Haptic Perception of Surface and Object Properties

People use their hands to obtain information about a variety of physical properties of surfaces and objects. They are particularly effective at haptically processing dimensions that pertain to the materials used in the construction of surfaces and objects. The most notable dimensions relate to texture, compliance, thermal qualities, and weight, the last being a hybrid of material and geometry. People are considerably less effective at haptically evaluating and discriminating an object’s geometric features, such as orientation, shape, and size. In the following sections, we discuss research on the principal dimensions of haptic perception.

Roughness

To date, most research on haptic texture perception has focused on the perception of surface roughness. Provided there is relative motion between skin and surface and that both speed and force are equated, roughness perception is equivalent whether the hand is stationary and the surface moves or vice versa. Thus, cutaneous information is critical for perceiving roughness. Perceived roughness of very fine surfaces (i.e., those with spatial periods of less than ~200 μm in size) is likely based on intensive coding of vibration by Pacinian or fast adapting type II (FAII) peripheral tactile units. For spatial periods ranging from ~200 μm to 2 mm, perceived roughness is neurally represented by the stochastic variation in the spike rates of slow-adapting type I units (SAI) innervated by Merkel complexes. Beyond a spatial period of ~2 mm, perceived roughness is processed spatially by SAI tactile units.

Compliance

Considerably less is known about the perception of compliance or other related physical properties, such as elasticity and viscosity. Early research investigated how expert bakers perceived four primary dimensions of dough: stickiness, elasticity, firmness or toughness, and extensibility (i.e., the extent to which dough may be stretched before it breaks). The bakers were most sensitive to variation in stickiness, an attribute judged to be quite unpleasant; however, they were relatively insensitive to changes in either elasticity or viscosity.

More recent research has shown that cutaneous information alone is both necessary and sufficient to judge the relative softness of rubber specimens with deformable surfaces. The discharge rate of SAI units increases with increasing average pressure during indentation and, thus, could serve as a peripheral neural code for perceived softness independent of the velocity of indentation. Because single-fiber response depends on indentation velocity as well as on surface compliance, this code must be based on a population response, particularly in SAI units. To differentiate the stiffness of compliant objects with planar rigid surfaces, cutaneous cues on their own are insufficient and must be combined with kinesthetic cues. Figure 1 shows the two different kinds of compliant stimuli used in this work.

Thermal

The resting temperature of the skin (25–36 °C) is usually higher than the ambient temperature of materials in the environment. Thermal cues, which are sensed by peripheral populations of thermoreceptors (warm and cool), may potentially contribute to the haptic identification of different materials by producing different thermal transients as the skin interacts with the material during contact. People can identify materials such as copper, stainless steel, granite, and foam merely by contact, but not equally well. Perceptual confusions among materials are probably the result of similar thermal transients.

Weight

Weight is optimally perceived when the observer actively lifts the object away from a supporting surface, thereby providing information from both cutaneous and kinesthetic mechanoreceptors, as well as from the associated neural correlates of the descending motor commands. Humans use more than object mass to haptically assess weight. For example, a small object feels heavier than a large object of the same mass, a very powerful illusion known as the haptic size-weight illusion.

Opinions vary as to the nature of the processing involved in haptic weight perception. Some researchers have argued that haptic observers use cognitive expectations based on prior experience of the correlation between weight and size (or density) to judge object weight. Others suggest that observers incorporate sensory cues (cutaneous and/or kinesthetic) to object volume into their weight judgments. Still others argue that weight, both veridical and illusory,
is assessed more directly in terms of differences in the magnitude of the moments of inertia, that is, resistance to rotational forces produced as the observer wields an object. This last interpretation constitutes an example of dynamic touch, a haptic subsystem that uses deformations of muscles, tendons, and ligaments to perceptually judge the attributes of objects wielded in the hand (e.g., length, weight, width, shape of the object tip, and the orientation of the hand and object relative to one another).

Curvature, Angle, and Orientation (Tilt)

Humans can haptically detect curvature over a wide range of spatial scales and haptic sensory inputs, according to the size of the explored object. The relative contribution of the cutaneous and kinesthetic signals varies with the spatial scale of the curved surfaces.

Humans are capable of haptically differentiating 2-D angular differences of $5.2^\circ$ between pairs of relatively large angles with an accuracy level of 75%, with performance depending on both cutaneous and kinesthetic (shoulder) inputs.

Finally, haptic perception of orientation has been measured by requiring that a test bar be positioned parallel to a reference bar presented together within a planar (horizontal) work space. The perception of orientation within this peripersonal space is systematically biased by several factors, particularly the location of the bars within the plane (e.g., distance from the midline of the body).

