminations involving surface discontinuities. Coding of other geometric properties, those involving spatial relations, tends to take more time, but at least some coarse discriminations can be made fairly early (e.g., horizontal versus vertical edge). These findings are in general agreement with our initial analysis, in that the properties found most accessible are associated with exploratory procedures instantiated within the haptic glance. Notably, the set of properties extracted early, by present criteria, is not synonymous with features known to be distinguished at the sensory periphery. Although some distinctions that produce flat search functions are peripherally coded (presence of a pressure gradient, as with a surface discontinuity, and heat flow, in particular), some are not (e.g., roughness, compliance). We turn now to the issue of how well those properties can support object identification.

6.7 OBJECT RECOGNITION WITH A HAPTIC GLANCE

The search experiments reveal that a rich description of touched objects is available soon after contact, with minimal exploration. How quickly can the property set be computed? The search data do not allow us to determine exact processing times. The intercept is not an adequate estimate because it is inflated by nonperceptual processes such as response generation and output. The slope is inadequate, because it represents only the additional time to process an extra finger and does not include time for perceptual processes that can occur in parallel across the fingertips. Such parallel processes may play a role even in discriminations that produce a positive slope. Given the mean response times of about 400 msec for some searches yielding virtually flat slopes, however, it seems possible that contact considerably less than this value—on the order of 250 msec, say—could be highly informative and could potentially support object identification.

Under free exploration, people are highly accurate at object identification, with a modal time of about 2 sec (Klatzky et al. 1985). To determine what level of object recognition is possible with brief contact, we conducted an experiment in which subjects identified objects to which they were exposed for only approximately 200 msec, with minimal movement of the fingertips. In other words, subjects were constrained to a haptic glance.

One might, at the outset, feel that little can be known about an object from brief, essentially passive contact. Both our analysis of exploratory procedures and our search data suggest that without actively initiated exploration, and with time limitations, even experienced observers can code only intensive properties and coarsely differentiated, local edge orientations. Theories of object recognition in the visual domain, in contrast, stress the importance of global, structural properties. These properties are thought to mark the categorical structure we impose on objects in the world and to be the key basis for visual object identification (Rosch 1978; Tversky and Hemenway 1984). We found that categorical partitioning at the basic level is still
largely based on shape, when subjects are told to think about identification by touch (Lederman and Klatsky 1990). This reliance on structure for partitioning the world suggests that early contact with an object, which provides only coarse, local structural information, could not be very useful for pattern recognition.

Indeed, it seems unlikely that a brief touch could provide volumetric primitives of the sort called for in Biederman and associates' model of visual object recognition (Biederman 1987; Biederman and Cooper 1991, 1992; Hummel and Biederman 1992). If the object is fingertip-scaled, and if the haptic glance is sufficient to extract its geometry, the volumetric approach might be extended to haptic object recognition. But if objects extend beyond the scale of the fingertip, how could one could build up a complete specification of volumetric primitives from sparse, local data?

Generally speaking, a local sample is not sufficient to define the whole, although there are obvious exceptions, such as the surface of a sphere. In a relevant study, Kappers, Koenderink, and Lichtenegger (1994) used geometrically complex, saddle-shaped objects that were designed so that shape and curvedness indexes remained fairly constant over all points on the surface; hence the objects were, in theory, locally discriminable. The shape index was determined by the relative curvatures of the two principal axes, and the curvedness index by the total curvature. The objects were also sufficiently large that they extended beyond the surface contacted by the hand. Although we do not know whether a haptic glance would have been sufficient to discriminate the objects because the subjects' exploration was not constrained to a brief local sample, it appears unlikely. They tended to scan the object with the whole hand over an extended duration, suggesting that they did not feel able to infer its geometry from a local and brief sample.

There are ways for object identification to proceed in the absence of a full volumetric description. It is possible that an incomplete description, built from the local sample, might sometimes suffice for object identification. It also appears that material properties have some diagnostic value. One indication comes from Lederman & Klatsky 1990, in which we asked subjects to list, from a closed set, the properties most diagnostic of a set of objects. When the objects were named at the basic level (e.g., "bread") we found, as was mentioned above, that shape was still the primary basis for categorization, although texture was also frequently cited. And when objects were named at the subordinate level (e.g., "stale bread"), various object properties, including material properties, were rated to be highly diagnostic. Another line of evidence for contribution of material in haptic object recognition arises from a study in which subjects were asked to name objects they felt through a glove (Klatsky et al. 1993). Performance was improved when the glove was open-fingered, allowing the material to be felt.

