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Stages of manual exploration in haptic object identification

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In a yes/no identification task using touch alone, subjects indicated whether an object belonged to a named category. Previously, we found that subjects explored in two stages—first grasping and lifting the object, then executing further exploratory procedures (Lederman & Klatzky, 1990b). We proposed that Stage 1 (grasp/lift) was sufficient to extract coarse information about multiple object properties, whereas Stage 2 was directed toward precise information about particularly diagnostic properties. In the current study, subjects were initially constrained to grasping and lifting, after which they could explore further. Accuracy was above chance after Stage 1, confirming our assumption that the grasp/lift combination was broadly useful. Stage 2 increased accuracy and confidence. It primarily elicited exploratory procedures associated with object geometry, but exploration was also influenced by diagnostic object properties.

The human hand is both dexterous and sensate. However, these functions are not independent. The sensory capabilities of the hand play an important role in its dexterity, as we can readily show by trying to pick up a small object with cold hands when sensation is impaired. It has also been demonstrated experimentally that blocking cutaneous inputs from the fingertips impairs grasping (Johansson & Westling, 1984; Westling & Johansson, 1984). Conversely, we have argued that certain hand movements serve to promote sensing, that is, that the sensory properties of the hand are "piggybacked" on its movement capabilities (Lederman & Klatzky, 1987).

To expand on this latter point, the skin on the hand is innervated by mechanoreceptors that sense pressure and vibration, and by thermal (and pain) receptors. Sensory mechanisms in muscles, tendons, and joints provide information about the positions and movements of the limbs and effectors. We have argued that the haptic perceptual system, which is based on inputs from these cutaneous and kinesthetic receptors, expands on the sensory primitives that they provide, ultimately computing higher level object properties such as surface roughness and compliance. Computation of these properties is made possible by exploiting the motor capabilities of the hand, in the form of *exploratory procedures* (EPs), that is, stereotyped movement patterns that are directed at extracting particular object properties.

Table 1 lists and briefly describes a set of procedures previously identified by us (Lederman & Klatzky, 1987) and indicates the object properties with which they are associated. *Lateral motion* is a tangential rubbing action associated with the extraction of information about surface texture. The *pressure EP*, associated with hardness, usually applies normal force to an object. With the *static contact EP*, the hand typically drapes over the object's surface, maximizing skin contact without an obvious effort to mold to the object. In contrast, *enclosure*, which is used to judge an object's global shape and size, involves more molding to object contours. We also distinguish enclosing the body of an object from enclosing a distinct part. *Unsupported holding*, associated with weight judgments, occurs when an object is held without external support; it is often accompanied by hefting. *Contour following*, used to encode precise shape information, generally takes the form of traversing along edges with the fingertips. Finally, a *part motion EP* applies force to a part while stabilizing the body of the object, so as to determine whether the part moves.

Others have also made distinctions among hand positions and movements used in various tasks. Gibson (1966) and Katz (1989) noted some of the same procedures described in Table 1. Several efforts have been made to classify haptic procedures used in judging shape (e.g., Davidson, 1972; Locher & Simmons, 1978; Revesz, 1950) and size (Appelle, Gravetter, & Davidson, 1980). We have also provided a more detailed description of enclosure and contour following in various matching and identification tasks (Klatzky, Lederman, & Balakrishnan, 1991; Lederman, Klatzky, & Balakrishnan, 1991).

Associations between exploratory procedures and object properties have been documented in a number of

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Table 1
Descriptions of Exploratory Procedures and Properties Associated with Each

Exploratory Procedure	Description
Lateral Motion	Induced shear between skin and object Associated with property of texture
Pressure	Force/torque applied while object stabilized Associated with property of hardness
Static Contact	Contact by large skin surface without effort to mold to contours Associated with property of temperature
Unsupported Holding	Object lifted above supporting surface Associated with property of weight
Enclosure	Molding to envelope of object body or part
(Body)	Associated with properties of shape, size
(Part)	Associated with property of shape
Contour Following	Tracing of edges Associated with properties of shape, part
Part Motion	Force/torque on object part while body stabilized (preceded by contour following and enclosure of a part) Associated with property of part motion

ways. In tasks in which a particular property is to be used as the basis of matching or classification, the EP(s) associated with that property is found to emerge spontaneously (Klatzky, Lederman, & Reed, 1987, 1989; Lederman & Klatzky, 1987; Reed, Lederman, & Klatzky, 1990). For example, when people classify objects on the basis of surface texture, the preponderant means of exploration is lateral motion.

