Haptic classification of common objects: Knowledge-driven exploration

Article *in* Cognitive Psychology · November 1990

DOI: 10.1016/0010-0285(90)90009-S · Source: PubMed

Roberta L. Klatzky
Carnegie Mellon University

COGNITIVE PSYCHOLOGY 22, 421–459 (1990)

Haptic Classification of Common Objects: Knowledge-Driven Exploration

SUSAN J. LEDERMAN

Queen's University

AND

ROBERTA L. KLATZKY

University of California, Santa Barbara

In Experiment 1, haptically available object properties that would be diagnostic for constrained common object classification at the basic and subordinate levels were elicited in a questionnaire. The results are considered in terms of the nature of the haptically derived representations of common objects. Initial data are also presented regarding knowledge of the natural co-occurrence of properties in haptic object perception. In Experiment 2, the hand movements executed during haptic classification of manipulable common objects were examined. Manual exploration consisted of a two-stage sequence, an initial generalized "grasp-and-lift" routine, followed by a series of more specialized hand-movement patterns strongly driven by knowledge of the property diagnosticity for the specific object (obtained in Experiment 1). The current results may guide computational models of human haptic object classification and the development of perceptual systems for robots equipped with sensate dextrous hands, capable of intelligent exploration, recognition, and manipulation of concrete objects.

The haptic system (Gibson, 1966; Loomis & Lederman, 1986) is a perceptual system that uses both cutaneous and kinesthetic (muscles, tendons, and joints) inputs that are commonly obtained through purposive manual exploration. Klatzky, Lederman, and Metzger (1985) have shown that people are surprisingly competent at recognizing objects haptically.

This study was funded by a contract from the Office of Naval Research (to both authors), and by a grant from the Natural Sciences & Engineering Research Council of Canada (to SJL). Their contribution is equal, and is not reflected by order of authorship. The authors would like to thank Selim Ulug and Cheryl Wilson for running the experiments, and along with Cathy Reed, the statistical analyses. Jackie Wardell (Experiment 2) and Sanjay Agrawal (Experiment 3) scored the videotapes with thoroughness and care, and Craig Summers performed the reliability check. Reprint requests may be addressed to Dr. R. L. Klatzky, Department of Psychology, University of California, Santa Barbara, CA 93106 or to Dr. S. J. Lederman, Department of Psychology, Queen's University, Kingston, Ontario, Canada K7L 3N6.

Subjects identified 100 common multidimensional objects with very few inaccuracies within usually only 1–2 s. These results serve to underscore the considerable information-processing capacities of the haptic system.

Subsequent studies in our lab have begun to shed some light on the reasons for this impressive performance. Each has used constrained tasks and custom-designed multidimensional objects, in order to slow the exploration process down and to render it more amenable to experimental control. The results of such studies highlight the fact that people actively explore their environment, executing a series of stereotypical hand movement patterns ("exploratory procedures" or "EPs") in search of the perceptual attributes and/or the identity of objects, as has been noted previously by Lotz (1856/1885), Katz (1989), and Gibson (1966). The experiments are described next.

Lederman and Klatzky (1987) have delineated the relationships between exploratory movements and perceptual dimensions in a haptic match-to-sample task, in which blindfolded subjects were initially presented with a multidimensional object, the standard, followed by three comparison objects. They were asked to pick the comparison object that best matched the standard on the basis of a particular dimension, for example, roughness. Hand movements during exploration of the standard were videotaped and analyzed as a set of stereotypical hand-movement classes. Each class of hand movement was found to be executed when a particular object dimension (or dimensions) was designated for matching.

More specifically, Lateral Motion (typically repetitive shearing motions along a surface) was most closely associated with the texture dimension, as was Pressure (typically applied normal to the surface) with hardness, Static Contact (static resting of the hand on the object) with temperature, and Unsupported Holding (lifting) with weight. All of these object dimensions are closely related to the substance or material out of which the object is constructed. We differentiate substance properties and their associated EPs from structure properties and their procedures: The structure dimensions include volume or size, which is most closely associated with Enclosure (molding of the fingers to the object contours), gross shape, associated with both Enclosure and Contour Following (dynamic exploration along edges), and precise shape, which is associated exclusively with Contour Following. The original study further defined procedures for testing the function of an object (as determined by its structure) and for determining the motion of an object part. The EPs are described in somewhat greater detail in the Results section of Experiment 2.

Additional experiments have strongly confirmed these object-knowledge/EP links. One study (Klatzky, Lederman, & Reed, 1987) used a task in which objects varying in texture, hardness, shape, and size were freely sorted into perceptually similar piles using haptics alone, or haptics with real vision or visual imagery. The frequency with which a given EP was observed during sorting was found to be directly related to the relative importance of the associated dimension, that is, its relative influence on the similarity judgment. For example, subjects given visual imagery instructions tended to sort primarily on the basis of shape, and also to execute Enclosure and Contour Following, the procedures associated with that dimension.

Using the same objects in a perceptual classification task, we subsequently demonstrated differences in the degree to which haptic object dimensions were integrated (Klatzky, Lederman, & Reed, 1989). Not all dimensions were equally integrated, and the extent of integration was apparently directly related to constraints imposed by exploratory patterns. In particular, texture and hardness information were integrated with each other more than either was with planar shape. The first two dimensions are extracted with compatible exploratory procedures, Lateral Motion and Pressure; these can be executed easily as a hybrid motion on a homogeneous portion of the surface. However, it is relatively difficult to combine either of these procedures with those linked to shape detection; Contour Following and static Enclosure are both typically performed at the edges, where Lateral Motion probably provides more limited texture information, and Pressure might distort the object's shape (particularly when the object is compliant).

We have argued (Lederman & Klatzky, 1987; 1990) that these exploratory movement patterns are critically important to haptic apprehension and recognition. Our approach adopts a cognitive perspective, proposing that exploratory procedures may be studied as a "window" through which it is possible to gain an understanding of the processing and representation in memory of objects assessed via the haptic system. Evidence was initially provided by the dimensional salience and integration studies above, which used custom-designed multidimensional objects. In the current study, we extend this approach still further.

We now focus on exploratory procedures in order to address a number of theoretical and empirical issues concerning haptic categorization of natural objects. The use of an object categorization task further allows us to study general issues concerning the representation of the world of objects accessed through haptics. The problem of classification has been considered in depth by investigators in many academic disciplines, no doubt because it is fundamental to human thought, action, and communication. We function in a world of objects that are regularly perceived in terms of their similarities and differences, and consequently, in terms of the categories to which they are accorded membership. The nature of classification is thus reflected in much of human behavior. Despite the importance of this topic, little attention has been devoted to effects of the sensory modality(ies) through which an object is encountered.

The primary issue in this work is, what determines the sequence of haptic exploration during object categorization? Clearly, human hand movements are not entirely random during object recognition. Perhaps object exploration is confined to simple grasp routines, since grasping usually involves the Enclosure EP. Below, we will describe evidence that Enclosure if a relatively nonspecialized procedure that can simultaneously extract low-level information about a number of dimensions and that also demands little motor energy. But predicting that categorization can be achieved merely by grasping assumes that variations among specific objects are sufficiently large so that diagnostic attributes can be extracted from the gross information provided by an Enclosure. Thus, we hypothesize that exploration is a two-stage process. The first stage involves the execution of general-purpose routines, such as a grasp; the second stage involves more specialized exploration that reflects knowledge-driven or data-driven processing.

Of relevance to the hypotheses above is the work of Rosch and her colleagues (e.g., Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). They have argued for a taxonomy of object classification that considers at least three levels of inclusiveness (or abstraction). The "basic" level is the one that carries the most information about objects and best reflects the correlational structure in the world (as described, for example, by Brunswik's [1956] probabilistic concept of ecological cue validity). That is, certain attributes tend to co-occur within basic-level categories. For example, feathers, wings, and a beak tend to occur with one another more often than do any of them with fur. Furthermore, it is at the basic level where members of different categories are most differentiated. Rosch et al. (1976) have operationally defined the basic level in terms of its being the most inclusive level at which member objects a) share a cluster of defining attributes, b) share a common motor program for using such objects, c) overlap most highly in terms of their shape, and d) share an average image of the category members. In contrast, as the more inclusive "superordinate" level, members of a category share considerably fewer attributes, while at the less inclusive "subordinate" level, members share many attributes with different subordinate categories. For different reasons, therefore, the correlational structure in the superordinate and subordinate levels is lower than at the basic level. Rosch et al. have also shown that basic level objects are typically sorted and named at an earlier age, are most codeable, most often coded, and most required in language. In keeping with Rosch, we will refer to "vertical" differences in classification in terms of level of abstraction (inclusion), with most abstract at the top and least abstract at the bottom. "Horizontal" classification will refer to category differentiation within a common level of abstraction.

These distinctions have potential ramifications with respect to our predictions concerning the course of exploration during haptic classification tasks. We would expect the nature of exploration to depend on whether the target category is at the basic or subordinate level. There are considerably more ways in which object classes are differentiated at the basic level than at the superordinate level; there are far fewer ways in which objects are differentiated at the subordinate level than at the basic level, since they may be similar in all but some critical feature(s). Accordingly, an important influence on the choice of EPs executed might be the extent to which they are broadly useful for several object attributes (and hence potentially most useful to detect a basic-level class) or, alternatively, specialized for a particular attribute (such as the critically diagnostic feature of a subordinate-level class).

In the Lederman and Klatzky study (1987, Experiment 2), EPs were shown to differ in this respect. Whereas each procedure tended to be optimal for the dimension with which it was commonly associated, it could also simultaneously extract other dimensions secondarily. The various EPs differed in terms of the secondary dimensions they could simultaneously extract. To assess this, rather than permitting free exploration in the match-to-sample task, we constrained subjects on each trial to execute a specific EP while matching on a specific targeted dimension (e.g., texture, hardness, etc., as described above). The performance achieved with a given procedure for a given dimension produced a continuum of EP specialization. At one extreme were the highly specialized EPs, which produced high performance on only one dimension of information (as Pressure did for hardness). At the other extreme were multipurpose EPs, which were sufficient for quickly extracting fairly crude information about a number of dimensions simultaneously. Enclosure proved to be the least specialized of all. As a consequence of these results, it was suggested that a generalized EP such as Enclosure would be particularly useful at the beginning of haptic exploration when only gross dimensional information was needed, for solving simple categorization problems, and perhaps for guiding further, more specialized exploration.

On the basis of the discussion above, we further reasoned that basic-level classification should generally be easier than subordinate-level classification. According to Rosch et al. (1976), the defining set of attributes is larger, and the differences between categories within each dimension are typically greater. Our hypothesis was thus modified to predict that when categorizing at the basic level, people would execute a generalized Enclosure EP very frequently. Moreover, a general-purpose routine of this kind might often be sufficient for differentiating the easier basic-level categories. However, since there are fewer dimensions that uniquely differentiate members of different subordinate-level categories, and since the differences are often smaller, we further predicted that people categorizing at this lower level would generally need to execute additional highly specialized EPs, the choice depending upon the dimension(s) known to be diagnostic of category membership ("knowledge-driven" processing directed by hypothesis-testing) and/or upon the nature of the information obtained with an initial Enclosure ("data-driven" processing). Our modified hypothesis rests on an important qualifying assumption, however—that the distinctions of Rosch et al. pertaining to the object knowledge base used when vision is permitted are likewise appropriate when knowledge is accessed by haptics alone. As this was unknown, we chose to address the issue empirically in Experiment 1, by assessing the attribute structure of basic and subordinate categories from a haptic perspective. Because our ultimate purpose was to predict the nature and sequence of manual exploration during haptic object classification, we used a forced-choice attribute rating rather than a free attribute-generation task of the type used by Rosch. Subjects were told to imagine that they were touching the named objects, without vision. They were then required to indicate which object properties would be diagnostic when deciding (a) whether a member of a named superordinate class was also a member of a named basic-level class, or (b) whether a member of a named basic-level class was also a member of a named subordinate-level class. This classification constraint was chosen to guide subjects to think about those attributes that differentiate the lower-level class from other classes at that level with the same higher-level name. This technique should provide a strong test of our predictions concerning links between haptic exploration and knowledge about object attributes; however, it necessarily allows only indirect comparison with the results of free-generation tasks performed in nonhaptic contexts.

