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# Hand Movements: A Window into Haptic Object Recognition

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Two experiments establish links between desired knowledge about objects and hand movements during haptic object exploration. Experiment 1 used a match-to-sample task, in which blindfolded subjects were directed to match objects on a particular dimension (e.g., texture). Hand movements during object exploration were reliably classified as "exploratory procedures," each procedure defined by its invariant and typical properties. The movement profile, i.e., the distribution of exploratory procedures, was directly related to the desired object knowledge that was required for the match. Experiment 2 addressed the reasons for the specific links between exploratory procedures and knowledge goals. Hand movements were constrained, and performance on various matching tasks was assessed. The procedures were considered in terms of their necessity, sufficiency, and optimality of performance for each task. The results establish that in free exploration, a procedure is generally used to acquire information about an object property, not because it is merely sufficient, but because it is optimal or even necessary. Hand movements can serve as "windows," through which it is possible to learn about the underlying representation of objects in memory and the processes by which such representations are derived and utilized.

When we feel extremely helpless in a situation, we commonly say, "My hands are tied!" Indeed, it is hard to imagine a world in which we cannot feel the soft fur of a kitten or even tie our shoelaces. Yet, psychology has often portrayed the hand as a second-class citizen. Research

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has repeatedly demonstrated that the haptic system is poor at perceiving spatial layout and structure—at least of stimuli presented in the form of raised two-dimensional displays or impoverished three-dimensional nonsense shapes (e.g., Bryant & Raz, 1975; Cashdan, 1968; Lederman, Klatzky, & Barber, 1985; Magee & Kennedy, 1980). For example, people can explore the contours of a two-dimensionally depicted object for as long as several minutes without being able to identify it.

In contrast, we have recently portrayed the hand in a more positive light, by demonstrating that real, 3-D common objects can be recognized very efficiently through haptic exploration—with virtually 100% accuracy in only a second or two (Klatzky, Lederman, & Metzger, 1985). We consider these findings to be an "existence proof" that touch can achieve very high levels of perceptual performance. Furthermore, the considerable motor skills exhibited by the hand during prehensile and manipulative activity have also been documented (e.g., Gentner, 1983; Jeannerod & Biguer, 1982; Napier, 1956).

The discrepancy between these negative and positive views can be reconciled when we think of the hand as comprising two haptic subsystems that are at least conceptually distinct: a *sensory* subsystem with cutaneous, thermal, and kinesthetic sensors (for present purposes, we will not discuss pain) that is used to learn about the world of objects and their spatial layout, and a *motor* subsystem that is used to actively grasp and manipulate objects. Work on two-dimensional displays only assesses a highly restricted version of the sensory system. In its simplest form, a typical display consists of a raised outline on a uniform medium, such as thin plastic. The skin receives essentially two-dimensional pressure patterns, since there is rarely variation in the third dimension. Thus the system is provided with minimal cutaneous variation, no thermal variation, and only planar kinesthetic variation. Assessment of performance under conditions such as these suggests that the hand is generally a poor system for extracting information about objects, patterns, and spatial layout.

But as we have indicated, there is a second haptic subsystem, that of manipulation. In this paper we raise the possibility that this second system serves to enhance the first: such motor enhancement, which we suggest is present with real objects but not planar stimuli, may account for the observed differences in performance. We view the hand as a freely moving effector organ that can capitalize on the resulting variation in sensory input. Although exploratory movements can be conceptualized independently from sensory inputs, the two are really interdependent. By "piggybacking" its sensory functions onto its effector capabilities, the hand may achieve higher levels of perceptual and cognitive performance than are otherwise possible.

This conception leads to a straightforward empirical hypothesis. If the hand can take advantage of its motor competencies to facilitate its perceptual and cognitive functions, hand movements should vary with the sensory input and with the type of information desired. There are many dimensions of objects that can be perceived haptically, e.g., texture, hardness, shape. It is not likely that the optimal marriage between hand movement and object knowledge is the same for each of these domains. In fact, common observation as well as past empirical research indicates that at least some hand movements are associated with certain object dimensions (e.g., Brodie & Ross, 1985; Katz, 1925; Lederman, 1982; Ruff, 1984). Consider, for example, what you might do if asked to assess the roughness of a surface. Your natural response is probably to rub the surface. Now consider what you might do if asked to assess the hardness of that same subject. You will probably use rather different movements, e.g., pressing into the object, tapping, or squeezing it. In short, our hypothesis is that there exist distinct classes of hand movements, which are directly related to distinct dimensions of desired knowledge about objects.

We propose further that by identifying these classes and their relationships to knowledge goals, we can investigate the underlying haptic representation of objects in memory and the processes by which these are created and utilized. In this sense, exploratory movements serve as "windows" through which the haptic system can be viewed.

### *The Nature of Haptic Exploration*

In order to address whether hand movements are purposively related to desired object knowledge, we must consider the types of movements that can reliably be observed, and the object dimensions with which they might be associated. The present and following sections describe what can be observed during haptic "apprehension," by which we mean assessing object properties and understanding how they combine to produce the whole. We contrast apprehension with "recognition," i.e., categorization.

The haptic system provides a uniquely rich domain of observation. Note that this is in marked contrast to the visual domain, where object encoding processes are largely (with the exception of eye fixations and movements) internal. Our description uses, as the basic unit of observation, a construct called an *exploratory procedure* or *EP*. An "EP" is a stereotyped movement pattern having certain characteristics that are invariant and others that are highly typical. It need not correspond to a particular configuration of the hand, a fixed pressure, or particular end effectors. In general, EPs are executed by a variety of effector configurations, but still maintain their invariant (and usually, their typical) properties.

Consider once again the evaluation of roughness. Regardless of the portion or area of skin used (e.g., palm vs fingertips) or the mode of touch (e.g., stationary hand on moving object, or moving hand on stationary object), there *must* occur relative motion between skin and textured surface (Katz, 1925; Lederman, 1982). This lateral motion is the invariant for an EP.

The nature of the proposed EPs and their relationships to object-based knowledge are summarized in Table 1, which organizes the EPs by the object properties they are assumed to elicit. The first set of properties perceived is related to the substance of the object: texture, hardness, temperature (most commonly, thermal flow), and weight. The next set is properties related to the object's structure: global shape, exact shape, volume, and again, weight. Finally, we propose two properties that are related to the object's function: one is the nature of the motion of some part of the object, and the second relates to the object's potential function as determined by form.

Figure 1 provides graphic illustration of typical movements used for each of the EPs. However, this figure indicates only one stereotyped version. There follows a brief description of the invariant and typical characteristics that are used for ascertaining that an EP has been executed (with the associated object property in parentheses). Details of scoring are available from the authors.