Shape of Two- and Three-Dimensional Forms Larger than a Fingertip

Spatial patterns that fit within the fingertip are sensed on the basis of cutaneous cues alone, and are thus not discussed further here. Humans haptically process relatively ineffectively 2-D and 3-D shapes of larger objects that are made of a single material. At this time, little is known about the underlying neural codes.

Purposive manual exploration critically influences how objects and their properties are haptically processed and cognitively represented. More specifically, the spatially restricted inputs derived from contacting objects with multiple fingers impose constraints on spatial integration. Furthermore, the sequential nature of manual exploration renders it slow to perform, creating notable demands on memory and...
temporal integration. Humans initially process an object haptically more by its local features than by its global shape, particularly when exploration time is limited.

**Size**

To date, most research has focused on the haptic perception of object length or width, as opposed to its area or volume. Haptic perception of the length of rods statically held at their ends between the two index fingers varies in a 1:1 fashion with physical length. Unlike most other sensory judgments, then, there is excellent correspondence between the percept and the physical property. However, in some cases the haptic perception of size may be systematically distorted. For example, people are haptically susceptible to a variant of the horizontal-vertical illusion, in which a vertical line is perceived to be longer than the same line oriented horizontally, in both T- and L-shaped configurations of this illusion. The horizontal-vertical illusion is believed to consist of two separate components resulting from bisection and radial-tangential effects. The bisection effect consists of the bisecting line being overestimated relative to the bisected line. However, the radial–tangential effect is an anisotropy of haptic space in which radial movements toward and away from the observer’s body are overestimated relative to those that are tangential to the body.

**Haptic Space Perception by Sighted and Blind Observers**

How spatial locations are coded haptically and which errors are induced by the coding system adopted are issues that have been extensively investigated. The focus here is on space within human reach, that is, manipulatory space. Do people represent the location of their hands in space by the kinesthetic posture needed to place them there or by some extrinsic spatial framework? A posture-matching strategy is adopted in tasks wherein the observers’ hands are passively moved to a location to which they must reach again. If this strategy is prevented, for example, by having the observer reach the second time with a pointer, performance by posture matching becomes relatively error-prone and variable.

A frame of reference may also be defined extrinsically with respect to the body when space is haptically explored. For example, observers who attempt to match the tabletop position to which one hand is moved by placing the other hand in the corresponding location underneath the table (Figure 2) appear to make spatial errors consistent with using an extrinsic frame of reference in which the haptic egocenter (origin) is located at the shoulder of the arm used to mark the position on the tabletop. The position of this haptic egocenter is not fixed; for example, it reverses when the roles of the hands are switched.

Still other research has shown that spatial coding can also occur using an extrinsic spatial frame of reference outside the body. For example, consider when an observer’s left or right finger is passively guided to a specific location. The observer must then actively reach to that location with the right hand. Systematic biases (constant errors) shift the endpoints outward laterally along the frontal plane and compress them sagittally and vertically. More significantly, variable errors are essentially independent of whether the observer uses the same hand or switches hands between initial exposure and test. The postures for the responding (right) arm depend little on the arm that originally locates the target. Therefore, target position after passive kinesthetic exposure can be represented in an amodal frame of reference that is not referred to reaching postures; rather, it is defined by extrinsic space and is shared by vision and kinesthesia. This representation is not always observed when relatively few target locations and responses are used.

It has been further proposed that multiple spatial representations are formed after haptic exposure in a temporal cascade. These begin with kinesthetic reference frames and proceed to extrinsic frames that might be egocentric or environmental.

Once spatial locations are encoded by means of reaching, they can be updated when people move in the absence of vision. Studies investigating nonvisual updating in manipulatory space have found that sighted and blind observers can update their representation of touched locations after moving their finger to a new reference location or after walking to a new location. However, updating is superior when observers can actually touch the target at the updated location rather than just point to it, suggesting that a specifically haptic code is updated more successfully during movement than is an abstract representation of location.

**Haptic Recognition of Objects**

Humans are remarkably effective at recognizing common objects using only their hands. When asked to identify them, participants attain close to 100% accuracy, most often within only 2–3 s.

**Role of Hand Movements**

Active manual exploration may play a critical role in the normal development of somatosensory perception in mammals. Nonetheless, as long as there is
relativemotion between the surface and the skin, for fingertip-size stimuli such as Braille characters and textures, it is not critical whether the hand moves over a stationary surface or the surface moves across the stationary hand.

Manual exploration contains the key to understanding why humans are so skilled at recognizing common objects haptically. People manually explore such multi-attribute objects and surfaces in highly systematic ways by executing a number of stereotypic hand-movement patterns known as exploratory procedures. Each procedure is voluntarily selected in association with one or more object properties to which the person is selectively attending.