Another task that illuminates EP-to-property associations is matching under directed exploration. Here, a subject is told to explore in a particular way (e.g., by using lateral motion only) and must pick the best match for an object on the basis of a particular property (Lederman & Klatzky, 1987, Experiment 2). In this task, each of several EPs can be examined in conjunction with each of several properties. We have found that the EP that produces *optimal* performance for matching on a given property (in terms of fastest responding, highest accuracy, or both) tends to be the same one that is chosen for extracting that property under free exploration conditions. For example, lateral motion is found to be optimal for texture matching under directed exploration, just as it is found to be executed spontaneously under free exploration. These optimal EP-to-property associations are documented in Table 1. If only one EP is found to be sufficient for matching on the basis of a given property, it is said to be *necessary* for that property. An EP that is not optimal may still be *sufficient*, defined as producing above-chance matching performance on the given property.

On the basis of the directed-exploration matching task, we found contour following to be the most broadly sufficient of the EPs, in that it produced above-chance performance on all of the properties tested. Enclosure was also broadly sufficient, producing above-chance performance on all but precise shape discriminations. For matching exact shape, however, contour following was not only optimal but necessary.

One might conclude, then, that the best way to learn about an object by touch is to examine its contours with the fingertips. However, we have argued (Klatzky & Lederman, 1990; Klatzky et al., 1989; Lederman & Klatzky, 1990a) that a number of constraints converge to determine how people choose to explore an object. The general sufficiency of an EP—which favors contour following—is only one. Another is cost in terms of execution time. Contour following is poor in this respect; it was found to have the longest duration of the EPs used in matching tasks with free exploration. Another important constraint is motor compatibility among EPs; that is, one should choose EPs that are jointly sufficient for the task at hand *and* that can be executed together.

In fact, in a haptic yes/no identification task, in which subjects were asked whether a given object was in a named category, exploration tended not to begin with contour following (Lederman & Klatzky, 1990b). Instead, they used enclosure (usually enclosing the body of the object rather than a small or eccentric part), frequently followed by unsupported holding. In more common parlance, they grasped and lifted an object they wished to identify. More specifically, on each trial of this task, the subjects were asked questions of the form, "Is this X further a Y?" (e.g., "Is this writing implement further a pencil?"). In some cases, the Y category identified the object at the basic level, that is, the level of common naming, in which same-category objects are most similar and contrasting-category objects are quite distinct (Rosch, 1978). In other cases, the Y category identified the object at a more specific, subordinate level (e.g., "used pencil"). Regardless of the level of classification or the correct response, a two-stage sequence of exploration was consistently observed over some 2,500 observations: The subjects began with enclosure (body) and unsupported holding, then subsequently performed other EPs that tended to be optimal for extracting targeted object properties. Lateral motion and contour following emerged first in this second group, followed shortly by pressure and enclosure (part). Part motion emerged last, after the part had been enclosed.

In short, results of the yes/no identification task suggested a two-stage sequence for haptic object exploration: grasp and lift, followed by other patterns of exploration. We have suggested several reasons why the grasp/lift combination might be given high priority in the exploratory sequence. First, as noted above, enclosure is broadly sufficient for at least coarse discrimination among object properties. Although it is not as generally sufficient as contour following, it is less costly to execute in terms of time. When contour following does occur, we would argue that it is generally being used not as a general-purpose procedure, but to extract the precise shape information for which it is a necessary means of exploration. Unsupported holding is more specialized than enclosure, but it too extracts information about planar size and the general shape of the object envelope. These two procedures are also motorically compatible. Generality, motoric ease, and compatibility therefore favor enclosure combined with unsupported holding: grasp and lift.

The second stage of exploration, we propose, is an attempt to obtain more precise information about properties that could not be extracted adequately by means of a simple grasp and lift. Given the broad sufficiency of enclosure and unsupported holding, we would predict that grasp and lift should often be sufficient to form a strong hypothesis about the correct identification response. Were this not the case, it is doubtful that the haptic system would come to rely on these procedures in an initial, stereotyped phase. However, subjects may still persevere, in order to confirm the hypothesis or because they remain uncertain. If an object property that is particularly relevant to or diagnostic of an object's identity has not been adequately encoded by the grasp and lift, an EP optimal for those properties should subsequently be executed. Testing a hypothesis about an object may also lead to a search for information correlated with that already obtained. For example, if a grasped object feels cool, its texture might be directly evaluated because smooth objects tend to feel relatively cooler.