In Experiment 1, the experimenter provided subjects with a list of attributes from which to choose those that were potentially diagnostic for a given object. The list included: texture, hardness, temperature, weight, shape, size, motion of a part, and part. The first seven were mentioned as being critical to identification in the phenomenological reports of subjects in the Klatzky et al. (1985) study, and were further studied in our work relating EPs to targeted object dimensions (Lederman & Klatzky, 1987). The last dimension was motivated by the work of Tversky and Hemenway (1984), which suggested that parts are particularly important at the basic level of object classification, as will be discussed subsequently. Also, in our early preparatory work, most subjects felt "part" was not specifically covered by any of the other perceptual dimensions.

The pool of object names formed sets of five members, each including: a superordinate name, two basic names with the same superordinate name, and two subordinate names with the same basic name (e.g., kitchen utensil/frying pan vs. saucepan/cast-iron frying pan vs. aluminum frying pan). The two subordinate-level objects were intended to vary on a dimension that would be particularly diagnostic during subordinate-level categorization (e.g., for a cast-iron frying pan, its weight). We chose object-name sets so that each of the haptic dimensions (texture, shape, etc.) was diagnostic with respect to the subordinate-level classes for at least some sets in the stimulus pool.

Ultimately, Experiments 1 and 2 were intended to verify, during categorization of natural objects, the previously observed associations between specific object dimensions and haptic exploratory procedures. The manipulation of diagnostic attributes at the subordinate level was intended to provide the most powerful test of our predictions, since it was at this level of categorization that the highly specialized EPs would be most likely to occur. We did not attempt to control which attributes were most diagnostic of the corresponding basic-level object classes. Nevertheless, for reasons already outlined, Experiment 1 elicited diagnostic attributes for the objects named at the basic level, as well as those at the subordinate level. (The superordinate-level names were used for context, as described below, and diagnostic attributes for these classes were not elicited.)

In Experiment 2, subjects haptically explored real objects that were capable of being manipulated, one from each of the different name-sets chosen after Experiment 1. They were asked to answer classification questions (constrained as in Experiment 1) of the form, "Is this X further a Y?," where X was a name at the superordinate or basic level, and Y was then a name at the basic or subordinate level, respectively (e.g., "Is this writing utensil further a pencil?" "Is this pencil further a used pencil?"). Both affirmative- and negative-response questions were included. Hand movements were videotaped, and each trial was subsequently scored as a sequence of EPs. The hand-movement data were used in conjunction with the attribute ratings obtained from Experiment 1 to test whether knowledge about objects would lead to the execution of EPs linked to particular diagnostic properties.

These experiments permit us to consider a set of empirical and theoretical questions pertaining to our modified hypothesis. Questions include the following: Does manual exploration include two phases, following a general-to-specialized sequence, as proposed above? If so, what are the general-purpose exploratory routines? Does exploration reflect the use of diagnostic attributes, that is, is it knowledge-driven? A constrained classification task of the sort used here permits us to deal specifically with this issue. We also ask, however, if there is a data-driven component to exploration under these experimental conditions.

The data obtained in the current study also provide information pertaining to the haptic representation of objects in memory. The empirically derived knowledge base obtained in Experiment 1 allows us to address two issues concerning the haptic processing of concrete objects with vision denied, including: (i) the relative importance of different dimensions for constrained object classification both within the basic level (but not within the subordinate level, where the distribution of diagnostic properties was controlled by the experimenters) and between basic vs. subordinate levels, and (ii) the specific knowledge about naturally occurring associations among dimensions of concrete objects. The results of Experiment 2 further allow us to examine differences in the nature of and relative ease with which basic- vs. subordinate-level object classification is performed haptically. Experiment 3 was a reduced version of Experiment 2, in which an alternate procedure was used to initiate contact with the stimulus objects. In confirming the presence of the initial grasp-and-lift routine, the results of that experiment serve to extend the generality of the two-stage exploratory sequence.

EXPERIMENT 1

Diagnostic Attributes for Haptic Object Classification

In Experiment 1, subjects indicated the attribute(s) they considered to be most haptically diagnostic of a given object class belonging to the higher-level class also named. This was necessary to produce conditions that would elicit the association between object attributes targeted for haptic perception and specific exploratory movements. These experimental conditions are used in Experiment 2 to address theoretical and empirical issues pertaining to haptic exploration during object classification, as outlined in the introduction.

Experiment 1 is also generally relevant to issues pertaining to the cognitive representation of objects, as noted earlier. Tversky and Hemenway (1984) have suggested that it is specifically the knowledge of object parts that determines the horizontal separation of basic classes, while knowledge of nonparts differentiates categories at the subordinate level. While the current data base differs substantially from those of either Tversky and Hemenway or of Rosch (which involved free generation of attributes), it permits us to look for the importance of structural diagnosticity, if not parts per se, at the basic level, as well as to compare the diagnosticity of nonparts at basic and subordinate levels.

In considering the relevance of previous assessments of object/attribute associations to our concerns, we note that those assessments did not consider haptic classification per se. In contrast, the present subjects were told to imagine touching the objects, without vision. Conceivably, structural attributes may be less important to defining basic-level categories in a haptic context than in a visual one. This is suggested by our own previous work. Klatzky et al. (1987) showed that shape proved more salient to those who were instructed to use real vision or visual imagery during a haptic sorting task than when haptics was used alone; conversely, haptics alone weighted substance properties more strongly in the sorts than when vision was also present. In the current haptic context, then, properties other than shape may prove to be important at the basic level.

The current study also provides a measure of the extent to which haptic perceptual attributes tend to co-occur, in the sense that both may be useful in classifying the same object. For example, in deciding that an object is a balloon, both its weight and its surface texture might be important diagnostics. Relatively little is known about such "natural redundancies" among object properties and whether they are used (see, e.g., Malt & Smith, 1984, for consideration of correlated properties in natural categories).

Method

Selection of object-name sets. Initially, sets of five object names were compiled with the following relationships. Each set consisted of one name of a concrete object from the "superordinate level," two "basic-level" names of concrete objects from that superordinate category, and finally two "subordinate-level" names of objects from one of those basic-level categories. As an example, "writing utensil" is a superordinate-level item, "pencil" and "crayon" are corresponding basic-level items, and "new pencil" and "used pencil" are corresponding subordinate-level items for pencil. In the initial selection of object sets, we deliberately attempted to represent each of the haptic attributes (excluding function) discussed by Lederman and Klatzky (1987). Thus, some of the subordinate-level classes were likely to be categorized by weight, some by size, and so on. We further attempted to keep the most diagnostic attribute category the same within corresponding subordinate names (so that, e.g., both new and used pencil would be categorized relative to pencil by the same property). Throughout this paper, we will use the term "object-name set" to refer to a set of five object names, with interrelations as described above.

The final list comprised highly familiar and acceptable object names, subdivided into 63 object-name sets of 5 items each. A preliminary experiment was performed to verify the familiarity of each name and its appropriateness for the designated vertical level; details of this study are available from the authors. This list was used in Experiment 1. The final pool of 57 sets that was used in Experiment 2 is presented in the Appendix.

Subjects. Sixty young adults (17 males and 43 females) were paid for participating. All subjects were drawn from an undergraduate perception class, but were experimentally naive as to the purpose and task.

Procedure. Subjects were asked a series of questions about objects and their properties. The general form of the question was: "What property(ies) of an X would lead you further to call it a Y?". For example, "What property(ies) of a book would further lead you to call it a dictionary?" Or, "What property(ies) of a cutting tool would further lead you to call it a scissors?". Subjects were instructed to imagine that they were touching the object, not seeing it. They were asked to write down in a booklet those properties, from an experimenter-provided list, that came spontaneously to mind when they first thought about touching the named object; they were told not to reflect on their answers.

The list of properties provided was based on the earlier work of Lederman and Klatzky (1987), and included: texture ("the way the surface feels as you rub your fingers over it"), hardness, temperature ("how warm or cool it feels to the touch"), weight, size, shape ("the particular shape or form of the whole object or its parts), and part motion (the way a part of an object moves). For reasons just described, we added an additional category, part ("the separate parts an object has"). The two examples above were used to explain further the attribute-classification procedure. Whenever the meaning of a property was potentially unclear, additional examples were provided. The category "part" was described as a category that should be used when people thought of a diagnostic section of the object, independent of any of its perceptual attributes, such as shape. The attributes were to be written down in the order in which they came to mind. Subjects were permitted to answer "don't know" if they were unfamiliar with the object or category named.

A set of questions about different common objects was prepared in the form of a booklet for each subject. The list of the eight diagnostic attributes was available on a separate card, although the random order in which they appeared varied across subjects. Four questions appeared on each page.

Experimental design. Four different types of question could be asked. Of the four, two were basic questions ("S/B1" and "S/B2"): these required a classification judgment about the diagnostic properties that make a member of a superordinate class (S) further a member of the corresponding designated basic-level class (B1 or B2). At this level, then, subjects were required to differentiate a designated class from all other classes belonging to the same superordinate class. The remaining two were "subordinate" questions ("B1/SB1" and "B1/SB2"): these required a similar type of judgment about attributes that make a member of a designated basic-level class, B1, further a member of the corresponding designated subordinate-level class. For the subordinate-level questions, then, subjects were being asked to differentiate a designated class from all other classes belonging to the same basic-level class.

In Experiment 2, the presented objects corresponded to those named in the SB1 questions; the SB2 items were named on negative trials but not presented. For example, subjects were always presented with a used pencil (SB1) but some were queried as to whether it was a new pencil (the SB2 name). In deciding which of the two subordinate names would be assigned to SB1 questions, the object with the more salient value on the anticipated diagnostic dimension was chosen. So, for example, if the diagnostic dimension was part motion, the SB1 object had a moving part whereas the SB2 object did not. Several examples of the four different types of questions are presented in Table 1.

The 60 subjects were randomly assigned to one of four groups, 15 subjects per group. Subjects were counterbalanced (as much as possible) by group across the 63 different object-name sets. Thus each subject received approximately equal numbers of the four types of questions (S/B1, S/B2, B1/SB1, B1/SB2) across the 63 object-name sets, but only answered one type of question within any set. Five different random orders of the 63 sets were used within each group of subjects, one for every three subjects. The entire experiment lasted between 45 min and 1 h.

Results

The absolute frequency of each attribute category listed, aggregated across subjects, object-name sets, and questions, was greater for basic-

TABLE 1

Examples of Four Types of Questions for Several Object-Name Sets

Object-name set	EXPT. 1		EXPT. 2
QN	SPECIFIC QUESTION	QN	SPECIFIC QUESTION
S/B1	What makes an eating utensil further a fork?	B^+	Is this eating utentil further a fork?
S/B2	What makes an eating utensil further a chopstick?	B^-	Is this eating utensil further a chopstick?
B1/SB1	What makes a fork further a dessert fork?	$*SB^+$	Is this fork further a dessert fork?
B1/SB2	What makes a fork further a dinner fork?	SB	Is this fork further a dinner fork?
Object-name set			
S/B1	What makes a clothing fastener further a button?	B^+	Is this clothing fastener further a button?
S/B2	What makes a clothing fastener further a zipper?	B^-	Is this clothing fastener further a zipper?
B1/SB1	What makes a button further a trouser button?	$*SB^+$	Is this button further a trouser button?
B1/SB2	What makes a button further a shirt button?	SB^-	Is this button further a shirt button?
Object-name set			
S/B1	What makes a timepiece further a watch?	B^+	Is this timepiece further a watch?
S/B2	What makes a timepiece further a clock?	B	Is this timepiece further a clock?
B1/SB1	What makes a watch further a woman's watch?	$*SB^+$	Is this watch further a woman's watch?
B1/SB2	What makes a watch further a man's watch?	SB^-	Is this watch further a man's watch?

than for subordinate-level classification (4537 vs. 3648, respectively, each out of a possible 15,120). Given that subjects were being asked to list attributes that would be diagnostic during classification, this outcome presumably indicates that more attributes serve to differentiate one basic class from others within the same superordinate class than serve to differentiate one subordinate class from others belonging to the same basic class.