In our experiment directly addressing object recognition with a haptic glance, we used objects in four categories, defined by two levels of size and
two levels of diagnostic property. The small objects had at least one axis that could be spanned by the middle fingers when placed transversely to the hand; with the large objects, both axes exceeded the finger span. The diagnostic value of various properties for object classification were determined by the rating study described earlier: objects were used for which texture was more diagnostic than shape, or for which shape was more diagnostic than texture. In addition to varying the attributes of the object, we varied the amount of information given to the subject in advance of object presentation, and hence the potential for top-down processing. There was no advance cue (“What is it?”), an advance cue in the form of a superordinate category (e.g., “It’s a container top: What is it?”), or an advance cue in the form of a possible basic-level name (e.g., “Is this container top a cork? Yes or no?”).

The subject began each trial by moving the hand along a guide down to the object, which was placed so that a particularly informative region, if any (e.g., the pouring lip on a pitcher), would be contacted. Although we did not have precise control over the duration of touch, a force-sensitive board placed under the object sensed initial contact, and a tone was emitted, instructing the subject to lift the arm away, during the last 100 msec of the desired presentation time of 200 msec or 3,000 msec. The responses were either a name (in the no-cue or superordinate-cue conditions) or a yes/no response (when the basic-level name was cued), along with a confidence rating.

The principal result of this study was that objects could be identified from a haptic glance at levels well above chance. (Chance was 50% in the yes/no condition and essentially zero in the no-cue condition, and it was empirically estimated by a control study for the superordinate-cue condition.) Overall, 15% of objects were named correctly in the 200-msec exposure condition with no advance cue (versus 93% with free exploration). In this condition, performance was lowest (5%) when the object was large and shape was diagnostic, as one would expect—the diagnostic shape cues extended beyond the contact area. Performance was highest (25%) when the object was large and texture was diagnostic.

The 200 msec exposure duration with no cue is obviously the most impoverished, and not surprisingly, both advance cueing and extending the duration improved performance. Extending the exposure duration when no cue was given almost doubled accuracy (increasing it to 26%), although the large, shape-diagnostic objects remained at a disadvantage. We cannot precisely quantify the effects of advance cues on accuracy, due to differential guessing rates in the different cue conditions, but confidence increased significantly with cue informativeness. With the basic-level cue, accuracy reached 72% (versus 50% chance) at the 200 msec exposure.

How were objects recognized with such brief, relatively passive contact? The effects of the advance cue indicate that top-down processing can be important in compensating for impoverished data from the stimulus.
But although the data may be impoverished, some stimulus properties can nevertheless be extracted from a haptic glance, providing the input to data-driven processing.

An analysis of confusion errors was highly informative as to the nature of the properties that a haptic glance provides. A confusion error occurred when an object was named other than the one presented. We analyzed nearly 600 such responses in detail. For each presented object, the proportion of error responses differing from it with respect to each of three binary dimensions was scored. The dimensions were: rigid versus compliant, rough versus smooth, and continuous surface versus 3-D discontinuity (defined as a bump, step, or hole within the interior of the region touched). In addition, we considered whether the erroneously named item matched the actually presented one with respect to the material of which it was made (using the fixed categories of metal, glass or porcelain, plastic, paper, cloth, or other). For example, if the target object was a piece of corduroy and the subject responded “silk,” it would be scored as a roughness mismatch; if the subject said “paper napkin,” it would be called a material mismatch. An example of a mismatch in surface discontinuity is calling a stick of gum a “paper clip.”

This analysis revealed that 75% of confusion errors matched the original object with respect to material. The named and presented object matched on the specific properties that we scored—compliance, roughness, and surface continuity—more than 90% of the time. Thus it appears from this analysis that subjects were picking up material properties and local shape cues with substantial accuracy, as we would expect from our search data and analysis of exploratory procedures embedded within the haptic glance.