The present experiment directly tested the two-stage model of exploration. Essentially, we forced the subjects to execute the first stage of exploration, after which they were free to explore further, if desired. This allowed us to evaluate the effectiveness of the first stage and also to examine the second stage in isolation. The subjects performed in the same yes/no object-identification task used previously (Lederman & Klatzky, 1990b), but their exploration was constrained initially to just a grasp/lift combination. Following this first phase, the subjects gave a yes/no response and a confidence rating. A second phase then began, in which they were allowed to explore the object as they wished. After this further exploration, if any, they again responded and estimated their confidence.

Our interpretation of the two-stage sequence leads to a number of predictions. The first concerns the level of accuracy that could be obtained in Stage 1: grasp and lift. Our hypothesis is that the first stage is adopted because the EPs involved are sufficient to extract at least coarse information about a number of object properties. If so, the subjects should be above chance, on average, in their first response. Second, we predict that whether they choose to go on after this response will be directly related to their uncertainty about the object, which would determine the need for more specialized exploration. Uncertainty should be reflected in both accuracy and confidence at the point of first response.

One might question whether uncertainty predicts subsequent exploration, given that the subjects in our earlier experiment (Lederman & Klatzky, 1990b) almost always (i.e., 96% of trials) followed the initial grasp and lift with more specialized EPs. However, a procedural aspect of that study might have biased the subjects to do extensive exploration. Specifically, each subject experienced a sequence of trials in which the two levels of classification (basic vs. subordinate) were randomly intermixed. The attributes that distinguished different subordinate-level categories (and hence determined the correct response) were relatively unobtrusive (e.g., the worn tip on a used pencil). This may have led the subjects to explore the object fully on all trials, even those in which the correct response was easily detected (especially basic negative trials, e.g., presenting a fork and asking if it was a chopstick). The current study therefore presented each subject with questions at only one level, allowing him/her to select an appropriate criterion for the precision of encoding.

To examine the second, unconstrained stage of exploration, we recorded and analyzed the subjects' hand movements, in order to determine which EPs emerged and in what order. The two-stage model suggests that the subjects should go on to execute EPs that are optimal for extracting desired object properties. In particular, the EPs that are observed after the initial grasp/lift phase should be directed at those properties that are critical to identifying the named object, rather than at those that are broadly sufficient and motorically convenient.

Consider, for example, what EP might be expected when a subject is asked, "Is this piece of bread further stale bread?" The property that primarily distinguishes stale bread from bread in general is rated to be its hardness (Lederman & Klatzky, 1990b). We call this the most diagnostic attribute (MDA) of the stale-bread category. One might predict, then, that subjects who were asked this question would use the EP associated with hardness, namely, pressure. Such a pattern tended to be found in our earlier study, particularly for trials at the subordinate level in which the presented object matched the given name (i.e., the correct answer was positive).