1. The "lateral motion" EP (texture) manifests sideways movement between skin and object surface, i.e., rubbing (Katz, 1925; Lederman,

TABLE 1
Postulated Links between Knowledge about Objects and EPs

| Knowledge about object | Exploratory procedure |
|---|---|
| Substance-related properties | |
| Texture | Lateral motion |
| Hardness | Pressure |
| Temperature | Static contact |
| Weight | Unsupported holding |
| Structure-related properties | |
| Weight | Unsupported holding |
| Volume | Enclosure, contour following |
| Global shape | Enclosure |
| Exact shape | Contour following |
| Functional properties | |
| Part motion | Part motion test |
| Specific function | Function test |

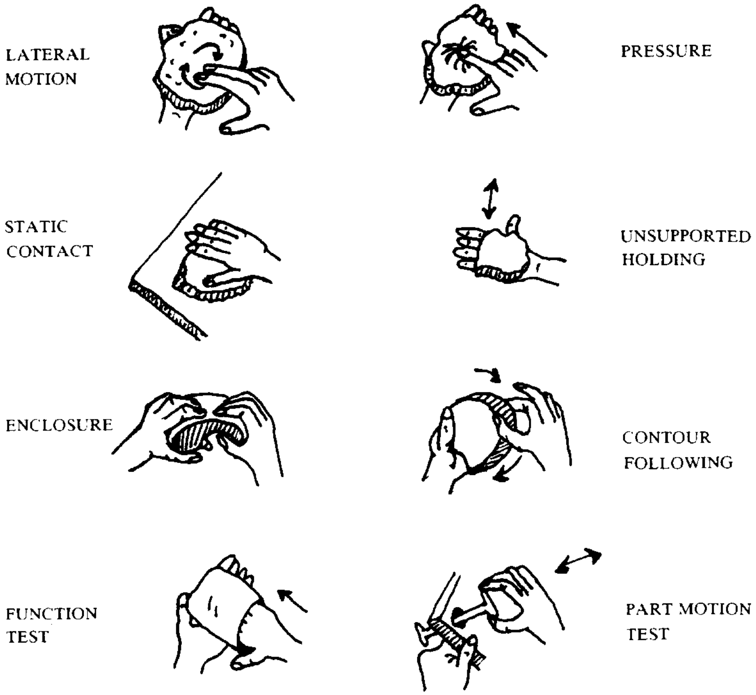


FIG. 1. Typical movement pattern for each of the exploratory procedures (EPs) described in accompanying text.

1982). Typically, the fingers quickly rub back and forth across a small, homogeneous area of the surface; interior surfaces are explored, rather than edges.

2. The "pressure" EP (hardness) is produced by applying torque or normal forces to one part of the object, while another part of the object is stabilized or an opposing force is applied. This can be seen by obvious movement, as in poking, or by signs of force evident in the fingers and hand.

3. The "static contact" EP (temperature) occurs when an object is supported externally—by an external surface or the other hand—while one hand passively rests on it without molding.

4. In the "unsupported holding" EP (weight), the object is lifted away from any supporting surface and maintained in the hand without any effort to mold the hand to the object. Typically, there is hefting of the arm or wrist.

5. With the "enclosure" EP (global shape, volume), the hand maintains simultaneous contact with as much of the envelope of the object as possible. Often one can see an effort to mold the hand more precisely to

object contours. Periods of static enclosure may alternate with shifts of the object in the hand(s).

6. "Contour following" (exact shape, volume) is a dynamic EP in which the hand maintains contact with a contour of the object. Typically, the movement is smooth and nonrepetitive within a segment of object contour, stopping or shifting direction when a contour segment ends, and it does not occur on a homogeneous surface.

7. The "part motion test" EP (part motion) is the act of making a part move, by applying force to the part while stabilizing or applying counterforce to the rest of the object. We only define this EP when there exists a moving part.

8. The "function testing" EP (specific function) executes movements that actually perform certain functions. The movements and functions of interest here are running the finger along a conduit, placing the hand or finger into a container, making noise with a noisemaker, or pinching together the ends of a pincer.

The present investigation is certainly not the first to consider the identification of hand movements. Zinchenko and Lomov (1960) modeled their description after theories of eye movements. They distinguished between micromotions and macromotions, the former being used to maintain a level of stimulation to the receptors, the latter serving to acquire information. Macromotions include movements that seek objects of interest and orient them, and movements that actually manipulate the objects—such as taking measurements or detecting critical junctures in object contours. Davidson and his associates (Davidson, 1972; Davidson, Abbot, & Gershenfeld, 1974; Davidson & Whitson, 1974) have described the position and movements of the hands during specific tasks, such as shape matching. They found that movements could be reliably classified from videotaped records (agreement was as high as 84%) into such categories as global search (simultaneous exploration of several object attributes), detailed search, palm search, tracing, gripping, pinching, and top sweeping. More recently, Ruff (e.g., 1984) investigated the effects of manipulating familiarity and object properties on infants' free exploration of objects using vision and touch (oral, manual). She reliably classified her videotaped data into looking, fingering, rotation, transferring of object between the hands, mouthing, banging, and dropping.

Zinchenko and Lomov appear to have produced a very abstract description of haptic exploration, motivated by the goal of finding similarities with visual perception. In contrast, the classificatory scheme of Davidson and his associates is quite concrete, probably because they constrained the task to nonsense shapes of uniform material and similar configuration; this would limit the domain of exploratory movements and positions. Ruff has focused on the developmental aspects of object manipulation in the presence of vision, emphasizing the importance of exploration for perceptual and cognitive development. The procedural description proposed here lies closest to the level of analysis used by Ruff, somewhere between those of Zinchenko and Lomov (1960) and Davidson (1972).

The present partitioning of hand movements was constructed with several goals and constraints in mind. (1) The EPs were intended to capture the nature of movement variation specifically during object apprehension and recognition. Previous work (Klatzky et al., 1985) identified dimensions that subjects reported having used to categorize objects; these specified dimensions are progenitors of the present EP classes. Clearly, the list of hand movements could be expanded; for example, one could include pencil-sharpening and tape-dispensing motions. However, we excluded such object-specific movements, focusing instead on procedures that would be more generally observable and related to determining object properties. This is true even of the present function-test EP, which examines general functions that could be discerned from the structural and surface properties of even unfamiliar objects. (2) The present set of EPs was also constructed with the goal of pooling movements that are functionally alike, rather than those that look identical. (3) Finally, each EP is intended to be an unambiguous as possible, which limited the level of specificity of our description. For example, slight variations in pressure might be valuable to consider, but are difficult to determine from purely visual data and are therefore not analyzed here.

Experiment 1 directly validates our classification of EPs and the proposed object knowledge/EP pairings. We instructed our observers to perform a match-to-sample task based on specified object dimensions (e.g., texture, hardness) and subsequently determined which EPs they used. Our observers' hands were videotaped as they explored objects freely and bimanually. By using variation in instructions to manipulate the type of knowledge likely to be sought, the experiment tests the assumption that EPs are driven by particular knowledge goals.

Experiment 2 addresses the reasons for the observed links between exploratory movement patterns and the desired knowledge about objects. It questions whether an EP is used because it is necessary, sufficient, or optimal for apprehending an object dimension. On any trial, observers were constrained to using a single EP during exploration in a match-to-sample task based on one specified object dimension (see Experiment 1). Across trials, all combinations were used in order to determine the relative efficacy of each EP for each knowledge goal.

## EXPERIMENT 1: INSTRUCTED HAPTIC EXPLORATION

### *Method*

*Observers.* Eighteen volunteers (11 females and 7 males) participated. Most were graduate students in psychology; their ages ranged from 21 to 41, with a mean of 26 years. All were experimentally naive.