Frequency ratings of each attribute category, weighted by order of report, were next calculated by object-name set and question (S/B1, etc.). That is, for each of the 252 object-name set (n = 63) by question (n = 4) combinations, a score of 5, 4, 3, 2, or 1 was given to an attribute according to whether it was listed first, second, third, fourth, or fifth, respectively, and these scores were summed over subjects in the given condition to produce an overall weighted frequency. Since attributes were almost never listed in sixth through eighth place, these ranks were excluded. The mean weighted frequencies (obtained by averaging over object-name sets, and aggregating S/B1 with S/B2 and B1/SB1 with B1/SB2) are presented in Fig. 1 for all attributes at both basic and subordinate levels. The relative importance of each attribute within the basic level was assessed using the Newman-Keuls multiple-comparisons tests of the means. As evident in Fig. 1, shape was weighted most strongly, followed by size and texture (all $ps < .01$). Attribute comparisons between basic and subordinate levels were also performed, using post hoc t tests for independent means. These tests indicated that shape was statistically more diagnostic at the basic than the subordinate level, whereas the converse was true for temperature (both $ps < .05$). None of the other attributes statistically differed in its basic-level diagnosticity with respect to the subordinate level.

The attribute with the highest weighted frequency for a given class name can be considered the most diagnostic attribute (MDA) of that class

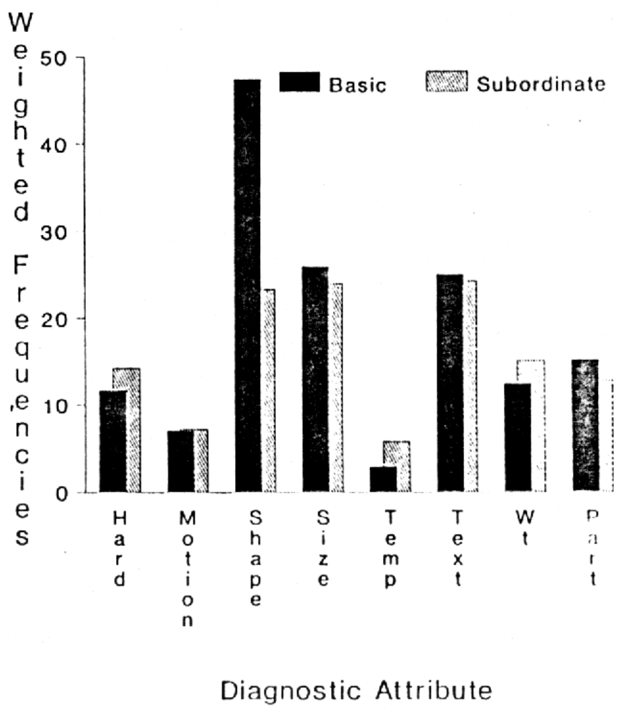

FIG. 1. Experiment 1: Mean weighted frequencies for object attributes at basic and subordinate levels of classification.

(e.g., the MDA for a B1 item is selected from the eight different weighted frequencies for the S/B1 question). The number of object-name sets for which a given attribute was most diagnostic was calculated by question. The data for six object-name sets were not included in the tabulation, because no attribute was strongly diagnostic and/or because at least one of the five names in each set was unknown to at least 40% of the subjects. Thus, the final pool used in Experiment 2 contained 57 object-name sets. These are included in the Appendix, showing the five class names along with their associated MDAs. The MDA of an object class is subsequently used in Experiment 2 to predict the occurrence of the exploratory procedure that is most closely associated with that attribute.

There are clear differences in the frequency distributions of diagnostic attributes (i.e., for each attribute, the number of object-name sets for which it was MDA) at the basic level, compared to the subordinate level. Within both basic and subordinate levels, the frequencies for the two questions were combined (i.e., S/B1 with S/B2; B1/SB1 with B1/SB2), as their frequency distributions were very similar. At the basic level, shape predominated with a maximum of 64 (of 114) object-name sets, while the numbers for hardness and temperature were minimal, with only 0 and 1 items, respectively. It is important to note that only the frequency distribution of the basic-level object-name sets was free to vary, since the associated object names at the subordinate level were chosen by the authors so that each attribute was diagnostic of several object names.

Attribute co-occurrence. For reasons outlined above, we also examined the frequency with which object attributes are perceived to be jointly diagnostic within our base of object-name sets. By jointly diagnostic, we mean that both attributes were listed as diagnostic for the same object name. The proportions of such co-occurrences were calculated for each pair of MDA categories; these were combined across classification levels (basic, subordinate), since the matrices proved to be highly similar, Pearson product moment correlation $r(26) = .894$, $p < .001$. The cells in the matrices were calculated as follows: ($2 \times$ the frequency with which both attributes A and B are listed as diagnostic)/(the sum of the frequencies for A and B, listed alone or in any combination with other attributes).

The major patterns are highlighted in a cluster analysis, which was performed using the co-occurrence scores as a measure of similarity. These results are presented as a tree diagram in Fig. 2. The pattern and sequence of clustering further confirm the distinction previously made between substance and structure dimensions. Note that the structure dimensions of shape and size cluster first, followed by the substance dimensions, texture, and hardness. Weight enters first with the substance group, and then with the structure group, as would be expected since

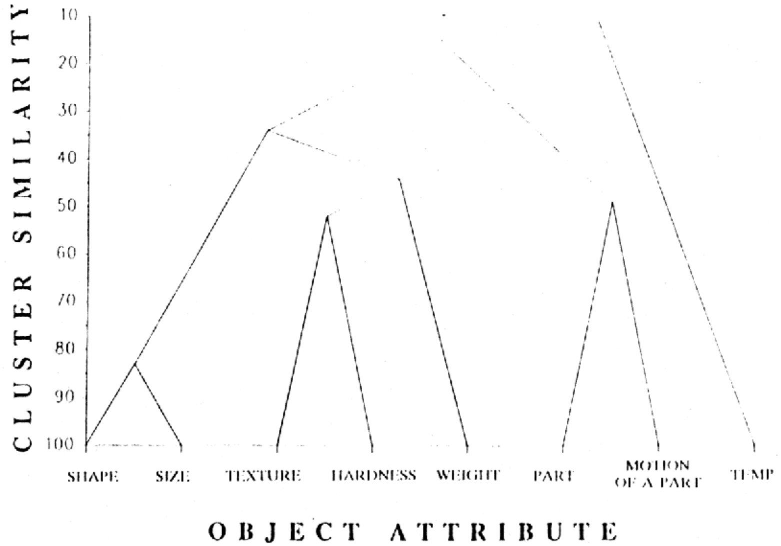

FIG. 2. Experiment 1: Tree graph of cluster analysis of attribute co-occurrence data.

weight is determined by both substance (density) and structure (volume) attributes. Temperature clusters late, suggesting that is not similar to other substance or structure attributes.

EXPERIMENT 2

Exploratory Procedures during Constrained Haptic Classification of Common Objects at Basic and Subordinate Levels

In Experiment 2, subjects were given a series of objects and for each one, were asked a question of the form: "Is this X further a Y?". Either X was the superordinate name and Y was the basic name for the designated object-name set (basic questions), or X was the basic name and Y the subordinate name (subordinate questions). Basic and subordinate questions required positive and negative responses an equal number of times.

The hand movements were videotaped and subsequently analyzed as a sequence of exploratory procedures. We used knowledge of the most diagnostic attribute of an object class (MDA), obtained in Experiment 1, to predict the EP most likely to be executed during haptic exploration in the object recognition task. Specifically, we predicted that the exploratory procedure previously found to be optimal in extracting a designated attribute in the constrained match-to-sample task (Lederman & Klatzky, 1987) would now be relatively likely to occur when that attribute was highly diagnostic for classification of a common object. This outcome

would reflect a purposive, knowledge-driven search for diagnostic features of objects.

Other, more general issues can be addressed by the profile of exploration as well. One issue is how object classification proceeds over time. According to our modified hypothesis, we predicted a two-stage exploration process. During early exploration, we expected to see the most generalized hand movement patterns noted in our earlier work (Lederman & Klatzky, 1987: Study 2). Therefore, we predicted specifically an Enclosure of the object's body, since the latter had been clearly shown to be the least specialized of our EP categories. Only later would the more specialized procedures occur, and then more for subordinate- than basic-level questions. Reaction times and rated task difficulty further permitted us to compare classification performance during the different types of classification conditions, for example, basic vs. subordinate, positive vs. negative, etc.

Method

Subjects. Forty-four (13 males and 31 females) different subjects were drawn from the same population as described in Experiment 1.

Apparatus. Each trial was recorded on videotape. The camera was positioned to the subject's left such that it captured movements as seen from behind and to the left side of the subject. An arrangement of two mirrors on the table provided two additional views of the subject's hand movements, one more directly from the front facing the subject, and one from the subject's right/front. A monitor was used to keep the subject's hand in view during recording. A microphone recorded verbal responses on the videotape. The table was covered with toweling to reduce the noise of objects contacting it.

Procedure. A series of prototypical objects representing the 57 object-name sets retained from Experiment 1 was presented to each subject. The presented objects exemplified the SB1 items from that experiment (members of basic class B1). Four types of questions were prepared for each of the 57 items, corresponding to the four questions used in Experiment 1. All questions were of the form: "Is this X further a Y?". For "Basic Positive" questions, X is the superordinate-level name (S), and Y is the corresponding basic-level name of the object to be haptically explored (B1); the correct response is "yes." For the "Basic Negative" questions, X uses the same superordinate name, but Y is the B2 name used in Experiment 1. The correct response is "no," because the named object is not the one actually presented for exploration. "Subordinate Positive" questions use the B1 name from Experiment 1 as X, and the SB1 name as Y; the correct response is "yes." Finally, "Subordinate Negative" questions also use the B1 name as X, but now include the SB2 name from Experiment 1 as Y; the correct response is "no." Sample questions are presented in Table 1.

Subjects were blindfolded throughout the experiment. On each trial, the experimenter began by reading the appropriate question out loud. He then placed the whole object (when small) or a nondiagnostic portion (when large) on the palm of the subject's preferred hand, as it rested fully open on the table in front. The subject was instructed to begin examining the object freely with one or both hands as soon as the experimenter indicated. He or she was to answer the question by responding "yes" or "no" as quickly and as accurately as possible.

If subjects did not know the class name of the object when the question was initially presented, the trial was discontinued. If they did not know the answer to the question after haptic examination, they were asked to indicate that this was so. Finally, subjects were asked to rate the difficulty of each question on a scale of 1 (very easy) to 5 (very hard). The subject's verbal responses were entered into the computer. The entire session lasted about 45 min to 1 h.

Experimental design. The same counterbalanced design of Experiment 1 was used in Experiment 2, although due to an error in counterbalancing, there were unequal numbers of subjects in the four groups (i.e., 10, 11, 12, and 11). As before, each group answered only one type of question per object-name set, for a total of 57 sets. In this experiment, the order in which the 57 objects were presented was randomized for each subject.

EP Scoring

Initially, the scorer structurally decomposed each of the 57 presented objects into a set of parts. A "body" part is clearly the main section of the object and is usually larger than the other parts, for example, the shaft of the razor. A "secondary" part is any part that is not considered a body part. This analysis was necessary to distinguish between enclosure of the whole object (i.e., body part) vs. enclosure of a part (i.e., secondary part). The whole/part distinction was made because we anticipated that the new attribute "part" would be more clearly predicted by an enclosure of secondary parts than by an enclosure of the body part.