The interaction between the object’s most diagnostic attribute and its size, described above, indicates the limitations of what can be picked up locally. This interaction was pervasive, being found in most conditions and in both accuracy and confidence; it is shown for the confidence ratings in figure 6.6. When texture was diagnostic, larger objects were recognized better; when shape was diagnostic, smaller objects were recognized better. This pattern reflects the different implications of object size for texture-diagnostic and shape-diagnostic objects. When texture is diagnostic, a larger size means a larger sample is available to the fingertips, enhancing the local cues that can be extracted. But when shape is diagnostic, a larger size means that the local sample is likely to be an insufficient representation of geometric properties, and hence performance suffers.

Recognition of large, shape-diagnostic objects was not, however, at chance. As we indicated above, successful identification might reflect any of several mechanisms, which are not mutually exclusive and might vary in applicability from object to object. One mechanism is to build a complete volumetric description of the object from a local sample. This is most likely to be successful with objects having a small number of geons and providing local surface cues. It seems unlikely to occur with more complex objects,
even if the local sample is theoretically sufficient to reconstruct the shape, as in Kappers, Koenderink, and Lichtenegger 1994. This mechanism might be used, for example, to recognize a bowl merely from contact with its rim, which could indicate width and curvature in two directions. The bowl was one of our more successfully recognized items (50% with no cue).

A second mechanism for recognizing objects having shape as the most diagnostic property, on the basis of a local sample, is to use that sample to recognize a small number of geons (which presumably can be inferred from the local cues available), and then input just those geons to a pattern comparator, in the effort to trigger recognition without the whole object being constructed a priori. For example, this might occur with the lip on a pitcher, although that object was not one that was recognized with high probability in our study (8% in the no-cue condition).

A third mechanism for identifying shape-diagnostic objects with a haptic glance is to rely on material as a cue, in compensation for loss of shape cues.
Although this might occur successfully, for example, with a milk carton, which has a distinctively waxy surface, the data do not single out this item for a high recognition rate (8% accuracy in the no-cue condition).

The take-home message from our study on object recognition with a haptic glance is that it can be successful, and that it appears to take advantage of fairly accurate perception of intensively coded properties and local shape. It is least successful where macrogeometric shape is diagnostic of the object's identity and the object's scale extends well beyond that of the probing fingertips.

6.8 APPLICATIONS OF HAPTIC GLANCE RESEARCH

Research on haptic perception has been applied in many areas. The appeal of commercial products often depends on their haptically accessible properties. In the food industry, for example, psychophysical experiments on texture, oiliness, and smoothness have been used to predict people's judgments of palatability. There has been substantial research on the development of displays for the blind, such as pictures, maps, and graphical aids (e.g., Bentzen 1982; Berla 1982; Kennedy, Gabias, and Nicholls 1991). The incorporation of tactual cues into interface designs has been considered not only as a substitute for vision and hearing (see Sanders and McCormick 1987) but as an augmentation to what other senses provide (e.g., Akamatsu, Sato, and MacKenzie 1994).

In this section, we consider potential applications of research on haptic perception in a very restricted context, namely, the use of touch early in perception and with highly constrained exploration—in short, under the limitations of a haptic glance. The potential applicability of this work arises from the fact that these exploratory constraints simulate information from early contact with objects. We believe that initial contact is highly informative and functional, and there are a number of contexts that might be better tuned to its capabilities. Those contexts arise both in everyday life and in specialized settings.

Implications for Functional Manipulation without Vision

We rely on early touch to find, position, and functionally manipulate objects when vision is occupied elsewhere. This may occur, for example, when we reach for a coffee cup or mouse on the desktop while reading electronic mail, insert an audio tape or operate radio controls while driving, reach for the telephone receiver while talking to someone else, or find the light switch during the night. We have observed for ourselves that in a familiar environment, blind grouping changes to functional manipulation virtually immediately after the desired object is contacted.

Our point here is that the information from early contact goes beyond object identity to guide manipulation. Contact with the rim of a cup, for ex-
example, may be sufficient not only to establish that it is a cup, but also to orient the hand to grasp and lift it. For this to occur successfully, the contact must provide input about the hand’s position in an object-based reference system, which can be related to a model of manipulation for that particular object. Of course, the hand may not be in the proper position at first contact, but the information provided should allow it to be moved into the manipulatory posture as directly as possible.