*Stimuli and apparatus.* Thirty-six sets of three-dimensional stimuli were used. Each object could be enclosed within one or two hands. Each set comprised one standard object and three comparison objects, one of which was the standard's "best match" along some particular dimension, such as hardness. The best match only resembled the standard most closely (according to pilot judgments; see below); it was rarely an exact match. There were nine dimensions of interest (as shown in Table 1), and for each, four sets of objects were constructed. Within each set, a deliberate attempt was made to alter and/or to decorrelate values of dimensions which were irrelevant to the target dimension. There was an approximate gradation in difficulty of matching across the four sets within each dimension, as evidenced by a range of agreement as to the best match in pilot work (see below). Table 2 gives a fairly comprehensive description of the different object sets. Very few of the objects used were familiar to our observers.

*Procedure.* A brief pilot study was performed with 10 observers to determine reasonable durations for exploring the objects and to establish a preliminary level of agreement for the set. The instructions and 36 trials were much the same as those to be described for the experimental trials, with one major difference. In the pilot study, observers were told to be as accurate as possible, and to perform the task at a "comfortable" speed. No time limit was imposed. The reaction times to explore the standards were recorded, and averages were calculated over the 10 observers and four object sets for each type of instruction. These mean durations plus one standard deviation were used to set comfortable limits in the experimental trials for exploring the standard object, under a given instruction.

At the beginning of the experiment session, observers were led, blindfolded, into the test room. They were told about the matching task and each of the matches they would be required to perform, as well as how long they could explore. The dimensions (and exploration times) were texture (7 s), hardness (8 s), temperature, described as "how relatively warm or cool the objects feel" (6 s), weight (6 s), volume, described as "three-dimensional size" (7 s), general shape, described as "the regularly shaped container into which the object would best fit with a minimum of empty space," independent of size (10 s), exact shape—precise local variation in contour, ignoring size transformations (20 s), nature of part motion (e.g., rotary vs translational—10 s), and function, described as "the purpose for which the object may be used" (16 s). The observers were instructed to pick the comparison object that *best* matched the standard in terms of the dimension specified, and that none of the three objects need to be identical to the standard on the designated dimension. They were also instructed to ignore all other dimensions of the objects, since they might vary in ways irrelevant to the solution. They were to be as accurate as possible, but also to be as fast as possible. Only rarely did the experimenter have to impose the time limits set with the pilot data. Observers were also instructed to "think out loud" during their exploration.

Practice trials were given with each of the instructions, using a variety of practice sets, until observers were comfortable with all aspects of the task. The order in which the 36 stimulus sets were presented was randomized for each observer. The experimental trials were videotaped in color, with sound. The camera was positioned on a tripod directly behind the observer's right shoulder at a height of 1.5 m, and tilted down approximately 45–55° from the horizontal. Headphones were used during practice and experimental trials to muffle environmental sounds.

TABLE 2
Experiment 1: The Object Set

| Dimension to be matched | Object description |
|---|---|
| Texture | |
| Sets 1 and 2 | Irregular ovals stuffed with fiber fill and covered with fabrics of varying roughness, e.g., vinyl, corduroy |
| Sets 3 and 4 | Variously shaped wood pieces with homogeneous surface altered by sanding or coating, e.g., paint, glass beads |
| Hardness | |
| Sets 5 and 6 | Fabric ovals stuffed with materials varying in hardness, e.g., fiber fill, glass beads |
| Sets 7 and 8 | Varying shapes and materials, e.g., pieces of plastic, copper tubing (harder than Sets 5 and 6) |
| Temperature | |
| Sets 9–12 | An assortment of shapes and sizes made of Styrofoam, foam rubber, porcelain, Plexiglas, aluminum, brass, copper |
| Weight | |
| Sets 13–16 | An assortment of objects varying in material, shape, size, and texture |
| Volume | |
| Sets 17–20 | Irregular 3D wooden shapes, with weight decorrelated from volume by adding or deleting internal material; small, medium, or large volume |
| Set 17 | Large standard |
| Sets 18, 20 | Medium standard |
| Set 19 | Small standard |
| General shape | |
| Sets 21–24 | Geometric shapes of Styrofoam or foam rubber, e.g., triangle, trapezoid; size and shape decorrelated and surfaces deeply scored to alter exact contour |
| Exact shape | |
| Sets 25–28 | Wooden objects with irregular 2D contour, varying in thickness of third dimension; in two sets, the standard and matching comparison differed by size transformation |
| Part motion | |
| Sets 29–32 | Various objects with one part capable of rotary motion or linear displacement |
| Function | |
| Sets 33–36 | Objects with form suggesting function; standards served as container, noisemaker, pincer, conduit |

The observers began each trial by cupping their hands together, palms upward over the table in front of them. The experimenter then indicated the type of match and how long they could explore the first "standard" object. He then began the videotape recorder, and placed the "standard" into the observer's hands. If exploration was completed before the end of the designated interval, observers indicated this by opening their hands wide. At this signal or at the end of the allotted time, the experimenter replaced the first object with each of the three comparison objects in succession, in pseudo-random order. (On temperature trials, observers quickly rubbed their hands together before examining each subject, to reduce misleading contrast effects.) The observers ended the trial by saying "first," "second," or "third," referring to the number of the best matching comparison object.

### *Results and Discussion*

We report the intersubject agreement (accuracy) data from the experimental subjects briefly here. Table 3 shows mean percentage agreement (averaged over 18 observers) for the four stimulus sets within each of the nine dimensions. There is a reasonable range of matching difficulty within each dimension. For all categories except texture, the term "agreement" describes objective accuracy, since the stimuli could be measured along some defined physical metric. With texture, however, no attempt was made to produce surfaces that varied along a physical dimension described to the observers. Chance performance is 33%.

*Hand movement analysis.* The videotapes of the hand movements performed during exploration of the 36 standards constituted the primary source of data in this experiment. A time code (hours, minutes, seconds, and frame number—30 per s) was marked on each tape.

A naive scorer evaluated the tapes of 11 observers. She began by noting the beginning and end times of each interval during which the standard was explored. The hand motions occurring during each interval were then scored, frame by frame, as a sequence of exploratory procedures (each EP being clearly discernible in its invariant or typical forms), or alternatively, as "task maintenance." The latter included any motions used to maintain the object in a stable position, or to reorient it for further examination. These typically preceded and followed the interval in question, and not infrequently alternated with EPs during that period. The task maintenance procedures were noted, but not analyzed further.

The scorer was instructed to use default rules in classifying ambiguous EPs. These were generally to default to the simpler class, i.e., to static contact if enclosure was questionable; and to enclosure or static contact (whichever was relevant) when pressure was questionable. Further default rules, developed later, are available from the authors. She was also instructed to choose only the most distinct EP if more than one occurred simultaneously. When completely uncertain how to resolve this last ambiguity, the scorer was instructed to note the occurrence of the multiple EPs. This happened relatively rarely, however.