The frequency and sequence of exploratory procedures were scored, using modified instructions from Lederman and Klatzky (1987; instructions available on request). Intervening intervals of "task maintenance" activity, that is, object manipulation for purposes of stabilizing or reorienting, were ignored. Eight classes of exploratory procedure were used: Lateral Motion, Pressure, Static Contact, Unsupported Holding, Enclosure (body), Enclosure (part), Contour Following, and Part Motion. Lateral Motion is a repetitive, back-and-forth shearing motion across the object's surface, typically on a homogeneous portion. Pressure (e.g., tapping, poking, pressing, twisting, etc.) involves application of normal forces or torque to some part of the object while the other parts of the object are stabilized or oppose that force. Static Contact involves resting the fingers on the object without actually molding to the contours. With Unsupported Holding the object is lifted away from a supporting surface, and frequently dynamically hefted. What was previously called "Enclosure" is now differentiated into molding the hand to the body part (Enclosure [body]) vs. molding to a secondary part(s) (Enclosure [part]). Contour Following is a dynamic procedure in which the hand maintains contact with a contour of the object; typically the movement is neither repetitive nor on homogeneous surfaces, but rather follows edged smoothly. Finally, Part Motion requires active manipulation of a part of the object relative to the whole; it is scored when a moveable part is manipulated or when there is a clear attempt to move a nonmoveable part. When two or more EPs occurred simultaneously, they were scored as a hybrid (e.g., Enclosure [body] + Unsupported Holding) and the frequency of both categories was increased by one. Reaction times (in seconds) were defined as beginning with the experimenter's "go," and ending with the subject's "yes" or "no" response.

Interscorer reliability. A second scorer was trained by one of the authors (SL) and the primary scorer. Following practice, he scored the frequencies with which each of the eight EPs occurred for a subset of the data (every fourth trial for 21 of the subjects). The percentage of EP agreement between the two scorers (i.e., the percentage of time the two scorers listed the same EP, without regard to order) was first determined for each trial, and subsequently as a mean over trials. The mean percentage EP agreement overall was an acceptable 84.2 ± 15%.

Intersubject reliability. As data were to be averaged over subjects for analysis, it was important to verify that subjects tended to explore in similar ways. Therefore, a split-half reliability test was performed on each of the four subject groups described in the experimental design. Recall that each group answered only one (of four possible) question pertaining to each of the 57 objects. For each of the four groups, an 8 × 8 matrix (representing EP [Pressure, Lateral Motion, etc.] × MDA [i.e., hardness most diagnostic, texture most diagnostic, etc.]) was prepared as follows. The eight raw EP-frequency scores for each trial were converted to percentage EP frequency scores ("% EP scores") by subject (by dividing each frequency score by the total number of EPs executed by that subject), since subjects varied in the overall number of EPs executed on any trial. Next, each group of subjects was divided into two equal subgroups and matrices for each subgroup prepared: For each of the eight MDA conditions, means for each of the eight EP conditions were calculated, consisting of the % EP scores, averaged over the appropriate subjects and those objects/questions with the designated MDA (from Experiment 1). Correlations between each pair of matrices were then calculated, based on the 64 pairs of scores described above. The split-half correlations, $r(62)$, for all four groups were extremely high (.925, .959, .999, and .958; all $ps < .001$), indicating very similar EP profiles across the eight different most-diagnostic attributes for subjects within each group.

Results

Error rates by subject and condition. Only two subjects made greater than 20% errors overall. The number of object-name sets with greater than 40% errors was 2 for the Basic Positive question, 1 for the Basic Negative, 3 for the Subordinate Positive, and 13 for the Subordinate Negative question. Note that in these and all subsequent analyses only the data from correct trials have been included. None of the 19 object-name sets noted above was misclassified by EP profiles in the discriminant analyses to be reported shortly; consequently, any misclassification errors there will be considered the result of factors other than those causing the response inaccuracies (e.g., relative unfamiliarity of object class names).

Performance by question. The four types of questions were defined by the level of categorization required (Basic, Subordinate) and the correct response (Positive, Negative). A priori, it was predicted that responses at the basic level would be relatively fast, because of the large number of potential diagnostic properties and the minimal overlap between contrasting categories. Negative responses might be faster than positive responses, if they terminated when a difference was detected. This would be especially likely at the basic level, where differences between the named and presented objects were more substantial.

To compare performance over the questions, three dependent variables were considered: response latency, number of exploratory procedures executed, and difficulty ratings. One-way repeated measures analyses of variance were performed with Question as a single four-level factor and subject as the unit of observation, averaged over the objects received by the subject for the designated question. (Intercorrelations among the three measures were highly significant for all questions.)

The effect of Question was only statistically significant with item difficulty and number of EPs as dependent variables, $Fs(3,172) = 10.43$ and 8.34, $ps < .0001$, respectively. Post hoc t tests on the four means for each ANOVA indicated that the Basic Negative questions were rated as easier and involved fewer EPs than the other three questions. Although there were no statistical differences in response latency, $F(3,172) = 1.35$, $p < .3$, the Basic Negative questions also tended to take less time than either the Basic Positive or Subordinate Negative questions. The means for reaction time, rated item difficulty, and number of EPs in the trial sequence are reported, by question, in Table 2.

In summary, all three dependent measures (although the effect of reaction time was not statistically significant) indicate that Basic Negative questions were less difficult than the other three. It appears that subjects were able to detect differences at the basic level relatively quickly and to terminate at that point. It is interesting, then, that they appear to search more exhaustively for properties when answering the Basic Positive questions, producing response latencies and exploratory sequences with lengths similar to those at the subordinate level, where disconfirming properties are often more difficult to locate. Since all subjects answered both levels of questions and therefore experienced trials with small distinctions between the target and actual object, it is possible that they expected subtler differences at the basic level than the questions actually demanded. In these circumstances, when a disconfirming property was not immediately encountered, they might have explored further to be more certain of their response.

In the following sections, we present a detailed examination of the exploration sequence during haptic object classification.

EP frequency distribution by question. The EP frequency distributions for positive and negative questions at basic and subordinate levels were initially considered, without regard to order. The distribution of EP frequencies, calculated as a percentage of the total number of EPs executed, were highly similar across all four questions. The maximum variation for any EP over questions was only 3%. Enclosure (body), Unsupported Holding, and Contour Following each occur about 25% of the time; Enclosure (part) accounted for about 13% of the EPs, and all remaining EPs for usually less than 5%.

TABLE 2
Means for Reaction Time, Item Difficulty, and Length of EP Sequence by Question

QN	Mean RT(s)[a]	Mean item diff.[b]	Mean # EPs in seq.[c]
Basic$^+$	4.38	1.69	4.02
Basic$^-$	3.72	1.38	3.46
Subord$^+$	4.17	1.86	3.98
Subord$^-$	4.55	1.86	3.87

[a] No significant differences, although tendency for Basic Negative to be faster than either Basic Positive or Subordinate Negative.

[b] Basic Negative easier than all other questions (max. $p < .002$).

[c] [illegible] shorter EP sequences than all other questions (max. $ps < .001$).

Evidence for an initial generalized exploratory phase. As the first one or two EPs usually seemed quite stereotyped, the scorer further coded each trial as having a particular initial EP sequence. Wherever relevant to the definition, the number of hands used for an EP, and if only one hand, which (that receiving the object or the nonreceiving hand), as well as the temporal ordering of initial EPs, were noted. The initial sequences are described in Table 3. Frequency distributions determined by question indicate very similar patterns: the "enclose, then lift" sequence (#1) performed by the hand receiving the object was used at the beginning of 43.1, 43.1, 44.1, and 48.2% of the trials for the Basic Positive, Basic Negative, Subordinate Positive, and Subordinate Negative questions, respectively. The next most common pattern was a "simple enclosure" (#9): 14.4, 16.7, 13.7, and 13.1% for the questions above, respectively. The third most common sequence was "enclose, then roll or push object

TABLE 3
Initial Temporal EP Sequences

Code	Description
1	Enclose, then Unsupported Holding (receiving hand, R, only) (one hand)
2	Unsupported Holding, then Enclose R (R only) (one hand)
3	Enclose and Unsupported Holding simultaneously (R only) (one hand)
4	Enclose (using nonreceiving hand, N), then Unsupported Holding (using R) (two hands)
5	Enclose (using R), then Enclose (using N), then Unsupported Holding (using R) (two hands)
6	Unsupported Holding (using R), then Enclose (using N) (two hands)
7	Enclose, then Contour Follow (roll or push object to fingertips), then Unsupported Holding when object reaches fingertips (R only) (one hand)[a]
8	Same as 7 above, only N performs the final Unsupported Holding in the sequence (two hands)
9	The first EP is an Enclosure *and* the second EP in the sequence is not Unsupported Holding (number of hands unspecified)
10	Enclose and Unsupported Holding simultaneously, or in named sequence, but pattern judged to be different from similar sequences above (number of hands unspecified)
11	No beginning sequence obvious, nor is the first EP an Enclosure

[a] *NOTE.* When there is no EP after the Unsupported Holding, Contour Following is considered task maintenance, and is not scored.

to fingertips, then lift when object reaches fingertips'' with the receiving hand (#7): the respective percent occurrences by question were 12.1, 9.7, 8.9, and 10.5. The other sequences generally occurred less than 10% of the time. The absence of any consistent beginning sequence (#11) occurred similarly infrequently across questions, resulting in an overall average of only 2.8% of the trials. Frequency distributions determined by subject indicated that subjects were stereotypical in their choice of beginning sequences. In summary, the data strongly support the existence of an initial generalized pattern of exploration, consisting of variations on an enclose-lift routine. These were highly similar for basic and subordinate levels of classification.

Evidence for a generalized-to-specialized sequence of exploration: EP frequency distributions by position in sequence. The complete timecourse of exploration may be considered in greater detail, by examining the relative frequency with which each EP was executed at each temporal position in the EP sequence. Thus, in Fig. 3 the frequency of each EP is expressed over positions in the exploratory sequence, as the cumulative percentage of the total frequency for that EP. (The analysis ignores differences in the absolute number of EPs executed. However, this information is provided at the top, permitting a further breakdown by position). Just the first seven positions in the EP sequence are considered, as only 75 of 2508 trials had sequences that extended beyond this length. The data are aggregated across questions, as all patterns are strikingly similar. This is statistically confirmed by calculating correlations between the EP by position (with position 7 eliminated, because the cumulative percent is always 100%) for all possible pairs of question, all $rs(46) > .95$, $p < .0001$; the corresponding regression slopes ranged from .94 to 1.01, indicating identical matrix values as well. To the extent that EPs do occur, then, their positions seem to be question-invariant.

The relative positions (abscissa) and steepness of the functions are both informative. The Enclosure (body) and Unsupported Holding functions are both quite steep. These EPs were often executed early on in the sequence. Whereas Enclosure (body) (n = 2251) usually occurred in position 1 and less frequently in positions 2 and 3, Unsupported Holding (n = 2121) was executed primarily in position 2 and less often in positions 1 and 3. Static Contact (n = 34) was executed infrequently and tended to occur throughout the sequence, although mainly in positions 1–3. In a number of cases, this EP might actually be a variant of Unsupported Holding, as the scorer was instructed to choose the former category whenever the object simply rested statically on the open palm, which in turn rested on the table. Such a situation tended to occur at the beginning of the sequence. Contour Following (n = 1949) and Lateral Motion (n = 344) were very similar: they usually appeared later in the sequence, pri-

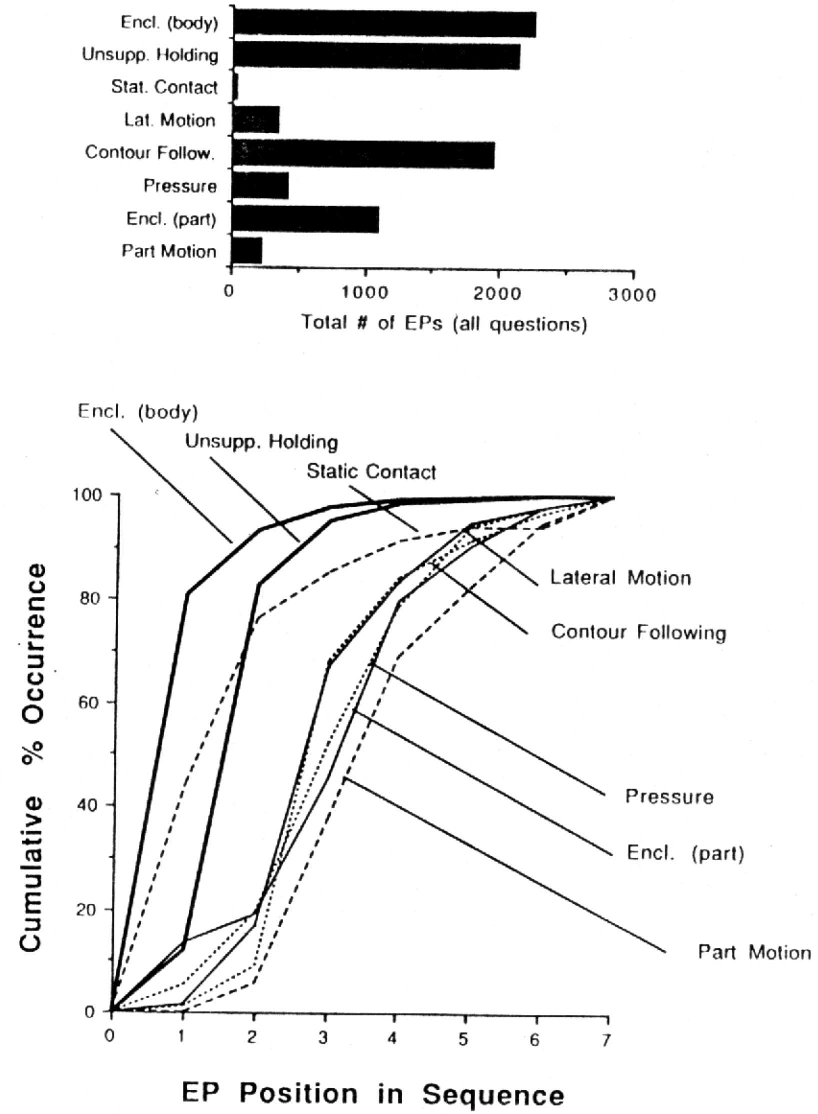

FIG. 3. Experiment 2: Cumulative percentage of occurrence of EP as a function of position in the EP sequence (aggregated over all questions).