METHOD

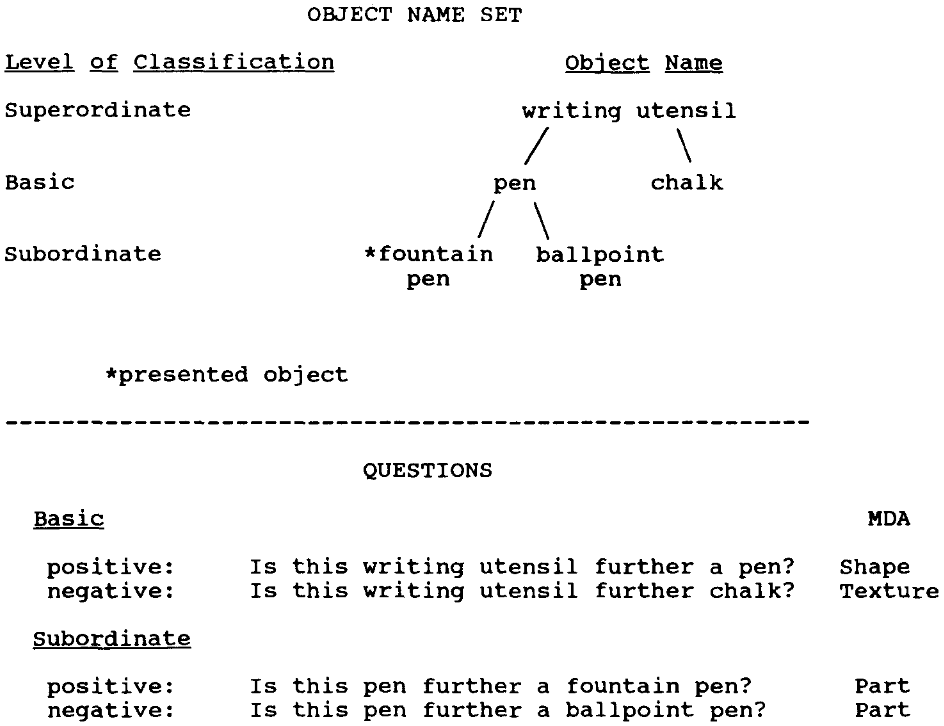
Subjects

Forty university students participated. All but 1 was right handed. The age range was 19-37 years; 1 subject was 54. The subjects were randomly assigned to two groups that varied in the classification level of the question (basic or subordinate).

Stimuli

The objects were the same as those used by Lederman and Klatzky (1990b; see Appendix of that paper for a complete list). There were 57 objects, each associated with an "object name set" (see Figure 1). For a given object actually presented in the experiment, the object name set comprised the names of its superordinate category, two basic-level names associated with that superordinate, and two subordinate-level names associated with one of the basic-level categories. One of those subordinate names corresponded to the presented object. For example, consider the object name set associated with the fountain pen. "Writing utensil" is a superordinate category, "pen" and "chalk" are basic-level categories within it, and "ballpoint pen" and "fountain pen" are subordinate-level names within "pen." These five names constituted the name set for the fountain pen object.

Associated with each basic-level and subordinate-level name in the set was an MDA, empirically defined as the attribute that another group of subjects (Lederman & Klatzky, 1990b, Experiment 1) had chosen as most predictive of the named category by touch alone. More specifically, these subjects were asked a question of the form,



		MDA
Basic		
positive:	Is this writing utensil further a pen?	Shape
negative:	Is this writing utensil further chalk?	Texture
Subordinate		
positive:	Is this pen further a fountain pen?	Part
negative:	Is this pen further a ballpoint pen?	Part

Figure 1. Design of object name sets (top) and questions (bottom). Also shown is the MDA for the categorization in each question.

"What property(ies) of an X would lead you further to call it a Y?" in which X and Y were either a superordinate- and basic-level name, respectively, or a basic- and subordinate-level name (e.g., "What property(ies) of a writing utensil would lead you further to call it a pen?"). The subjects were told to think about identifying the object by touch alone. They selected the predictive attribute(s) from a closed list: hardness, texture, weight, temperature, size, shape, part (defined for the subjects as a section of the object independent of any of its perceptual attributes, such as shape), and motion of a part. For each named category Y, an attribute from the list was assigned a score reflecting its frequency of listing by the subjects, weighted by serial position. The attribute with the highest weighted frequency was the object's MDA. (The MDA for each stimulus can be found in the Appendix to Lederman & Klatzky, 1990b.)

The MDAs were determined for each basic- and subordinate-level name in the 57 object name sets. The subordinate-level names had initially been chosen to represent a variety of diagnostic attributes, whereas the MDAs of the corresponding basic-level categories were not experimentally predesignated. Among the 114 basic-level names, shape turned out to be the most frequent MDA (i.e., for 64 categories), and hardness and temperature were MDAs for zero and one categories, respectively.

Design and Procedure

Each subject was presented with all 57 objects, one at a time. An object's presentation was accompanied by one of four possible questions, derived from the object name set for the given object (e.g., writing utensil/pen/pencil/ballpoint pen/fountain pen, in which the last name identifies the object actually presented). Example questions are shown in Figure 1. Each question was of the form, "Is this X further a Y?" We will designate questions by the category level of the Y name (B for basic; SB for subordinate) and by the correct answer (+ for positive; − for negative). In a question of type B+, X corresponded to the superordinate name, and Y corresponded to the basic-level name of the presented object. In a question of type B−, X corresponded to the superordinate name, and Y corresponded to the contrasting basic-level name. In a question of type SB+, X corresponded to the object's basic-level name, and Y to its subordinate-level name. In a question of type SB−, X corresponded to the object's basic-level name, and Y to the contrasting subordinate-level name.

The subjects were divided into two groups, one receiving B questions and the other SB questions. Within each group, half of the objects were accompanied by the positive version of the question (which named the actually presented object) and half by the negative version. The assignment of objects to questions was counterbalanced across subjects. The session began with nine practice trials that used additional objects.