TABLE 3
Experiment 1: Mean Percentage Agreement (Accuracy) for Object Sets

| Matching dimension | Object set | Mean % agreement for each object set (accuracy) | Overall category mean |
|---|---|---|---|
| Texture | 1 | 88.9 | |
| | 2 | 100.0 | 93.05 |
| | 3 | 94.4 | |
| | 4 | 88.9 | |
| Hardness | 5 | 94.4 | |
| | 6 | 88.9 | 94.43 |
| | 7 | 100.0 | |
| | 8 | 94.4 | |
| Temperature | 9 | 94.4 | |
| | 10 | 100.0 | 88.73 |
| | 11 | 88.3 | |
| | 12 | 72.2 | |
| Weight | 13 | 88.9 | |
| | 14 | 72.2 | 65.28 |
| | 15 | 55.6 | |
| | 16 | 44.4 | |
| Volume | 17 | 100.0 | |
| | 18 | 77.8 | 80.55 |
| | 19 | 83.3 | |
| | 20 | 61.1 | |
| General shape | 21 | 100.0 | |
| | 22 | 83.3 | 87.48 |
| | 23 | 72.2 | |
| | 24 | 94.4 | |
| Exact shape | 25 | 66.7 | |
| | 26 | 88.9 | 76.40 |
| | 27 | 72.2 | |
| | 28 | 77.8 | |
| Part motion | 29 | 88.9 | |
| | 30 | 100.0 | 93.05 |
| | 31 | 100.0 | |
| | 32 | 83.3 | |
| Function | 33 | 88.9 | |
| | 34 | 83.3 | 84.70 |
| | 35 | 83.3 | |
| | 36 | 83.3 | |
| Grand mean | | 84.6 | |

The data from this study are "profiles" of exploration durations for each instruction condition. That is, for each object dimension that was to be used as the basis of a match, the total durations during which each EP was used were calculated. The part-motion and function-test EPs were scored only on the 8 trials where part motion and function were to be matched. The remaining six EPs—lateral motion, pressure, static contact, unsupported holding, enclosure, and contour following—were scored on all 36 trials. Thus there was a total of 232 scores.

*Intersubject reliability.* Following the scoring of the data from the first 11 observers, a split-half reliability check was performed to evaluate intersubject agreement. The data were split into one set consisting of the mean EP durations (for each relevant EP by instruction combination) averaged across the first 5 observers, to be correlated with a second set consisting of the corresponding mean EP durations averaged over the remaining 6 observers. The correlated data were the mean durations for each relevant EP, by instruction. Calculation of the Pearson product–moment correlation indicated that the intersubject reliability was very high, $r(258) = .92$, $p < .0001$. As scoring was extremely time-consuming, we based all subsequent analyses on the data from these 11 observers.

*Analysis of movement profiles.* The profiles averaged across 11 observers and four object sets per instruction are shown in Table 4a as simple durations. Analysis of variance on this matrix, excluding the part-motion and function-test EPs (which were not part of a factorial design), revealed significant effects of EP, $F(5,50) = 33.3$, $p < .001$, but not instruction, $F < 1$, and an interaction, $F(30,300) = 29.9$, $p < .001$. This indicates that EPs were not uniform over instructions.

We next tested whether this nonuniformity was as predicted. A contrast was performed on these data, testing against the interaction error term. The weights for the predictor matrix were obtained from the original EP/dimension links postulated, i.e., lateral motion/texture, pressure/hardness, static contact/temperature, unsupported holding/weight, enclosure and contour following/volume, enclosure/global shape, and contour following/exact shape. This contrast was highly significant, $F(1,300) = 97.31$, $p < .001$. Thus, there is strong support for the EP/dimension pairings initially proposed. There were two noteworthy departures from these original predictions which, if incorporated into the weights, would increase the contrast substantially. First, an enclosure EP, rather than the originally predicted static contact, predominated on temperature-matching trials. Second, contour following, rather than the initially predicted enclosure, was greatest for global shape. However, contour following generally has a considerably longer duration.

This latter departure from predictions points out a problem with the raw duration analysis; it does not take into account the fact that different EPs inherently take different times to execute. Accordingly, Table 4b presents the duration data in the form of $z$ scores computed over columns, which adjust for this difference. The part-motion and function-test procedures have again been excluded, since they were only scored for selected trials. Each cell entry shows the $z$-score deviation of the

TABLE 4a
Mean Duration (Seconds) of Exploratory Procedures under Each Instruction

| | Instruction procedure | | | | | | |
|---|---|---|---|---|---|---|---|
| | Lat'l motion | Press. | Static contact | Unsupp'd holding | Encl. | Contour follow. | Part mo./fcn. |
| Text. | 3.46 | 0.18 | 0.00 | 0.00 | 0.07 | 0.82 | — |
| Hard. | 0.66 | 2.24 | 0.01 | 0.05 | 0.03 | 0.52 | — |
| Temp. | 0.02 | 0.13 | 0.06 | 0.00 | 2.00 | 0.58 | — |
| Wt. | 0.10 | 0.08 | 0.00 | 2.12 | 0.28 | 0.55 | — |
| Vol. | 0.20 | 0.01 | 0.04 | 0.07 | 2.61 | 2.15 | — |
| Shape (global) | 0.32 | 0.13 | 0.00 | 0.00 | 1.00 | 4.30 | — |
| Shape (exact) | 0.35 | 0.00 | 0.00 | 0.03 | 1.92 | 11.20 | — |
| Part mo. | 0.00 | 0.06 | 0.03 | 0.00 | 0.43 | 2.13 | 3.26 |
| Fcn. | 0.24 | 0.18 | 0.08 | 0.00 | 0.26 | 2.42 | 3.50 |

TABLE 4b
Duration of Exploratory Procedures under Each Instruction (*z* Scores Normalized by Columns)

| | Instructional procedure | | | | | |
|---|---|---|---|---|---|---|
| | Lat'l motion | Press. | Static contact | Unsupp'd holding | Encl. | Contour follow. |
| Text. | 2.78 | −0.22 | −0.89 | −0.38 | −0.96 | −0.60 |
| Hard. | 0.06 | 2.82 | −0.46 | −0.30 | −1.00 | −0.69 |
| Temp. | −0.56 | −0.31 | 1.43 | −0.38 | 1.13 | −0.67 |
| Wt. | −0.48 | −0.38 | −0.89 | 2.83 | −0.73 | −0.68 |
| Vol. | −0.38 | −0.48 | 0.61 | −0.28 | 1.80 | −0.18 |
| Shape (global) | −0.27 | −0.30 | −0.89 | −0.38 | 0.05 | 0.48 |
| Shape (exact) | −0.24 | −0.49 | −0.89 | −0.34 | 1.05 | 2.63 |
| Part mo. | −0.58 | −0.41 | 0.11 | −0.38 | −0.57 | −0.19 |
| Fcn. | −0.34 | −0.23 | 1.79 | −0.38 | −0.76 | −0.10 |

given exploratory procedure for the dimension-matching instruction, relative to the same procedure when other dimensions were specified.

Again, the distributions for each instruction are far from uniform. There tend to be clear cases where a procedure is executed, and cases where it is not. To test whether those present were the ones which we originally predicted, the observed matrix was correlated with a predictor matrix of zeros and ones, according to whether a procedure was predicted for a given instructed dimension or not. Using our original predictions (as per Table 1), this correlation is .78. In comparison, the maximum post hoc correlation we could obtain, predicting observed positive $z$ scores with one and observed negatives with zero, is .86. The most striking departure from our original predictions was a tendency to enclose an object to assess its temperature, rather than to use static contact. This seems reasonable in retrospect, in that enclosure would maximize the contacting skin surface for the relatively small objects that we used. We have also informally noticed that this use of enclosure is less molded to the detailed contour of the object than is enclosure for the purpose of assessing shape.