marily in position 3, the relative frequency tapering off beyond that point. Enclosure (part) (n = 1100) and Pressure (n = 414) clearly differed in frequency of occurrence, but were quite similar in terms of occurring throughout the sequence, particularly in the middle positions. We also noted in the videotapes that Contour Following and Enclosure (part) EPs often occurred in alternation with one another, after the initial EP sequence. This suggests that Enclosure (part) is not simply a variant of the highly generalized Enclosure (body), which is always executed at the beginning of each sequence. Relative to the other EPs, Part Motion (n = 223) tended to occur most often in the later sequence positions.

On the whole, these data support the notion of a general-to-specific pattern of exploration. Early positions in the exploratory sequence are dominated by gross enclosure and lifting. Given that Enclosure is broadly sufficient, together with the more specialized weight information produced by Unsupported Holding (and undoubtedly some hardness information produced by the pressure needed to grasp the object without dropping it), this opening sequence would quickly provide at least low level information about many object attributes. Other exploratory procedures tend to dominate later in the sequence, suggesting a more specialized function. The data also provide strong support for a second stage of exploration during which the more highly specialized EPs are performed. As with the initial EP sequence data, there would again appear to be little difference in the exploratory profiles for basic and subordinate levels of classification.

It is interesting to note that the number of trials during which subjects executed only one of the initial EP sequences above, with no subsequent EPs, varies with question. These values were 14, 47, 21, and 26 (out of 626, 627, 628, and 627 trials) for the Basic Positive, Basic Negative, Subordinate Positive, and Subordinate Negative questions, respectively. This suggests that when answering Basic Negative questions (as opposed to any of the other three types), subjects show a greater tendency to execute only the initial generalized phase of exploration. This pattern is consistent with the other evidence for early self-termination on Basic Negative questions, as discussed above. However, the number of trials terminating after just the initial exploratory phase is still rather small, indicating that even this least difficult condition elicited some specialized exploration.

The next analyses were performed to confirm and extend the validity of our previous work concerning object attributes and EPs to a real-object classification context. We actually attempted to predict the occurrence of an EP solely from knowledge of the MDA for a designated object. Recall that the MDA was that attribute (of eight) with the largest weighted frequency value (from Experiment 1). If, for example, the most diagnostic attribute for a tennis ball is texture, we would predict that Lateral Motion would be most likely to occur on that trial, and so forth. To evaluate our predictions, we chose two different multivariate approaches, the quadratic assignment paradigm (Hubert, 1983) and linear discriminant analysis.

Quadratic assignment paradigm. The first technique provides us with a gross estimate of the predictability of the hypotheses regarding the links between EP categories and MDAs. In general, this technique evaluates the correlation between two matrices. The general method involves randomly permuting rows and columns of one of two matrices an arbitrarily large number of times to produce a pseudo gamma distribution, from which the probability of the obtained correlation coefficient between the two matrices may be determined.

In the current work, a predictor and obtained data matrix were used. On the basis of our previous research, we predicted the following links between MDAs and EPs:

Texture MDA	—Lateral Motion EP
Hardness MDA	—Pressure EP
Temperature MDA	—Static Contact EP
Weight MDA	—Unsupported Holding EP
Shape MDA	—Contour Following and Enclosure (body; part) EPs
Size MDA	—Enclosure (body) EP
Part MDA	—Enclosure (part) and Contour Following EPs
Motion MDA	—Part Motion EP

In the predictor matrix (8 MDAs × 8 EPs), a "1" was placed in cells representing all combinations above, to indicate a predicted link; a "0" was placed in all other cells. The corresponding data matrix was prepared as in the intersubject reliability check; thus, entries were means of the % EP scores (i.e., for each trial, the proportion of the total number of EPs that were of a given type), averaged across all subjects and those object-name sets with the designated MDA. As we were interested in knowing the relative contributions of the various EPs within object-name sets having a particular MDA, the matrix of means was subsequently converted to z scores (within EPs, over MDA categories—see Lederman & Klatzky, 1987). This normalization of the data seemed justified as the intrinsic frequency of occurrence of the EPs varied considerably.

The most critical test of our MDA/EP predictions concerns the subordinate-level questions, as object-name sets were specifically chosen to obtain subsets of objects for each MDA category at this level of classification. For the Subordinate Positive questions, the quadratic assignment paradigm produced a highly significant correlation coefficient between the 8 × 8 predicted and data matrices, $r(62) = 0.57$, $p < .0005$. For the corresponding pair of Subordinate Negative matrices, a complication was introduced because of the difficulty of scoring the Part Motion EP when the objects had no moving part. The EP was counted if there was an obvious effort to move a stationary part, but such occasions were few. Accordingly, the matrix entries corresponding to the Motion MDA and Part Motion EP were eliminated. The resulting correlation coefficient was again significant, $r(47) = .36, p < .02$. Thus, there is confirmation for the predicted links for the Subordinate Negative questions as well.

Determining correlations for the pairs of Basic Positive and Basic Negative matrices is complicated by the following reason. We neither attempted, nor obtained, a broad representation of objects across the set of eight MDA categories at the basic level. Recall that for our pool of common objects, hardness was never diagnostic of Basic Positive items, nor was either hardness or temperature critical for answering Basic Negative questions. Lacking certain MDA categories, we eliminated entries for those MDAs and the corresponding EPs from the predictor matrices (for Pressure in the Basic Positive matrix and for both Pressure and Static Contact in the Basic Negative matrix). The Basic Negative matrix also eliminated entries involving the Motion MDA and Part Motion EP. The resulting matrices were 7×7 (positive) and 5×5 (negative). The correlation coefficient for Basic Positive questions was not statistically significant, $r(47) = 0.19$, but that for Negative questions was, $r(34) = .43, p < .05$. Thus despite the fact that we could not test the full set of predictions at the basic level, there was some evidence for links between MDAs and associated EPs.

Discriminant analyses. The second technique, linear discriminant analysis, allows us to investigate more thoroughly the nature of the statistically significant associations between the predicted and data matrices above. The % EP profiles were used by the analysis to classify each object into one of the eight MDA classes. In all discriminant analyses reported in this paper, the prior probabilities of each MDA class were adjusted for unequal class frequencies.

Table 4 shows the number of objects with a given MDA that were correctly classified, out of the total number with that MDA (hits). It also shows the number that were incorrectly assigned to the given MDA class, out of the number of objects not in that class (false alarms). These data are shown for each question.

Out of the 57 objects, 35 (61%) were classified correctly on Subordinate Positive questions and 29 (51%) on Subordinate Negative questions, rates considerably greater than chance (12.5%). The data for both types of question are probably skewed somewhat by the relatively large number of items in the size class. Incorrect classifications into this class as well as correct ones were relatively high. However, as the bias is similar for positive and negative questions, it is meaningful to note the tendency for items in the Subordinate Positive questions to be classified relatively

TABLE 4
Hit and False Alarm Rates of Classification by Discriminant Analyses Broken Down by Question and MDA

	Basic$^+$		Basic$^-$		Subord$^+$		Subord$^-$	
MDA	Hit	False alarm	Hit	False alarm	Hit	False alarm	Hit	False alarm
Hardness	0/0	0/57	0/0	0/57	5/7	2/50	1/5	2/52
Part motion	2/2	1/55	0/1	1/56	4/4	0/53	0/1	0/56
Shape	31/35	8/22	24/29	17/28	0/6	0/51	2/9	4/48
Size	2/5	1/52	1/7	1/50	15/17	17/40	9/13	17/44
Temperature	0/1	1/56	0/0	0/57	1/3	0/54	1/2	0/55
Texture	6/10	2/47	5/14	5/43	5/10	3/47	8/14	3/43
Weight	1/2	1/55	1/2	1/55	3/4	0/53	2/5	1/52
Part	1/2	0/55	1/4	0/53	2/6	0/51	6/8	1/49
Overall (%)	75	4	56	9	61	5	51	7

better by EP profile than the corresponding ones in the Subordinate Negative questions.

The classification rates for the basic questions are also well above chance, 43/57 (75%) and 32/57 (56%) for positive and negative, respectively. However, these figures are deceiving, because of the high prior probability of objects in the shape MDA class. Of the 57 responses, 39 in the Basic Positive condition and 41 in the Basic Negative are "shape." The program's success is inflated because it fares well in shape classification, which is also the most frequent MDA. However, a substantial number of nonshape items are incorrectly assigned to the shape class.

A discriminant analysis also yields a set of linear functions with a standardized coefficient for each predictor variable, which is used to assign observations to classes. The relative weight of a variable (in this case, an EP) indicates its importance for each class (here, each MDA). However, in the present case one variable could not be included, because the data matrix for each question was necessarily degenerate. (The EP frequencies were normalized within each trial relative to the total frequency and hence were proportions that sum to 1, producing one less degree of freedom than required to produce the full set of linear discriminant coefficients). To overcome this difficulty, we first included seven EPs by dropping the frequencies for Enclosure (part). This EP was chosen as it was not part of our original set (Lederman & Klatzky, 1987). To then obtain the coefficients for the Enclosure (part) variable, a stepwise analysis was used, and the weights were taken from the final step, where the weakest of the eight predictor EPs was not included. If this was Enclosure (part) (as it was for Basic Positive questions), the next weakest was forced out of the analysis. According to Tabachnick and Fidell (1983), the relative ordering by magnitude of the standardized coefficients of the other variables remains quite similar to the original ones, particularly for the strongest variables.

With these data, we can determine, for each EP variable, the MDA class(es) to which the designated EP contributes most strongly. The standardized coefficients for each EP variable are shown, by question, in Table 5. Where there was no MDA category for a given question, or where relevant EPs could not be scored (i.e., Part Motion on Negative questions), "NA" is entered. To the extent that the highest weighted MDAs (i.e., first or second in rank) for a given EP are those we expected, these data serve to elucidate the basis for the positive correlation obtained with the quadratic assignment analysis. (Assuming each EP has one associated MDA, the chance probability of observing at least as many predicted first or second weightings is less than .025 for each question.)

As can be seen, the predictions were upheld. For the most critical Subordinate Positive questions, the highest discriminant coefficients for a given EP were generally obtained when predicting strongly associated MDA classes (as indicated by an asterisk). An exception is the Static Contact EP, for which temperature was the associated MDA. However, this is not surprising, as Static Contact was also scored whenever the object remained stationary in the open palm resting on the table. Undoubtedly, some information concerning weight can also be obtained in this way. The remaining questions also tended to show predicted relationships—even the Basic Positive condition, the only one with a nonsignificant correlation in the previous analysis.