The exploratory procedures that have most frequently been the focus of scientific investigation are shown in Figure 3 in association with the property(ies) with which each is most closely linked. Lateral motion involves a back-and-forth shearing motion across a surface and provides the most precise information about the textural properties of a surface. Pressure involves the application of force normal to a surface or a torque about some axis of the object and provides the most precise information about properties relating to compliance. Static contact, as its name implies, involves making simple static contact with a surface and is used to extract optimal information about thermal qualities. Unsupported holding involves lifting the object away from a supporting surface, often jiggling it, to learn best about its weight. Enclosure involves molding the fingers to the object’s contours.

Figure 3 Six haptic exploratory procedures and the object property(ies) with which each is most closely associated: (a) lateral motion, texture; (b) pressure, hardness; (c) static contact, temperature; (d) unsupported holding, weight; (e) enclosure, global shape and volume; (f) contour following, global shape and exact shape. Reproduced from Lederman SJ and Klatzky RL (1987) Hand movements: A window into haptic object recognition. *Cognitive Psychology* 19(3): 342–368, with permission from Elsevier Ltd.
and provides the most precise information about an object’s size and general shape. Finally, contour following involves tracing around an object’s edges or contoured surfaces and provides the most precise spatial details about an object.

These six exploratory procedures have been further compared in terms of four different performance characteristics: precision of information, breadth of object property information, average duration, and co-executability. A summary of the first three relative performance characteristics is presented in Figure 4.

### Figure 4 Costs and benefits as influenced by three relative performance characteristics of haptic exploratory procedures: precision of information (chance, sufficient, optimal, or necessary), breadth of sufficiency or generality, and average execution duration.

<table>
<thead>
<tr>
<th>EP</th>
<th>Property</th>
<th>Breadth</th>
<th>Duration (s)</th>
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<tbody>
<tr>
<td>Lateral motion</td>
<td>Text</td>
<td>Low</td>
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<td>Hard</td>
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<td>Exact shape</td>
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<tr>
<td>Pressure</td>
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<td>Static contact</td>
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<tr>
<td>Unsupp. holding</td>
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<td>2</td>
</tr>
<tr>
<td>Enclosure</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Contour following</td>
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<td>11</td>
</tr>
</tbody>
</table>

- **Chance**
- **Sufficient**
- **Optimal**
- **Necessary**

#### Relative precision of information

The empty cells indicate that the designated exploratory procedure (row) does not provide any information about the target property (column). Such is the case when unsupported holding is used to provide information about texture. The gray cells indicate that the designated exploratory procedure provides only coarse information about the target property, such as when pressure is used to extract texture information. The blue cells indicate that the designated exploratory procedure provides the most precise information about the target property, as is the case when lateral motion is used to extract texture. Finally, the red cell indicates that the designated exploratory procedure not only provides the most precise information about the target property (exact shape) but that this information is necessary for the haptic perception of fine shape details.

#### Breadth of property information

The exploratory procedures also vary in terms of the number of properties about which information is made available, minimally at a coarse level. Thus, lateral motion and pressure, the least general hand-movement patterns, provide only three types of property information that are all related to an object’s material. In contrast, enclosure and contour following each offers information about both material and geometric object properties.

#### Duration

Most exploratory procedures are relatively quickly performed, as is the case for those that provide relatively precise information about material. In contrast, although relatively quickly executed, enclosure provides only coarse information about an object. Contour following takes notably longer to perform than any other exploratory procedure.

#### Co-executability

A fourth relative performance characteristic relates to the extent to which exploratory procedures can be co-executed. To the extent that this is possible, the observer gains information that each exploratory procedure is not only optimal (or necessary), but also sufficient, at providing.

### Implications for Haptic Object Classification

The relative performance characteristics of exploratory procedures just discussed have both costs and benefits for the haptic perception of the physical...
properties of the concrete world and for object recognition and identification.

First, material properties of objects tend to be more salient (i.e., more active) in our conscious experience than others. Consider what happens when observers are biased by instructions to focus on either haptic or visual information when sorting multi-attribute objects into several piles. The most similar objects are to be placed within the same pile. When objects are constructed so that material (e.g., texture and compliance) and geometric (e.g., shape and size) dimensions vary in perceptually equivalent (i.e., discriminable) ways, the importance of material properties for people’s judgments of object similarity increases when they are given haptic-bias instructions compared to when they are given vision-bias instructions (Figure 5). The reverse occurs for the importance of geometric properties when people are given vision-bias (as opposed to haptic-bias) instructions. This result may be explained by the relative efficacy with which people perform material, as opposed to geometric, exploratory procedures.