These initial tests indicated that the observed EPs were generally predictable from the specified object dimenion. Next we considered how different the movement profiles were under different instructions. The durations of exploration were subjected to a classificatory discriminant analysis, to determine whether the matching instruction of a trial could be predicted from the movement profile, that is, from the duration of each procedure. Again, we eliminated the part-motion and function-test procedures as predictor variables, because they did not apply to all objects. However, we did include the part-motion and function-test instructions in the set to be classified. This analysis indicated that the profiles of movement were sufficiently different to classify a trial according to the dimension that was specified as the basis for the match. Classification was entirely accurate except for the part-motion and function-test trials, which tended to be confused with one another. (Recall, however, that the EPs that would be most diagnostic of those trials were excluded.)

The generalized measure of the distance between classes, Mahalanobis $D^2$ (i.e., the distance between the mean vectors of two classes, normalized by the variance/covariance matrix), was used in a $U$-statistic hierarchical clustering analysis (D'Andrade, 1978) to determine the relationships between the various instructions in terms of duration profiles. Figure 2 shows the results of this analysis by plotting the cluster formed against the similarity value at the point of formation. Part motion and function are maximally similar with respect to the durations of the six procedures included in this analysis. Next to cluster are temperature and volume, which tended to concentrate on enclosure and static contact, although we assume for different reasons. Global shape then clusters in with part motion and function test, and so on up the tree. Exact shape enters last because its duration profile is distinguished by long periods of contour following.

The similarities in Fig. 2 reflect the finding that part-motion and function-matching instructions tend to induce substantial contour following and static contact. The first of these seems reasonable, since knowledge of motion and function are likely to follow from structural analysis of the

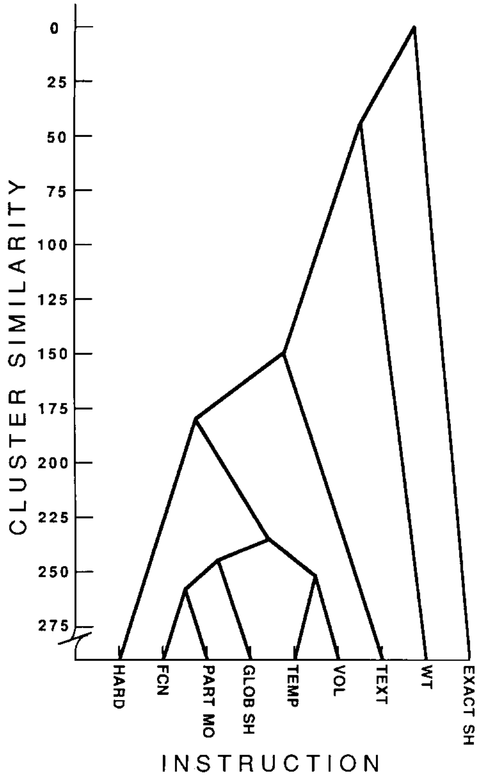


FIG. 2. Experiment 1: Cluster analysis of matching tasks on the basis of movement profiles. The clusters formed are plotted as a function of the similarity values at the points of formation.

object. Static contact, however, is less predictable, because it is the EP associated with temperature detection, and it seems unlikely that temperature would be highly diagnostic of part motion or function. In fact, we take these periods of static contact to be intervals of cognitive analysis, when purposive movement is temporarily stalled. Thus, they might alternatively be viewed as maintenance periods, intended simply to maintain the object in contact with the hand.

*Reliability checks.* A second scorer (the experimenter) was used to check the reliability of a substantial portion of the first scorer's output. One-quarter of the trials for each of 11 subjects were randomly chosen for scoring by the second scorer, i.e., a total of 99 trials from the complete set of 396 trials in the experiment. Several different kinds of reliability checks were performed, which together indicate an acceptable level of interscorer agreement for this first study. Since the scoring rules were still under development, Scorer 2 received expanded scoring instructions and default rules. As a result, this scorer tended to note more short EPs that varied in kind than Scorer 1, particularly during long periods of structural exploration (alone, or in conjunction with part motion and function test). Therefore, the reliability scores obtained are probably lower than will occur in future studies. Details of the reliability checks may be obtained from the authors.

Recall that most exploratory periods began and ended with task-maintenance movements, with a period of purposive exploration in between (lasting from the beginning of the first EP to the end of the last EP). To determine whether there was confusion between the maintenance and purposive periods, the number of trials in which the pair of corresponding purposive intervals overlapped between scores by at least 80% was divided by the total number of trials, and converted to a percentage. Over nine randomly chosen trials, this value was 88%; as the remaining data looked quite similar, no further analysis was performed.

The percentage agreement between scorers regarding the specific EPs executed was considered next. The item reliability score was simply twice the number of EPs observed by both scorers on a trial, divided by the total number of EPs observed by either. To calculate this score, certain relaxation rules were applied to the data because of the difference in the detail with which the scorers were instructed to evaluate the hand movements. In the first reliability check, the changes consisted essentially of combining certain EPs that occurred in rapid alternation (i.e., between contour following and enclosure; between contour following and part motion or function test), or that were only separated by a task maintenance. To smooth the data, any event that lasted less than 15 frames, i.e., 0.5 s, was eliminated, except for pressure EPs (which can be very brief, as in a poke). The resulting reliability was 77%. In a second reliability check, we also permitted matches between contour following and enclosure (this occurred on 5 out of 99 trials); these EPs, which occurred during structural exploration, were so brief that it was difficult to tell whether one or both had occurred. The resulting reliability rose to 80%. Finally, the percentage overlap in the durations of EPs scored in the same way by the two judges (under the second reliability check rules) was 86%.

When scorers disagreed on which EP had occurred (17/292 cases checked, under the second reliability check rules), confusions appeared to be legitimate when we examined the videotape. No single pair of EPs was particularly confused; the greatest confusion was between enclosure and contour following (4 cases), which are often discriminated only by movement and may alternate rapidly. When only one of the scorers noted the presence of an EP (46 cases), it seems to reflect particular scoring biases for each judge, determined mainly by the new rules introduced for the second scorer.

The results of Experiment 1 clearly indicate that in a free exploration task, the movements of the human hand are well defined and nonrandom. Moreover, the various EPs appear to be linked to specific knowledge about the object, is predicted in Table 1. The movement profiles are not only predictable, but distinctive enough to identify the type of desired knowledge from observations of the hand. We have suggested that these links result from motor enhancement of purely sensory competencies of the hand.

## EXPERIMENT 2: CONSTRAINED HAPTIC EXPLORATION

Although Experiment 1 clearly links exploratory activity to desired knowledge about objects, the underlying reason for the connection remains uncertain. An EP might be used because it is the only means of ascertaining an object dimension or because it is optimal, i.e., the best way. It is also possible that an EP will be used when it is only sufficient (rather than necessary) for learning about a given dimension. In this case, its utility might lie in the fact that although it extracts information about some other dimension better, it can also obtain sufficient information about several specified dimensions simultaneously.

We conducted Experiment 2 to determine the reason for the various EP/dimension links observed in Experiment 1. Observers performed the same match-to-sample task, but were restricted to the use of a single prespecified EP on any trial. Each EP was paired with each dimension-matching instruction. This design allowed us to determine the necessity, sufficiency, and optimality of EPs, defined as follows.

An EP is considered "sufficient" if it permits above chance performance. An EP is "necessary" if it is the only method which results in above chance performance. Finally, a sufficient EP is also considered "optimal" for obtaining information about a named property if, compared to other sufficient EPs, it results in the most accurate performance, or is the fastest when accuracies are comparable.