"Data-driven" analysis of EP frequencies by MDA class. In the preceding analyses of negative questions, the MDA class used to predict EPs was that named in the question, rather than the object actually explored. For example, if the subject was asked whether an object was a fork but

TABLE 5
Linear Discriminant Analyses: MDA Class with the First- and Second-Highest Standardized Coefficients for Each EP Variable by Question

EP	Highest ranked standardized coefficients							
	Basic$^+$		Basic$^-$		Subord$^+$		Subord$^-$	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Lateral Motion	Part	*Text	Part	*Text	*Text	Wt	*Text	Shape
Pressure	N/A	N/A	N/A	N/A	*Hard	Wt	Wt	Size
Static Contact	Part	Size	N/A	N/A	Wt	Part	Hard	*Temp
Unsupported Holding	Size	*Wt	*Wt	Size	*Wt	Text	Temp	*Wt
Enclosure (body)	*Size	Part	Part	*Shape	*Shape	*Size	Temp	*Size
Enclosure (part)	Motion	Wt	*Part	Motion	Motion	*Part	Motion	*Part
Contour Following	Size	*Part	*Part	*Shape	Text	*Shape	Temp	*Size
Part Motion	*Motion	Wt	N/A	N/A	*Motion	Wt	N/A	N/A

explored a chopstick, the predictor for the analysis was the MDA of fork rather than chopstick. We refer to these initial analyses as "top-down," or "knowledge-driven," because they refer to the category the subject expected. Conversely, hand movements might be driven by properties of the object actually being touched. To assess the extent of this data-driven exploration, quadratic assignment and discriminant analyses were performed on the negative-question data, replacing the MDAs of the objects named in the question with those of the objects actually presented. (In 37/57 and 29/57 Basic and Subordinate cases, respectively, these two MDAs were identical). For the Basic Negative question, the quadratic-assignment correlation was $-.04$, ns; for the Subordinate Negative question, it was .28, $p < .03$. In the discriminant classification, the prior probabilities at the Basic level were even more strongly skewed toward shape than in the previous top-down analysis, rendering interpretation difficult. At the Subordinate level, the discriminant analysis based on the bottom-up MDAs fared worse than before (only 24/57 objects were correctly assigned). Hence these data suggest relatively little control of exploration by information found during the exploratory process in a constrained classification task of this sort.

EXPERIMENT 3

Generalizability of the Two-Stage Sequence to Alterate Modes of Initial Object Contact

In Experiment 2, uniformative parts of the objects were gently placed on the subject's open palm, which was supported by the table. This presentation procedure was deliberately chosen because the palm's relatively low spatial resolving capabilities made it most unlikely that the object could be identified from that contact alone. Likewise, by having the object rest on the supported palm, weight information was minimized. We reasoned that an initial grasp and/or lift routine would presumably be in the service of perception, not manipulation.

It is important to show that the initial grasp-and-lift sequence generalizes to other possible presentation modes, particularly those that do not involve placing the object directly in the hand. Accordingly, we ran a brief experiment in which subjects placed their hands about 38 cm apart, on the table in front of them. The object was then placed on the table in between. A stable object base and an orientation within the plane of the table were both chosen randomly for each object, which was positioned in the same way for all subjects. Subjects were instructed that they were free to use one or both hands when manually exploring the object. Sixteen of the 57 object-name sets were randomly selected for additional study (with four additional sets for practice). Eight new subjects (students ranging in age from 17 to 23 years) each answered one of the four possible classification questions about the 16 object-name sets (numbered, in the Appendix, 2, 3, 5, 8, 9, 16, 17, 18, 19, 23, 33, 37, 44, 49, 50, 54), according to the design described in the previous experiment. Experiments 2 and 3 were identical in all other respects.

The initial sequence (if any) of each trial was scored according to those described in Table 3, with sequences eliminated (e.g., Unsupported Holding cannot precede Enclosure with this mode of presentation) or added, as appropriate. Accordingly, six different sequences were scored, although two of these categories had less than 2%, and will not be considered. The remaining sequences (and proportion of trials observed) were: Enclosure, then Unsupported Holding (50.8%); Enclosure and Unsupported Holding simultaneously (28.9%); Enclosure without Unsupported Holding (12.5%); no beginning sequence involving either Enclosure and/or Unsupported Holding (5%). The results presented here for 128 trials are aggregated across questions, because the four question profiles are extremely similar.

These data are remarkably similar to those reported in Experiment 2, despite the marked difference in the mode of initial contact with the object. There, some variant of the enclose-and-lift routine occurred for 81.9% of the trials (compare 79.7% in Experiment 3), followed by 14.5% for simple enclosure (compare 12.5%), and 2.8% for no initial sequence (compare 5%). Additional analyses did indicate that the subjects used two hands throughout the initial EP sequence about twice as frequently as in Experiment 2. Presumably this difference merely reflects the fact that when an object is initially placed in only one hand (Experiment 2), the subject is more likely to perform Stage 1 of the exploratory period with that hand alone. When neither hand is favored by the initial mode of contact, the subject tends to use both hands throughout.

GENERAL DISCUSSION

Haptics may well release its secrets more easily than the visual system, since exploration is more extensive and more strongly bound to local object properties than is the case with eye movements. We have previously argued that in this respect, exploratory hand movements concretize the processes and representations that underlie haptic object perception and recognition. Our earlier work identified exploratory patterns directed toward desired perceptual attributes in matching, similarity judgment, and classification tasks with artificial objects.

The results of the current study extend this work by addressing two distinct but related sets of issues, which we will discuss in turn. The first set of issues concerns the nature and course of haptic object exploration during the classification of real objects. We proceed beyond our previous work by predicting exploratory movements on the basis of the properties most diagnostic for common object classification. Our results speak to the adequacy of those predictions, and hence to the knowledge-directed basis of exploration.

The second set of issues addresses the knowledge individuals possess concerning the haptic properties of objects. How are haptically derived properties of objects weighed at the basic level per se, and what is the relative importance of those properties at the basic and subordinate level? Previous work on the representation of objects in memory has used a context that is relatively neutral (e.g., object names presented), or that is biased toward vision (e.g., concrete objects or their pictorial representations presented visually), or motoric interactions with objects (e.g., actions on named objects are visually viewed or imagined). The haptic context imposed here could potentially indicate different weightings. However, it is important to note that the present experimental paradigm is more constrained than previous tasks, because it was designed for different purposes. Given substantial differences in the data bases, comparisons should therefore be made at a general level.

Is There a Systematic Sequence to Haptic Exploration?

In the introduction, we predicted a two-stage sequence, involving an initial generalized routine followed by a more specialized series of hand movements. The data clearly support the existence of this general-to-specific sequence, both when objects that are commonly manipulated (small and/or light) are placed in the hand and when they are placed between the hands, on a separate surface.

There were very few trials that did not begin with some stereotypical variant of the "enclose + lift" sequence. There are several reasons why this routine might take precedence in object categorization. First, our previous work would predict that this combination should be highly effective, since it can extract much gross information. Recall that the Enclosure (body) EP is the most generalized of our set of procedures; it is easy to execute, and can extract low-level information about multiple object dimensions simultaneously. While Unsupported Holding, which usually follows, is a more specialized EP (for weight), it is still capable of extracting additional information concerning planar size and envelope shape. Given the general utility of the combination of grasping and lifting, it may be sufficient for classifying some objects at the basic level. In keeping with assumptions of Rosch et al. (1976), if the basic level is the one at which we most often function, a routine that is useful at that level may also be extended to classifications at more subordinate levels as well.

Further, grasping and lifting are both quick to execute and motorically compatible. We have argued (Klatzky et al., 1989) that motoric ease and from 17 to 23 years) each answered one of the four possible classification questions about the 16 object-name sets (numbered, in the Appendix, 2, 3, 5, 8, 9, 16, 17, 18, 19, 23, 33, 37, 44, 49, 50, 54), according to the design described in the previous experiment. Experiments 2 and 3 were identical in all other respects.

The initial sequence (if any) of each trial was scored according to those described in Table 3, with sequences eliminated (e.g., Unsupported Holding cannot precede Enclosure with this mode of presentation) or added, as appropriate. Accordingly, six different sequences were scored, although two of these categories had less than 2%, and will not be considered. The remaining sequences (and proportion of trials observed) were: Enclosure, then Unsupported Holding (50.8%); Enclosure and Unsupported Holding simultaneously (28.9%); Enclosure without Unsupported Holding (12.5%); no beginning sequence involving either Enclosure and/or Unsupported Holding (5%). The results presented here for 128 trials are aggregated across questions, because the four question profiles are extremely similar.

These data are remarkably similar to those reported in Experiment 2, despite the marked difference in the mode of initial contact with the object. There, some variant of the enclose-and-lift routine occurred for 81.9% of the trials (compare 79.7% in Experiment 3), followed by 14.5% for simple enclosure (compare 12.5%), and 2.8% for no initial sequence (compare 5%). Additional analyses did indicate that the subjects used two hands throughout the initial EP sequence about twice as frequently as in Experiment 2. Presumably this difference merely reflects the fact that when an object is initially placed in only one hand (Experiment 2), the subject is more likely to perform Stage 1 of the exploratory period with that hand alone. When neither hand is favored by the initial mode of contact, the subject tends to use both hands throughout.

GENERAL DISCUSSION

Haptics may well release its secrets more easily than the visual system, since exploration is more extensive and more strongly bound to local object properties than is the case with eye movements. We have previously argued that in this respect, exploratory hand movements concretize the processes and representations that underlie haptic object perception and recognition. Our earlier work identified exploratory patterns directed toward desired perceptual attributes in matching, similarity judgment, and classification tasks with artificial objects.

The results of the current study extend this work by addressing two distinct but related sets of issues, which we will discuss in turn. The first set of issues concerns the nature and course of haptic object exploration during the classification of real objects. We proceed beyond our previous work by predicting exploratory movements on the basis of the properties most diagnostic for common object classification. Our results speak to the adequacy of those predictions, and hence to the knowledge-directed basis of exploration.

The second set of issues addresses the knowledge individuals possess concerning the haptic properties of objects. How are haptically derived properties of objects weighed at the basic level per se, and what is the relative importance of those properties at the basic and subordinate level? Previous work on the representation of objects in memory has used a context that is relatively neutral (e.g., object names presented), or that is biased toward vision (e.g., concrete objects or their pictorial representations presented visually), or motoric interactions with objects (e.g., actions on named objects are visually viewed or imagined). The haptic context imposed here could potentially indicate different weightings. However, it is important to note that the present experimental paradigm is more constrained than previous tasks, because it was designed for different purposes. Given substantial differences in the data bases, comparisons should therefore be made at a general level.

Is There a Systematic Sequence to Haptic Exploration?

In the introduction, we predicted a two-stage sequence, involving an initial generalized routine followed by a more specialized series of hand movements. The data clearly support the existence of this general-to-specific sequence, both when objects that are commonly manipulated (small and/or light) are placed in the hand and when they are placed between the hands, on a separate surface.

There were very few trials that did not begin with some stereotypical variant of the "enclose + lift" sequence. There are several reasons why this routine might take precedence in object categorization. First, our previous work would predict that this combination should be highly effective, since it can extract much gross information. Recall that the Enclosure (body) EP is the most generalized of our set of procedures; it is easy to execute, and can extract low-level information about multiple object dimensions simultaneously. While Unsupported Holding, which usually follows, is a more specialized EP (for weight), it is still capable of extracting additional information concerning planar size and envelope shape. Given the general utility of the combination of grasping and lifting, it may be sufficient for classifying some objects at the basic level. In keeping with assumptions of Rosch et al. (1976), if the basic level is the one at which we most often function, a routine that is useful at that level may also be extended to classifications at more subordinate levels as well.

Further, grasping and lifting are both quick to execute and motorically compatible. We have argued (Klatzky et al., 1989) that motoric ease and mutual compatibility are general constraints that motivate the selection of exploratory procedures. Another point is that multiple functions may be served by the grasp/lift sequence. In particular, these procedures are common to both exploration and manipulation, whereas other EPs (e.g., Lateral Motion or Static Contact) do not have an obvious manipulatory function.

It remains an empirical question whether under other circumstances the initial grasp-and-lift sequence would still occur in its entirety. For example, we anticipate that as the size and/or weight of the object increases beyond the span of two hands, the reliability of the full initial sequence may decrease because one (or both) component procedure(s) can provide progressively less information within the same period of time.