The subjects were blindfolded throughout the experiment. To reduce any sound cues, they also wore earphones, and a towel placed on the table reduced any noise from contact with the object. The procedure for a trial involved two stages, as follows. In Stage 1, the question was asked, and a nondiagnostic part of the object (as designated by the experimenters) was then placed in the palm of the preferred hand (e.g., for the fountain pen, the body and not the tip). The subject was instructed to grasp and lift the object with one or both hands, and to respond "yes," "no," or "I don't know" to the question as quickly as possible. The subject then immediately gave a confidence rating on this first response, using a 1-5 scale (with a *don't know* response recorded as zero confidence). This initiated Stage 2, in which the subject was free to explore the object further. After exploration, an answer to the original question was again given, along with a revised confidence rating. If the subject did not wish to explore after Stage 1, he/she said "stop" and opened the hand to return the object to the experimenter.

The trial was filmed, and the subject's exploration in Stage 2 was categorized as a sequence of exploratory procedures. This analysis includes all trials with exploratory movement after the first response.

RESULTS

Effects of Type of Question

We first consider performance as a function of classification level (B vs. SB) and correct response (positive or negative). Discriminations at the subordinate level are, by definition, more difficult than those at the basic level. Basic negative questions were previously found to be easiest, because the features disconfirming membership in the target category can easily be discovered. These expected trends were confirmed in the present data.

Table 2 presents the mean confidence and accuracy scores at each stage by classification level and correct response. Also shown is the proportion of trials involving a voluntary second stage of free exploration. These means first average over objects for each subject, then pool subjects. Stage 1 scores are shown for all trials and also for the subset of trials in which the subject went on to Stage 2. Stage 2 scores include only those trials for which the subject went on to Stage 2. Table 2 also shows, for comparison, the accuracy obtained under free exploration by Lederman and Klatzky (1990b, Experiment 2).

Analyses of variance (ANOVAs) were conducted on the measures in Table 2 (for Stage 1, using data from all trials), using both subjects and items as the units of observation, and with independent variables of classification level and response. Table 3 reports *F* tests for each measure over subjects and items; in each test alpha was set at .05. Where there is a significant interaction, means that differ significantly (Newman-Keuls test with alpha at .05) are also reported.

On the whole, these ANOVAs indicate that confidence and accuracy were lower for negative subordinate items, as was observed in our earlier study. The positive subordinate items also received somewhat lower confidence and accuracy than those at the basic level. There was a greater tendency to go on to Stage 2 for subordinate-level questions, and as expected, the least tendency occurred for negative questions at the basic level.

Confidence, Accuracy, and Use of Stage 2

Performance after Stage 1 (all trials) was above chance even for the negative subordinate questions, which yielded 59% correct. It increased after further exploration in Stage 2 to approximate our earlier results with free exploration. The increase between stages was significant for both accuracy [pooling over conditions, ANOVAs examining the effect of stage over subjects and items, respectively, yielded $F(1,77) = 126.6$, $p < .0001$, and $F(1,217) = 124.7$, $p < .0001$] and confidence [ANOVAs over subjects and items, respectively, yielded $F(1,77) = 270.6$, $p < .0001$, and $F < (1,217) = 280.4$, $p < .0001$].

Table 2 indicates that compared with overall Stage 1 performance, the accuracy and confidence in Stage 1 were considerably lower for the subset of trials in which the subjects chose to explore further in Stage 2. The relations among accuracy, confidence, and Stage 2 exploration can be clearly seen with correlational analyses. The confidence and accuracy in Stage 1 were highly correlated over objects, and both were strong predictors of the likelihood of choosing a second stage of exploration, as shown in Table 4. That is, the subjects tended to go on to Stage 2 when they were inaccurate, low in confidence, or both.

Exploratory Procedures

We also examined the subjects' exploratory procedures during Stage 2, for those trials on which a second stage was observed. (Any that occurred during Stage 1, immediately prior to the confidence report, were also recorded

Table 2
Mean Accuracy (Proportion Correct) and Confidence (1-5 scale) at Each Stage and Proportion of Trials Proceeding to Stage 2, by Classification Level (Basic vs. Subordinate) and Correct Response (Positive vs. Negative)

	Classification Level and Correct Response			
	B+	B−	SB+	SB−
	Accuracy			
Stage 1, All Trials	.73	.76	.71	.59
Stage 1, Subset Eliciting Stage 2	.65	.56	.58	.48
Stage 2	.90	.86	.88	.74
Lederman and Klatzky, 1990b	.93	.96	.90	.82
	Confidence			
Stage 1, All Trials	3.6	3.9	3.4	3.3
Stage 1, Subset Eliciting Stage 2	2.2	2.4	2.3	2.3
Stage 2	4.7	4.8	4.4	4.2
	Proportion Trials Proceeding to Stage 2			
	.50	.42	.58	.60

Note—B = basic; SB = subordinate. Stage 1 data are shown for all trials and for the subset that elicited exploration in Stage 2. Also shown are accuracy data from Lederman and Klatzky, 1990b.