### *Method*

*Observers.* Forty-eight student volunteers from an introductory psychology class participated. All were experimentally naive and had no problems associated with sensory or motor hand function. The observers were randomly assigned to three groups.

*Stimuli and apparatus.* The stimulus objects and videotape equipment have been described in detail in Experiment 1. The stimuli were firmly held in place using two-sided tape or playdough; the choice of adherent was determined by whichever provided the most 3-D exposure to the object, given the EP required for exploration.

*Procedure and experimental design.* Observers were instructed as in the match-to-sample task of Experiment 1, except that they were required to limit their hand movements in carefully prescribed ways during each trial. It was emphasized that although the hand movement specified by the experimenter might not be the one(s) they would have preferred to use to learn about a particular object property, they should do the very best they could under the circumstances. They were told the study was designed to learn how well people can perform when they are only allowed to move their hands in a certain way.

Precise descriptions of the six EPs to be used in exploration were provided. Each EP was referred to by name throughout the experiment. For "lateral motion," the middle finger was placed on some homogeneous part of the object's surface, and observers rubbed the surface in a quick back and forth motion. For "pressure," the middle finger was placed on the object, and observers pushed directly into the object's surface, alternately pushing and relaxing. For "static contact," the entire palm of the observer's preferred hand was placed gently against the object, where it relaxed without moulding to the object's contours. For "unsupported holding," the object was placed in the observer's hand, which rested palm up on the table. He or she lifted the hand off the table and hefted the object up and down, cupping the hand a little to prevent the object from rolling, but without molding. For "enclosure," observers rested one hand palm up on the table, with the wrist on the table edge. When an object was placed in this hand, observers closed their fingers around its edges, using the other hand as well if desired. Finally, for "contour following," the middle finger was placed on an edge of the object resting on the table. Observers were to follow along its contours, using as many fingers of either/both hands as they wished. For each EP instruction, observers were told not to use any of the other forms of exploratory motions which had been explained. Movement was monitored by the experimenter.

Observers were permitted to explore an object using a specified EP for a limited period of time. The times chosen for the six different EPs were determined from the data shown in Table 4a, since these were chosen freely by observers during investigation of the standards. The "regular duration" value for each EP was in most cases simply the average duration of that EP on trials with the most relevant instruction, rounded to the nearest second (lateral motion EP—from texture instruction, 3 s; pressure EP—from hardness instruction, 2 s; unsupported holding—from weight, 2 s; enclosure—from volume, 3s; contour following—from exact shape, 11 s). The regular duration of the static contact EP was calculated as the sum of both the static contact and enclosure durations during temperature trials (2 s), because enclosure on those trials appeared to be a special form of static contact. Two other EP duration levels ("short" and "long") were then set at ½ and 2 times the regular values. Duration of exploration was manipulated between observers ($n$ = 16 per duration condition). If the observers completed their exploration before the allotted time interval was finished, they simply withdrew their hand from the object; otherwise, the experimenter indicated when they should stop.

Each of the six EP instructions was paired with each of the seven dimension-matching instructions, for a total of 42 trials. The order in which these trials occurred was randomly determined, with the stipulation that no object set could appear more than once every 10 trials. The four different object sets used for each instruction in Experiment 1 were also used here with that same instruction (and no other, as they had originally been designed for that instruction), but equally often with all six EPs, counterbalanced across blocks of either observers.

### *Results and Discussion*

The principal results are the accuracy levels, in terms of number of subjects giving the correct response (as defined from Experiment 1), within each combination of exploration time, instruction, and exploratory activity.

*Effect of EP duration.* The effect on accuracy of altering the length of time that the observer was permitted to explore each object was quite variable, and no systematic trends were apparent. No further analysis involving this factor was therefore performed, and data were combined over groups.

*Accuracy analysis.* Figures 3a–3g show, in histogram form, the accuracy level (percentage) for each EP, under each dimension-matching instruction. The EPs are ordered from best to worst along the X axis, with an asterisk marking the predominant EP for that instruction observed in Experiment 1. Within each instruction, the six EPs were each tested against chance performance (using $z$ scores with alpha adjusted for six comparisons). The EPs resulting in only chance performance are indicated in Figs. 3a–3g.

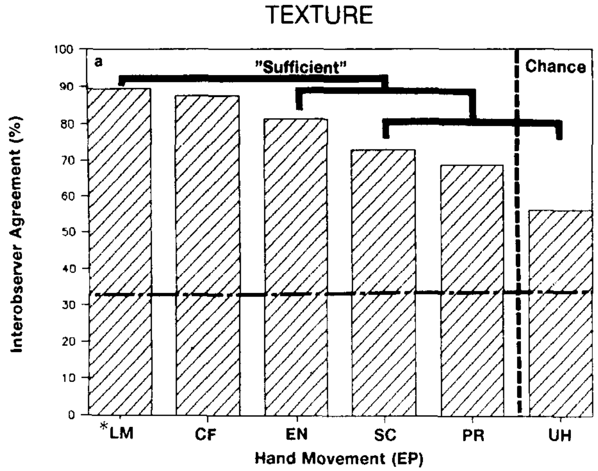
*EP necessity.* An EP is necessary if it is the only one to produce above chance performance. The results of the accuracy analysis indicate that only one EP can be considered "necessary" for any of the dimensions. It is contour following, which is necessary when matching objects on the basis of their exact shape.

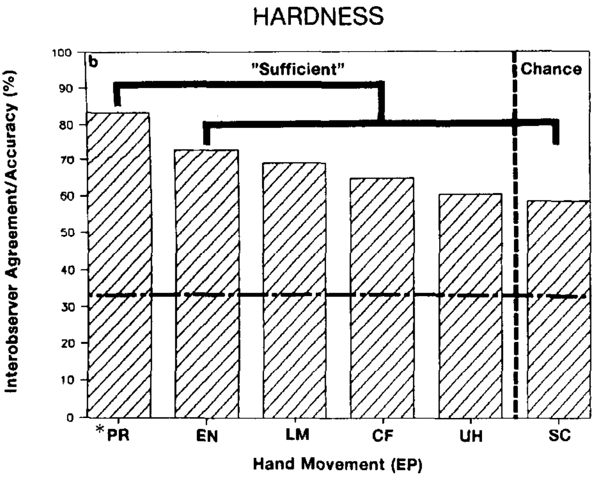
*EP sufficiency.* For each instruction, only those EPs which performed the task at above chance levels may be considered to be "sufficient." There are from 1 to 6 EPs sufficient for each instruction, as shown in Fig. 3.

*EP optimality.* An EP is optimal for a given dimension if it leads to greater accuracy than any other EP. It may be seen that for each dimension-matching instruction (with the exception of global shape), the highest accuracy scores tended to be those expected from the results of Experiment 1. In that sense, then, the predicted EP was usually optimal. The EPs can be further grouped by relative accuracy on the basis of an estimate of the .05 confidence intervals around the number of correct responses. This interval varies with the actual number, but when calculated from the mean number of correct responses over all conditions (29.76, out of a possible 48), the upper and lower bounds of the interval were $+8.46$ and $-9.98$. The average of these intervals, i.e., observed number ± 9.25, was used.

Figures 3a–3g show the EPs (or groups of EPs) which were significantly different from one another by this test. The predicted EPs were clear winners for the dimensions of pressure and temperature, whereas for other dimensions, they were statistically grouped with competing EPs. Initially, perhaps the only surprising results are that static contact and contour following performed the global shape task best, although enclosure, the predicted EP, performed above chance.