Second, when vision is available during object recognition, humans tend to use their sense of touch primarily when the most diagnostic object property relates to material, as opposed to geometric, properties (e.g., sandpaper vs. spoon, respectively). As shown in Figure 6, when people are instructed to make difficult discriminations between pairs of common objects whose most diagnostic property is based on material (e.g., texture and compliance) or geometry (e.g., shape complexity and size), they choose to also haptically explore the objects for which material differences are most diagnostic. This is much less the case for highly discriminable pairs, presumably because information is semantically available.

Third, when people haptically recognize an object, manual exploration proceeds in a stereotyped way that is determined by the relative breadth of property information afforded by exploratory procedures and by their associated durations. Thus, humans begin their manual exploration by grasping (enclosure) and lifting (unsupported holding) the object. Both movement patterns provide information about many object properties and are relatively quickly executed. This highly standard routine is followed, albeit less frequently, by executing the exploratory procedure that provides optimal information, that is, that offers the most precise information about the property that is highly diagnostic of the object.

Fourth, humans may capitalize on the fact that multiple properties often predict an object’s identity. For example, a pencil is long and narrow; in addition, it frequently has a section at one end consisting of an interior metal band adjacent to a rubber end. With the haptic system, the perceptual gain resulting from property redundancy(ies) is potentially constrained by manual exploration. The addition of a second predictive property does not reduce the time needed to categorize objects if the two exploratory procedures that are optimal for those properties cannot be co-executed, either because of biomechanical constraints or because the second property is available at a region that cannot be explored simultaneously with the first.

Consequences of Constraining Manual Exploration in Space and/or Time

Restricting manual exploration helps to reveal how object properties are haptically encoded. More specifically, limiting spatial access to objects highlights the significance of both shape and material information.
for object identification. Limiting temporal access speaks, rather, to the sequence in which object properties emerge.

**Spatial constraints** Small-scale, cutaneous spatial constraints may be imposed by covering the fingertip in a rigid sheath. Without the spatially distributed force array that is normally available, observers can access only the summed forces stimulating receptors in the skin, muscles, tendons, and joints. Under such circumstances, they retain their ability to sense vibration and remain sensitive to coarse pressure differences; however, they are unable to discriminate fine spatial patterns within the scale of the fingertip.

It is also possible to constrain larger-scale spatial variation in objects that are typically explored using contour following and/or enclosure exploratory procedures. Consider, for example, what happens when observers are required to identify a set of common objects selected because they are all rigid, fairly smooth, and fixed to a supporting surface. A thick glove is worn to reduce the cutaneous information from the spatially distributed deformation patterns and vibrations normally created during contact. Under such circumstances, kinesthetically derived shape information becomes critical for object identification. Performance may be compared across gloved haptic exploration conditions that vary in the extent to which the kinesthetic inputs from muscles, tendons, and joints are spatially constrained. For example, the kinesthetic cues may remain intact. Alternatively, kinesthetic information may be reduced by wearing finger splints to prevent any flexion at the joints or by restricting the number of fingers used during exploration. By comparing performance across conditions, we can assess the extent to which reduced kinesthesia impairs object recognition when cutaneous sensing is minimized. Regardless of the method used to reduce kinesthetic information, performance declines, and it worsens as the number of exploration constraints is increased. When a rigid interface (i.e., sheath) between hand and object or a rigid, pencil-shaped probe is used, performance declines still further.

**Temporal constraints** The costs and benefits of exploratory procedures imply that features become available at different points in time, depending on the duration of haptic exploration and the processes (e.g., intensive and spatial) used to encode the explored features. Haptic access to information pertaining to material, to the presence of edges, and to geometric features has been shown to differ in terms of the relative availability of information about these feature subclasses over time. More specifically,
material attributes and edges, which are processed intensively, emerge earlier than do the spatial arrangement of an object’s geometric features, even when those features lie within the span of a fingertip.

**Applications**

The results of studies based on the scientific investigation of human haptic processing of surfaces, objects, and their properties have been applied to a number of application domains. Examples include the design of tangible graphics displays (maps, drawings, graphs, etc.) for the blind that are apprehended by hand as opposed to eye, the design of haptic and multisensory interfaces for exploring and acting on remote real and virtual environments, and haptic art for the blind and sighted. Several examples are presented in Figure 7.

*See also:* Cross-Modal Interactions Between Vision and Touch; Machine Haptics; Mechanoreceptors; Perception of Surfaces and Forms; Proprioception; Reaching and Grasping; Sensorimotor Control of Manipulation; Shape Representation in Inferotemporal Cortex; Somatosensory Perception; Somatosensory Cortex: Functional Architecture; Somatosensory Pathways (Ascending): Functional Architecture; Spatial Transformations for Eye–Hand Coordination; Tactile Coding in Peripheral Neural Populations; Tactile Texture; Temperature Sensation.

**Further Reading**