The current data support the existence of a second stage in the haptic exploration sequence, beyond the initial grasp-and-lift. This involves executing the more highly specialized EPs (i.e., Lateral Motion, Pressure, Static Contact, Contour Following, Enclosure (part), and Part Motion), as indicated by the later positions that these EPs occupy within the sequence. Presumably, this second stage serves to provide additional, more finely tuned perceptual information. What drives the choice of EPs is considered separately below.

Does the Two-Stage Sequence Vary with Classification Level and Question?

In keeping with the distinction made by Rosch concerning level of classification, we modified our hypothesis to propose that classification at the basic level would be easier than at the subordinate level, and that subjects might terminate exploration following the first generalized stage, for basic-level questions. The current data suggest in fact that only the negative questions are relatively easy at the basic level (although the reaction time differences were not statistically significant). These questions lead to faster responses and lower rated difficulty, and they are the most likely to terminate after an initial stereotyped routine. The data suggest that subjects cease exploring when they find a dimension of difference between the targeted and presented objects. These differences are salient in the Basic Negative questions, because the objects are from different basic-level categories. More extensive exploration is performed on Basic Positive questions, suggesting that subjects do not quickly converge on a positive decision but rather seek substantial evidence that no differences obtain. We have suggested that the mixed context of classification, with relatively subtle differences between named and presented objects on Subordinate Negative trials, may bias subjects to virtually exhaust haptically available dimensions in making any positive categorization decision.

Knowledge-Driven Aspects of Haptic Object Classification

The associations between targeted object attributes and particular patterns of exploration that were obtained in earlier work with unfamiliar, custom-designed objects clearly apply to the haptic exploration and recognition of natural, common objects as well. The results of Experiment 2 strongly confirmed the predictions concerning the associations between diagnostic attributes and EPs at the subordinate level of classification, which should provide the most powerful test. The intermatrix correlations calculated by the quadratic assignment paradigm were highly significant for both positive and negative subordinate questions.

There was support for the predicted associations between targeted attributes and exploratory patterns when answering questions at the basic level as well. Although only one correlation (Basic Negative) was significant, the other was in the predicted direction, and both questions at the basic level produced discriminant functions that tended to assign stronger EP coefficients for the predicted MDA categories.

We conclude that the hypothesized EP/MDA associations occur in conjunction with both basic and subordinate levels of real object classification. Such associations reflect the contribution of knowledge-driven processing to haptic exploration. Subjects clearly used knowledge of the most diagnostic attributes to direct the more specialized phase of their haptic exploration in these classification tasks. Unfortunately, as many of the questions are relatively difficult, this specialized exploration does not always guarantee success (recall particularly the relatively high error rate for Subordinate Negative questions).

Another important issue is the contribution of data-driven processing to haptic exploration during object categorization. The analyses that addressed this issue revealed little evidence for a strong data-driven component. However, the present constrained categorization context, in which subjects were explicitly given a target category, no doubt strongly motivated a hypothesis-testing approach. What might we predict of a less constrained context, where the issue is, "what is this object?". It is expected that the generalized grasp-and-lift sequence would be initially implemented, as a means of providing coarse multidimensional inputs quickly. However, subsequent exploratory patterns might well be more strongly driven bottom-up, by serendipitously discovered object attributes. For example, if an initial grasp-and-lift routine indicates that an object is unusually rough, Lateral Motion might be selected so that texture could be assessed more precisely.

What Is the Nature of the Haptically-Derived Representation of Common Objects?

In addition to generating testable EP/MDA predictions for Experiment

2, the empirical data of Experiment 1 provide valuable information concerning the haptic knowledge base for assessing information about objects. The results of this constrained classification task address the relative weighting of properties for basic-level representations, and further, the relative importance of each attribute at basic versus subordinate levels. Comparisons between representations of common objects derived in haptic vs. nonhaptic contexts are tentative, inasmuch as the constrained classification task, which was required to study the nature and sequence of manual exploration, does not provide a data base comparable to that of free generation. Our data also allow us to include in the haptic object representations, associations reflecting knowledge about the co-occurrence of attributes among common objects.

We first consider the relative importance of object properties in designating category membership. Given that the diagnosticity of attributes at the subordinate level was fixed by the selection of objects, only that pertaining to corresponding basic-level objects was free to vary. Thus, for comparisons among properties, we consider only the weighted-frequency means for the basic-level conditions, presented in Fig. 1. These data indicate that shape, a structural property, is most strongly diagnostic of the common objects, followed by another structural property, size, and by a substance property, texture. Thus, structure is important in the basic-level classification of haptically accessed objects, in keeping with work using nonhaptic contexts (e.g., Biederman, 1985; Rosch, 1978). However, the current results further emphasize the special role of material properties in haptic object classification, as we note again below.

Experiment 1 also indicates the relative weighting of each attribute at basic versus subordinate levels of classification. We observe first that a greater number of diagnostic attributes were listed at the basic level than at the subordinate level. This finding is compatible with results of Rosch (1978) concerning a knowledge base of objects that is accessed by naming, vision, or motoric interactions. Our constrained classification task essentially assesses the shared attributes of category members that are added when categorization moves down a level of abstraction, since subjects are given the higher-level name and asked to rate attributes that would be further diagnostic of the low-level category. Rosch found that whereas many attributes were gained in moving from the superordinate to the basic level (comparable to our basic-level rating), few were added in proceeding one step further down to the subordinate level (comparable to our subordinate-level rating).

Further, we may examine the relative importance of each attribute to haptically derived representations of common objects at basic versus subordinate levels of classification. Here, we find that shape was considerably more important at the basic level; conversely, temperature proved to be statistically less important to basic-level classification. There was no statistical effect of level on any other attribute; arguably, this last result indicates that, with the exception of thermal properties, those pertaining to an object's material (cf. structure) are always important for haptic classification. We note several ways in which thermal properties behave differently from other remaining properties. For the basic-level condition, in which the distribution of diagnostic properties was unconstrained by the experimenters, only 1 of 114 basic-level names was differentiated in terms of its thermal properties. And for the subordinate level, where such constraints were deliberately imposed, it was difficult to find items with thermal diagnosticity (5 of 114), despite our expectations that this attribute would be considerably more important. Thermal properties are further distinguished from the other attributes considered here in that they are processed by a phylogenetically older part of the somatosensory system. Finally, they are also differentiated by being last to cluster in the hierarchical cluster analysis performed in Experiment 1 (Fig. 2).

Is a Partonomic Taxonomy Appropriate for Distinguishing between Basic and Subordinate Levels of Haptic Object Representation?

The following discussion must be tentative, given the considerable differences in the data bases available for comparison. The object-attributes data base for naming and visual classification, obtained by Rosch et al. (1976), were subsequently differentiated into "parts" and "nonparts" by Tversky and Hemenway (1984). The latter investigators defined "parts" as those that ". . . refer to segments of wholes that are less than wholes; they are judged by a majority of naive informants to be parts, and they fit into a, has a, or is made of or is partially made of sentence frame." A part possesses dual status, in that it serves some function and is perceptually distinct from other parts. All other attributes were classified as "nonparts".

What can be said with regard to a partonomic distinction between basic and subordinate levels of classification? Tversky and Hemenway showed that subjects freely listed more object parts (measured as raw number and proportion of all attributes) at the basic rather than at the subordinate level (although the corresponding number and proportion of judge-amended tallies were both about equal at the two levels). In the current study, we cannot determine the number of parts per object, since the category "part" could be used only once, but we can compare the importance of parts to the haptic representations of objects at basic versus subordinate levels. Considering the relative frequency with which "part" was listed, weighted by the order in which it was reported (Fig. 1), we note that subjects tended to weight part as a diagnostic attribute more strongly at the basic level. Although this difference is not statistically significant, it would likely be greater were subjects allowed to list diagnostic attributes freely, as was true for the Rosch data analyzed by Tversky and Hemenway. Subjects might then list more than one part as a diagnostic attribute (e.g., both spout and handle are diagnostic attributes of a teapot).

Thus in examining the current data, it may be more relevant to consider the diagnosticity of shape at the basic and subordinate levels. Tversky and Hemenway have noted the intimate relation between an object's part and its shape. One would expect shape to be more important than other attributes for classification at the basic level. As noted previously, this prediction is strongly confirmed: the weighted frequency for shape is considerably greater for basic- than for subordinate-level classification. The shape data indicate the relative importance of this form of structural information to haptic knowledge representation of common objects at the basic level, and are in the direction predicted by the results of Tversky and Hemenway.

Are Natural Redundancies among Object Attributes Represented?

Rosch (1978) has argued that the basic level of classification best maps the structure contained in the world of concrete objects by reflecting the natural co-occurrence of attribute clusters. The basic level is the most inclusive level at which this informational structure is present. Rosch and her colleagues appear to be largely concerned with the natural correlations among object parts. However, clearly this form of object knowledge extends to nonpart attributes of concrete objects as well. We know, for example, that cold objects are usually smooth and hard, and that large objects are usually heavy. By finding highly similar attribute co-occurrence results at both the basic and subordinate levels of object classification, it can be said that the basic level is also the more inclusive level at which natural redundancies among haptically accessible object attributes are found. The patterns that emerge in the cluster analysis data also emphasize the distinction previously made between structure and substance. Specifically, we found that substance attributes are perceived to co-occur most strongly, as are structure attributes. While some substance and structure dimensions are perceived to co-occur, the strength of these associations is usually weaker.

The study of dimensional redundancies is an important topic in its own right. That people do perceive the redundant information about common objects potentially offers a powerful heuristic for haptic perception and manipulation. We are currently investigating two possible complementary functions of attribute co-occurrences in haptic object perception. First, when processing information about one dimension, subjects might use [illegible]

subsequent grasp. (Our previous work has demonstrated just such redundancy effects). Second, an object that violates a common dimensional association may be identified more quickly because of its distinctiveness; for example, unlike most large objects which are also heavy, a balloon is large and light. Similar effects of redundancy would be likely to occur in manipulation tasks as well.

CONCLUDING COMMENTS

In summary, the current study has presented information concerning a number of theoretical and empirical issues relating to the haptic exploration and representation of common objects during haptic classification. A constrained classification task was adopted as a means of creating the strongest test of our predictions. The results confirm the prediction that haptic exploration involves a two-stage sequence, beginning with a highly generalized "grasp-and-lift" routine, followed by a series of more specialized exploratory procedures (EPs). The second stage occurs less consistently, depending upon the level of difficulty of the task as well as level of classification. It tends to occur somewhat less often in conjunction with the easier Basic Negative questions, where the search process appears to be self-terminating (as opposed to exhaustive in the three other, more difficult questions). The choice of EP is strongly dictated by knowledge-based processes. The contribution of data-driven processes cannot clearly be inferred from the present study, however.

The results provide information concerning the nature of haptically derived representations of common objects at the basic level: shape (followed by size and texture) is particularly important. In comparison to subordinate-level representation, shape is more important at the basic level, while thermal properties are less diagnostic; all remaining properties are equally diagnostic of basic and subordinate levels.