In the case where an EP is not a clear winner in accuracy, optimality can be defined as a speed advantage. The EP durations derived from Experiment 1 and used in this study seem to be reasonable indicators of relative speed. Observation of subjects indicates that either the assigned





FIGS. 3a–3g. Experiment 2: Histograms of the accuracy level for each EP under each dimension-matching instruction. EPs are ordered left to right from highest to lowest accuracy. EPs which did not attain above chance performance are shown to the right of the dashed vertical line. EPs to the left of the vertical line were all sufficient for performing the task. The heavy brackets at the top join EPs that did not statistically differ. The asterisk indicates the EP predicted to yield the highest performance, on the basis of the standardized duration scores of Experiment 1 (Table 4b).

intervals were fully used (in the "short" condition, and the "regular" before extensive practice), or, if truncated, the EPs tended to retain the same relative ordering. Thus, we may conclude that lateral motion is optimal for texture matching, even though contour following is statistically equally accurate, because the former is considerably faster than the latter. The same argument may be made for unsupported finding (2 s)

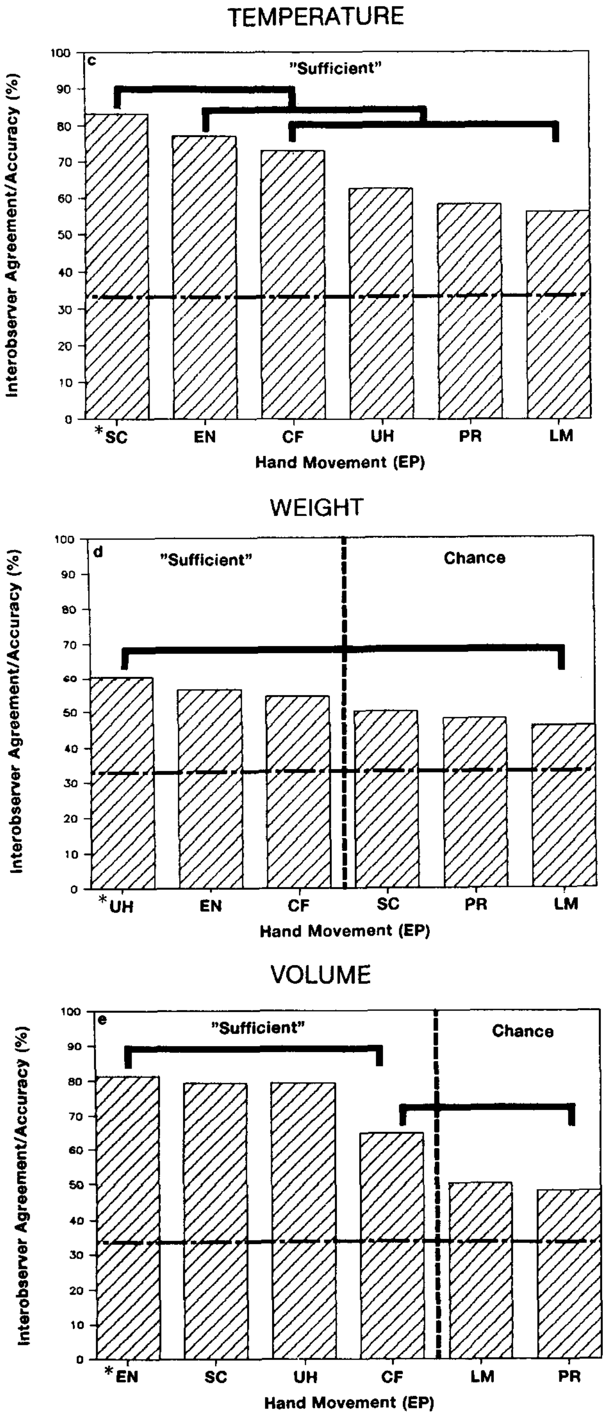


FIG. 3—*Continued.*

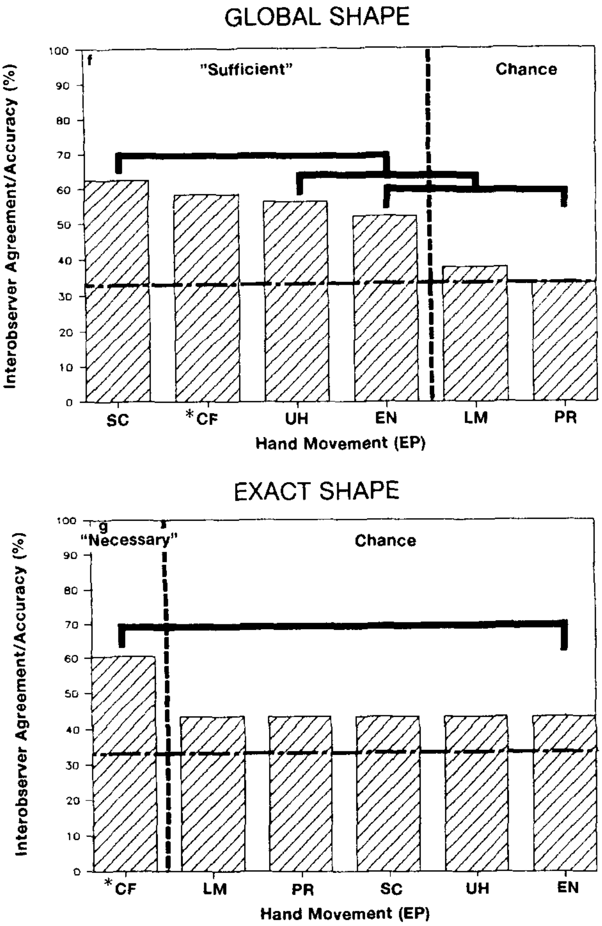


FIG. 3—*Continued.*

over both enclosure (3 s) and contour following (11 s), in weight-matching trials.

Two considerations suggest that our indices of optimality here should be taken as indicating a lower bound. First, execution of one EP may inevitably involve another to some degree. For example, lateral motion is probably effected during contour following, even though in an unconstrained context these two EPs would be performed quite differently. This inseparability of EPs means that the effectiveness of nonpredicted EPs may be inflated, through their involvement with predicted ones. Second, the particular instructions given here may have reduced the effectiveness of an EP, by constraining its execution. For example, enclosure was designed here to eliminate unsupported holding, and thus to minimize weight cues. However, this may also have limited the amount of three-dimensional structural information obtainable. This version of an enclosure EP then probably underestimates performance in global shape and volume matching.

*EP specialization.* While one EP may be used to obtain specialized information about a single property, another may be used simultaneously to obtain information about a number of different object attributes. We therefore calculated a measure of the relative specialization of each EP. Essentially, this measure indicates how much better an EP does in its most successful condition than in other circumstances.

The accuracy scores of the six EPs within each dimension-matching instruction were converted to $z$ scores, indicating how well the EP performed relative to others in ascertaining the given dimension. The highest such $z$ score for an EP, across instructions, indicates the condition of the EP's most superior performance. The mean of the remaining six $z$ scores for the EP was also calculated, indicating its performance under other instructions. The difference between the highest $z$ score and the mean of the remaining scores is the specialization score for that EP. If an EP's most superior performance was not much better than its performance under other instructions, this score is close to zero. If the EP was very superior in one condition, and very inferior in others, the score will be high. An estimate of a reasonable maximum is twice the largest $z$ score, or 4.5.