We suggest that our work has implications for the design of objects that promote nonvisually guided manipulation. For a haptic glance to guide manipulation, the location and orientation of critical structurally defined regions must be specified relative to the position of initial contact. To the extent that an object provides intensively coded cues that differentiate spatial regions, the initial contact can be localized faster relative to the structures that support manipulation. We also note that multiple, differentially coded regions are needed to disambiguate object orientation. By touching a knife, we may know we are in contact with the blade and not the shaft, but knowing the direction in which the knife is pointing, and hence where to search for the handle, requires that we contact two distinct regions (e.g. blade and shaft, or blade and knife point). Our work indicates that those regions should be intensively coded.

Manipulation without vision is also a common goal in knobs-and-dials environments, where orientation is not an issue so much as segmentation and discrimination. It is remarkable how little attention is paid to the haptic properties of control knobs in many everyday contexts, despite long-standing work in the area. Our research suggests, for example, that adding texture or edge orientation cues to dials on a car radio could reduce the need for foveal vision in its operation, by identifying target buttons and segmenting them from supporting surfaces. Similar coding of telephone keys could reduce the need for vision to operate a cellular phone in the car.

Implications for Designing Haptic Interfaces

A haptic interface provides a human operator with haptically perceptible cues to the operation of some system. If the system is remote from the operator, it is said to be “teleoperated”—the remote device senses forces at the remote environment, and the interface provides feedback to the operator through vision, force displays, vibrators, and the like. An industrial crane is a common example of a teleoperated environment, although it lacks force feedback (except for coarse cues, such as vibration of the cabin). In more technologically advanced environments, a remote robot may be equipped with tactile sensors on its end effectors to determine what cues to send to the controller, or an endoscopic tool may sense forces to deliver to the hand of a surgeon who is controlling the tool visually. Because they can simulate contact with objects and surfaces during exploration and manipulation, haptic interfaces are desirable for virtual environments as well.
Teleoperators, who must often respond “on the fly,” need cues that are maximally perceptible. Our experiments on the information from early contact are useful in identifying properties most accessible to the haptic system, like compliance, roughness, or abrupt surface discontinuities. Kourtanitis and Howe (1995) have shown that using vibration to indicate contact in the remote environment is highly useful in preventing excessive manipulatory force; and we consider it likely that subjects searching for a vibrating element in an otherwise static display would find vibration highly accessible (see Whang, Burton, and Shulman 1991).

Implications for Guiding Haptic Exploration in Humans and Machines

We have discussed two extremes of haptic exploration in this chapter: brief contact, using minimal movement, and extended contact, using highly purposive movements, the latter in the form of haptic exploratory procedures. These two forms of exploration undoubtedly differ in their information value. While current studies establish that perceptual properties can be extracted early and with minimal contact, this information is likely to be at a fairly coarse level. To achieve virtually 100% identification accuracy on any arbitrary set of objects, more precise information is required. Subjects typically explore an object over seconds, not milliseconds, and their contact with an object is far more extensive than that of a brief haptic exposure.

There is a natural transition between these two means of exploration, in that early contact can serve to guide subsequent, extended exploration (Klatzky and Lederman 1992). The contexts in which we have observed dedicated exploratory procedures are often top-down; that is, information about a property is desired because it is explicitly called for by the task context or it is diagnostic of a hypothesized object. Early contact may also elicit such top-down processing by leading to hypotheses about what object is present or by establishing at a coarse level that the object has certain properties that should be extracted with greater precision.

An applied context in which both brief and extended modes of exploration are useful is exploratory robotics. Robots are now being designed to explore planetary terrain or environments that are not highly structured and are also not visually accessible, such as silty underwater areas. (An unfortunate example is the Florida Everglades site of the Valu Jet plane crash in May 1996.) Our work on haptic exploratory procedures has been modeled in robots with appropriate sensory apparatus as well as manipulatory end effectors (Allen and Michelman 1990; Allen, Michelman, and Roberts 1992; Stansfield 1988). The present work on the efficacy of early contact suggests a two-stage sequence for robotic explorers, in which haptic sensors initially extract coarse values, then use those values to guide the selection of subsequent exploratory procedures.
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