The results of the current study are critical to the development of computational models of human haptic object classification. We also propose that such knowledge concerning biological perceptual systems may be of additional value to those who design perceptual systems for robots equipped with sensate, dextrous hands, capable of intelligent exploration, recognition and manipulation of concrete objects (see, e.g., Stansfield, 1988). The current data address such relevant issues as the nature and sequence of end-effector exploration (as predicted by the weightings determined by the necessity, optimality, and general sufficiency of various exploratory procedures), the diagnosticity weightings of properties in haptically derived object representations at basic and basic-versus-subordinate levels, and the relative weighting of perceived dimensional associations (which could be exploited to reduce the need for a full scan of sensor data within a given time period—see Jacobsen, McCammon, Big-

APPENDIX

QN		OBJECT NAME	MDA
1.	S	eating utensil	—
	B+	fork	SH
	B−	chopstick	SH
	*SB+	dessert fork	SI
	SB−	dinner fork	SI
2.	S	clothing fastener	—
	B+	button	SH
	B−	zipper	PT
	*SB+	shirt button	SI
	SB−	trouser button	SI
3.	S	timepiece	—
	B+	watch	SI
	B−	clock	SI
	*SB+	womans's watch	SI
	SB−	man's watch	SI
4.	S	pant support	—
	B+	belt	SH
	B−	suspenders	PT
	*SB+	man's belt	SI
	SB−	woman's belt	SI
5.	S	security device	—
	B+	key	SH
	B−	lock	SH
	*SB+	house key	SI
	SB−	filing cabinet key	SI
6.	S	drink container	—
	B+	milk carton	SH
	B−	soda pop bottle	SH
	*SB+	pint milk carton	SI
	SB−	half-pint milk carton	SI
7.	S	bathroom article	—
	B+	soap	TX
	B−	toilet paper	TX
	*SB+	hotel soap	SI
	SB−	bathroom soap	SH
8.	S	stopper	—
	B+	drain plug	SH
	B−	cork (stopper)	TX
	*SB+	bathtub-drain plug	SI
	SB−	bathroom-sink drain	SI
9.	S	footware	—
	B+	sandals	SH
	B−	sneakers	TX
	*SB+	child's sandal	SI
	SB−	adult's sandal	SI
10.	S	container	—
	B+	pitcher	SH
	B−	bottle	SH
	*SB+	cream pitcher	SI
	SB−	juice pitcher	SI
11.	S	liquid holder	—
	B+	cup	SH
	B−	vase	SH
	*SB+	liquid measuring cup	SI
	SB−	coffee mug	SH
12.	S	office supplies	—
	B+	paper	TX
	B−	file card	SH
	*SB+	computer-printer paper	PT
	SB−	3-ring-binder paper	SI

QN		OBJECT NAME	MDA
13.	S	drinking vessel	—
	B+	glass	SH
	B−	cup	SH
	*SB+	wine glass	SH
	SB−	brandy glass	SH
14.	S	writing utensil	—
	B+	pen	SH
	B−	chalk	TX
	*SB+	fountain pen	PT
	SB−	ball-point pen	PT
15.	S	writing utensil	—
	B+	pencil	SH
	B−	crayon	TX
	*SB+	used pencil	SI
	SB−	new pencil	SH
16.	S	hanger device	—
	B+	hook	SH
	B−	nail	SH
	*SB+	picture hook	SI
	SB−	cup hook	SI
17.	S	container	—
	B+	tin	TP
	B−	jar	SH
	*SB+	sardine tin	SH
	SB−	tuna tin	SH
18.	S	electrical item	—
	B+	battery	SH
	B−	lightbulb	SH
	*SB+	flashlight battery	SI
	SB−	transistor-radio battery	SI
19.	S	grain	—
	B+	cereal	TX
	B−	rice	SH
	*SB+	Alphabits	SH
	SB−	Cheerios	SH
20.	S	food	—
	B+	noodle	SH
	B−	raisin	TX
	*SB+	spiral noodle	SH
	SB−	macaroni noodle	SH
21.	S	container	—
	B+	bowl	SH
	B−	pan	SH
	*SB+	stainless-steel bowl	TX
	SB−	wooden bowl	TP
22.	S	paper fastener	—
	B+	paper clip	SH
	B−	staple	SH
	*SB+	steel paper clip	TX
	SB−	plastic paper clip	TP
23.	S	door opener	—
	B+	doorknob	SH
	B−	doorhandle	SH
	*SB+	metal doorknob	TP
	SB−	wooden doorknob	TX
24.	S	eyeglass parts	—
	B+	glasses frame	SH
	B−	glasses lens	SH
	*SB+	metal glasses frame	TP
	SB−	plastic glasses frame	TX

APPENDIX—*Continued*

QN		OBJECT NAME	MDA
25.	S	office supplies	—
	B+	pencil sharpener	SH
	B−	eraser	SH
	*SB+	metal pencil sharpener	TP
	SB−	plastic pencil sharpener	WT
26.	S	food jar	—
	B+	mayonnaise jar	SI
	B−	spice jar	SI
	*SB+	full mayonnaise jar	WT
	SB−	empty mayonnaise jar	WT
27.	S	kitchen pan	—
	B+	frying pan	SH
	B−	saucepan	SI
	*SB+	cast-iron frying pan	WT
	SB−	cheap frying pan	WT
28.	S	baking utensil	—
	B+	pie plate	SH
	B−	cupcake tin	SH
	*SB+	glass pie plate	TX
	SB−	foil pie plate	TX
29.	S	sports equipment	—
	B+	baseball bat	SH
	B−	racquet	SH
	*SB+	toy baseball bat	WT
	SB−	wooden baseball bat	TX
30.	S	cutting tool	—
	B+	razor	SH
	B−	scissors	MO
	*SB+	disposable razor	PT
	SB−	refillable razor	WT
31.	S	smoking material	—
	B+	ashtray	SH
	B−	cigarette	SI
	*SB+	disposable ashtray	HA
	SB−	decorative ashtray	SH
32.	S	tableware	—
	B+	plate	SH
	B−	coaster	SH
	*SB+	paper plate	HA
	SB−	stoneware plate	TX
33.	S	box	—
	B+	cereal box	SI
	B−	shoe box	SH
	*SB+	box of puffed rice cereal	WT
	SB−	box of granola cereal	WT
34.	S	woodworking implement	—
	B+	sandpaper	TX
	B−	file	TX
	*SB+	fine sandpaper	TX
	SB−	coarse sandpaper	TX
35.	S	adhesive	—
	B+	tape	TX
	B−	glue	TX
	*SB+	scotch tape	TX
	SB−	masking tape	TX
36.	S	wiping cloth	—
	B+	dish towel	TX
	B−	J-cloth	TX
	*SB+	terrycloth dish towel	TX
	SB−	linen dish towel	TX

QN		OBJECT NAME	MDA
37.	S	container top	—
	B+	lid	SH
	B−	cork	TX
	*SB+	screw-on lid	SH
	SB−	snap-on lid	PT
38.	S	clothes hanging device	—
	B+	clothespin	MO
	B−	hanger	SH
	*SB+	wooden clothespin	TX
	SB−	plastic clothespin	TX
39.	S	fabric	—
	B+	corduroy	TX
	B−	satin	TX
	*SB+	narrow corduroy	TX
	SB−	wide corduroy	TX
40.	S	reading material	—
	B+	periodical	WT
	B−	book	WT
	*SB+	comic book	SI
	SB−	newsmagazine	TX
41.	S	clothing top	—
	B+	shirt	PT
	B−	sweater	TX
	*SB+	cotton shirt	TX
	SB−	silk shirt	TX
42.	S	office supply item	—
	B+	eraser	TX
	B−	ruler	SH
	*SB+	ink eraser	TX
	SB−	gum eraser	TX
43.	S	reading material	—
	B+	book	WT
	B−	magazine	SI
	*SB+	hardcover book	HA
	SB−	paperback book	HA
44.	S	incendiary material	—
	B+	match	SI
	B−	candle	SH
	*SB+	matchbook match	SI
	SB−	matchbox match	HA
45.	S	bathroom container	—
	B+	tube	SH
	B−	plastic bottle	WT
	*SB+	tube of shampoo	HA
	SB−	tube of toothpaste	HA
46.	S	sports ball	—
	B+	football	SH
	B−	baseball	SI
	*SB+	deflated football	HA
	SB−	inflated football	HA
47.	S	confectionary	—
	B+	candy	SI
	B−	cupcake	SH
	*SB+	licorice stick	SH
	SB−	peppermint stick	SH
48.	S	food	—
	B+	noodle	TX
	B−	carrot	SH
	*SB+	dry noodle	HA
	SB−	cooked noodle	HA

APPENDIX—*Continued*

QN		OBJECT NAME	MDA
49.	S	food	—
	B⁺	bread	TX
	B⁻	cracker	TX
	*SB⁺	stale bread	HA
	SB⁻	fresh bread	TX
50.	S	recreation equipment	—
	B⁺	ball	SH
	B⁻	paddle	SH
	*SB⁺	squash ball	SI
	SB⁻	jacks ball	SI
51.	S	writing implement	—
	B⁺	pen	SH
	B⁻	crayon	TX
	*SB⁺	pen with screw-on cap	MO
	SB⁻	pen with pull-off cap	PT
52.	S	communication device	—
	B⁺	telephone	SH
	B⁻	walky-talky	PT
	*SB⁺	dial telephone	PT
	SB⁻	push-button telephone	PT
53.	S	table seasoning container	—
	B⁺	pepper container	SH
	B⁻	sugar bowl	SI
	*SB⁺	pepper grinder	MO
	SB⁻	pepper shaker	PT

QN		OBJECT NAME	MDA
54.	S	security device	—
	B⁺	padlock	SH
	B⁻	chain	SH
	*SB⁺	combination lock	MO
	SB⁻	keyed padlock	PT
55.	S	wall attachment	—
	B⁺	light switch	MO
	B⁻	electrical outlet	SH
	*SB⁺	flip light switch	MO
	SB⁻	dimmer light switch	MO
56.	S	money holder	—
	B⁺	coin purse	SH
	B⁻	wallet	SH
	*SB⁺	zipper-closure coin purse	PT
	SB⁻	clasp-closure coin purse	PT
57.	S	clock	—
	B⁺	alarm clock	PT
	B⁻	wall clock	PT
	*SB⁺	wind-up alarm clock	PT
	SB⁻	battery-operated alarm clock	PT

REFERENCES

Biederman, I. (1985). Human image understanding: Recent research and a theory. *Computer Vision, Graphics and Image Processing*, **32**, 29–73.

Brunswik, E. (1956). *Perception and the representative design of experiments*. Berkeley: University of California Press.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton-Mifflin.

Hubert, L. (1983). Inference procedures for the evaluation and comparison of proximity matrices. In J. Felsenstein, (Ed.), *Numerical taxonomy*. Berlin: Springer-Verlag, Heidelberg.

Jacobsén, S., McCammon, I., Biggers, K., & Phillips, R. (1988). Design of tactile sensing systems for dextrous manipulators. *IEEE Control Systems Magazine*, 8(1), 3–13.

Katz, D. (1989). *The world of touch* (Edited and translated by L. E. Krueger.) Hillsdale, NJ: Erlbaum.

Klatzky, R. L., Lederman, S. J., & Metzger, V. (1985). Identifying objects by touch: An "expert system." *Perception & Psychophysics*, **37**, 299–302.

Klatzky, R. L., Lederman, S. J., & Reed, C. (1987). There's more to touch than meets the eye: relative salience of object dimensions for touch with and without vision. *Journal of Experimental Psychology: General*, **116**, 356–369.

Klatzky, R. L., Lederman, S. J., & Reed, C. (1989). Haptic integration of object properties: Texture, hardness, and planar contour. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 45–57.

Lederman, S. J., & Klatzky, R. L. (1990). Haptic exploration and object representation. In Goodale, M. (Ed.) *Vision and action: the control of grasping* (pp. 98–109). Norwood: Ablex.

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, **19**, 342–368.

Loomis, J. & Lederman, S. (1986). Tactual perception. In K. Boff, L. Kaufman, & J. Thomas (Eds.), *Handbook of human perception and performance* (Chap. 31, pp. 1–41). New York: Wiley.

Lotz, H. (1856/1885). *Mikrokosmus*, (Vol. I) (Translated by E. Hamilton & E. E. C. Jones). Edinburgh: T. & T. Clark.

Malt, B., & Smith, S. (1984). Correlated properties in natural categories. *Journal of Verbal Learning and Verbal Behavior*, **23**, 250–269.

Rosch, E. (1978). Principles of categorization. In E. Rosch & B. Lloyd (Eds.), *Cognition and categorization*. Hillsdale, NJ: Erlbaum.

Rosch, E., Mervis, C., Gray, W., Johnson, D., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology*, **8**, 382–439.

Snodgrass, J., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*, **6**(2), 174–213.

Stansfield, S. (1988). A robotic perceptual system utilizing passive vision and active touch. *International Journal of Robotics Research*, **7**, 138–161.

Tabachnick, B., & Fidell, L. (1983). *Using multivariate statistics*. New York: Harper & Row.

Tversky, B., & Hemenway, K. (1984). Objects, parts, and categories. *Journal of Experimental Psychology: General*, **113**, 169–193.

(Accepted November 20, 1989)