Table 5 shows each EP's highest $z$ score, the mean of the others, and the specialization value. Pressure proves to be the most highly specialized EP, followed by lateral motion. Enclosure is considerably less specialized than any of the other EPs. It is above chance for most dimensions, but not a clear winner for any.

Table 6 summarizes the status of EPs in terms of necessity, sufficiency, optimality, and specialization. Where there is no statistical difference in accuracy, the optimal EP was chosen on the basis of the "regular" EP durations derived from Experiment 1 (also shown). Thus, for volume,

TABLE 5
Calculation of EP Specialization Scores

| | Exploratory procedure | | | | | |
|---|---|---|---|---|---|---|
| | LM | PR | SC | UH | EN | CF |
| Highest $z$ score | +1.18 | +1.81 | +1.50 | +1.58 | +1.02 | +2.25 |
| Ave. of lowest 5 $z$ scores for each EP | −0.88 | −0.98 | −0.06 | −0.37 | +0:40 | +0.33 |
| EP specialization | +2.06 | +2.79 | +1.56 | +1.95 | +0.62 | +1.92 |

although enclosure had a higher accuracy score, static contact is determined to be optimal because it is statistically equal and has a duration advantage.

## GENERAL DISCUSSION

Our current research originated with the remarkable contrast noted between the skill with which haptics recognizes common objects at the "basic" level, and its inability to perceive and identify simple planar displays. This marked difference has led us to consider the nature of haptic object recognition. What is there about this task that lends itself so well to the haptic system? Our long-term goal is the development of a model of human haptic object recognition. The current study constitutes our first step in this direction.

Our thinking begins with the observation that haptics commonly takes information in sequentially by means of a series of stereotypical exploratory movements. We have assumed, moreover, that these movements are purposive, and that the classes of movement (i.e., haptic exploratory procedures or EPs) are dictated by the object properties that the haptic system chooses to process, both perceptually and cognitively. Thus, by investigating exploratory procedures, it becomes possible to investigate haptic representation and processing in a more general sense.

Similar arguments have been made for using eye movements to identify the processes that underlie visual pattern recognition (Noton & Stark, 1971). Considerations of the success of this approach aside, we do not believe that the visual and tactual situations are all that comparable. First, vision is an objective sense, inasmuch as we tend to experience the external world when the eye is stimulated, whether we perform eye

TABLE 6
Specialization Score, Duration, and Performance Status on Specified Object Dimensions for Each Exploratory Procedure (EP)

| | | | Object dimension | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| EP | Spec'n score | Dur'n[a] (s) | Tex. | Hard. | Temp. | Wt. | Vol. | Gl. sh. | Ex. sh. |
| LM | 2.06 | 3 | O | S | S | — | — | — | — |
| PR | 2.79 | 2 | S | O | S | — | — | — | — |
| SC | 1.56 | 2 | S | — | O | — | O | O | — |
| UH | 1.95 | 2 | — | S | S | O | S | S | — |
| EN | 0.62 | 3 | S | S | S | S | S | S | — |
| CF | 1.92 | 11 | S | S | S | S | S | S | N |

*Note*. O = optimal, S = sufficient, N = necessary, — = chance performance.

[a] Duration refers to the "regular" durations of EPs that were selected from Experiment 1 for use in Experiment 2.

movements that are purposive or not. But as Gibson (1962) has pointed out, contact between skin and object tends to yield experiences of objects and surfaces only when we purposively explore the external world. When contact is effect by an external agent, we tend to focus our experienced inwardly as subjective punctate sensations. Thus, purposive hand movements appear critical for haptically experiencing the world outside ourselves. Second, with a single visual glance, it is usually possible to take in considerable information about many objects, even an entire scene. While purposive eye movements certainly do occur, a single fixation is often sufficient to foveate an entire object. In contrast, a haptic glance is usually confined to a single object; moreover, in that instant, the object is rarely accessible in its entirety to the fingertips, which may be considered the skin's foveae (Weinstein, 1968). Thus, movement is required, not just in the way that micromovements of the eyes prevent the visual image from disappearing, but also for access to the complete object.

But will any movement suffice? The results of Experiments 1 and 2 answer this question with a clear negative. Experiment 1 considered how the haptic system gathers information about the properties of objects, which generally vary along a number of physical dimensions at the same time. Our results indicate that observers' exploratory movements depend upon the dimensional information required. The links observed between a specified object dimension and a particular EP generally confirmed those initially proposed in Table 1. Experiment 2 indicates that the EPs preferred during free exploration are usually optimal (i.e., most accurate or efficient), if not necessary, for performing the kind of match-to-sample task specified.

The data from the second study also provide information about the relative specialization of these exploratory movements, and hence suggest a general sequence in which EPs might be performed, i.e., from general to specialized. When an object is initially examined, especially one that is unfamiliar, it may be desirable to obtain fairly crude information quickly about as many different object properties as possible. The data of Experiment 2 indicate that the appropriate EP in this case is enclosure, which is a nonspecialized, broadly sufficient EP. The general information obtained by executing an enclosure EP (accomplished, for example, by an initial quick grasp) could be used to guide subsequent exploration. For example, observing a particularly salient dimension in the broad first pass would dictate next using the EP that is most highly specialized for that dimension.

The distinction between recognition and apprehension is critical for predicting the nature of the movement process during object exploration. Our previous work (Klatzky et al., 1985) indicates that object naming (at the "basic" level) based on haptic exploration can be accomplished very quickly from relatively crude apprehension of an object's dimensions, often by means of just a single grasp. However, when the task requires more precise information concerning an object's dimension(s), it is more likely that a variety of hand movements will be performed that extend over time. We are currently pursuing this prediction.

Some of our hypotheses about the determining factors in object exploration have been more broadly developed as a simple LISP program that we call "HAND"—for haptic apprehension and naming device (Klatzky, Lederman, Roan, & Andre, 1986). This program describes how such variables as the amount and nature of previously acquired information, as well as hypotheses about the explored object, jointly direct the selection of subsequent exploratory procedures. Finally, although this model currently serves a purely conceptual function, a future program conducted along these lines may have direct application. There is now considerable interest in developing robotic perception systems for manipulating and identifying objects by touch (e.g., Allen, 1985; Bajcsy & Goldberg, 1984; Browse & Lederman, 1985; Gaston & Lozano-Peres, 1984). Such an approach as ours could be developed into a model which would serve to guide the exploration and decision-making processes necessary for tactual object recognition by multisensor robots.

To conclude, our earlier research demonstrated that the hand can serve as an efficient perceptual device. Now, we suggest that the hand (more accurately, the hand and brain) is an intelligent device, in that it uses motor capabilities to greatly extend its sensory functions. In providing evidence for this proposal, we have also offered a taxonomy for purposive hand movements that achieve object apprehension. Specific exploratory procedures appear to be linked with specific object dimensions. In most cases, these linkages optimize the speed or accuracy with which readings of the object along the named dimensions are obtained. Our future work will address such questions as what underlying sensory primitives are extracted by the various exploratory procedures, whether dimensions are differentially salient to haptic with and without vision, and how exploration is modified to accede to contextual as well as perceptual demands.

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