Table 3
Results of Subject and Item ANOVAs on Response (Positive vs. Negative) and Classification Level (Basic vs. Subordinate) for Each Measure

	df	*F* value	*p* value
Stage 1 Accuracy (All Trials): Subject			
Response	(1,38)	4.71	.036
Level	(1,38)	6.90	.012
Interaction	(1,38)	12.76	.001
Stage 1 Accuracy (All Trials): Item			
Response	(1,56)	4.32	.042
Level	(1,56)	6.46	.014
Interaction	(1,56)	6.08	.017
B− > SB−; B+ > SB−; SB+ > SB− By Subject Only: B− > SB+			
Stage 2 Accuracy: Subject			
Response	(1,37)	11.74	.002
Level	(1,37)	6.42	.016
Interaction	(1,37)	3.17	.083
Stage 2 Accuracy: Item			
Response	(1,56)	9.78	.003
Level	(1,56)	4.09	.049
Interaction	(1,56)	3.50	.068
Stage 1 Confidence (All Trials): Subject			
Response	(1,38)	1.11	.299
Level	(1,38)	4.52	.040
Interaction	(1,38)	8.23	.007
Stage 1 Confidence (All Trials): Item			
Response	(1,56)	0.52	.472
Level	(1,56)	7.63	.008
Interaction	(1,56)	4.78	.033
B+ > SB−; B− > SB−; B− > SB+ By Subject Only: B+ > SB+; B− > B+			
Stage 2 Confidence: Subject			
Response	(1,37)	0.20	.656
Level	(1,37)	12.75	.001
Interaction	(1,37)	4.13	.049
Stage 2 Confidence: Item			
Response	(1,56)	0.16	.694
Level	(1,56)	8.87	.005
Interaction	(1,56)	4.29	.044
B+ > SB−; B− > SB−; B− > SB+ By Subject Only: B+ > SB+; B− > B+			
Proportion Proceeding to Stage 2: Subject			
Response	(1,38)	2.14	.152
Level	(1,38)	4.61	.038
Interaction	(1,38)	5.35	.026
Proportion Proceeding to Stage 2: Item			
Response	(1,56)	1.88	.176
Level	(1,56)	13.16	.001
Interaction	(1,56)	4.49	.038
B+ > B−; SB+ > B−; SB+ > B+; SB− > B−; SB− > B+			

Note—B = basic; SB = subordinate. Results of significant Newman-Keuls tests are given when interaction is significant.

but were not included in these analyses.) Our interest was in the nature of exploration after the enforced Stage 1, particularly whether this exploration was predicted by those properties that were known, a priori, to be diagnostic of the named object category. Procedures were scored according to the criteria we have described previously (Lederman & Klatzky, 1987, 1990b), with certain exceptions: If, after the initial confidence report, the subject simply continued to hold the object in the same way, it was scored as an enclosure of the body during Stage 2, but not as unsupported holding. The latter was scored only if additional hefting was present.

A total of 3,325 EPs were scored in Phase 2. Of these, 1,319 occurred in the group given basic-level questions, and 2,006 occurred in the group given subordinate-level questions. This confirms our original prediction that subjects would adjust the extent of exploration to the difficulty of discrimination, which is greater between subordinate categories.

Table 5 presents the frequency of each EP in the current data and in our earlier paper (Lederman & Klatzky, 1990b). Also shown is the ratio of the current frequency to the earlier one (adjusted for the small difference in number of subjects between the two studies). The main point to note is that the existence of an imposed Stage 1 in this experiment substantially reduced exploration relative to the 1990 results. The magnitude of this drop suggests that it is due to more than the separation of basic from subordinate questions, which could induce a more lax criterion for precision of encoding among the former group.

Given our scoring convention, the frequencies of enclosure (body) given here include those cases where the subject continued to enclose the body of the object without interruption after the initial response, whether or not exploration changed in some way (e.g., enclosing with the alternate hand). It is difficult to interpret such enclosures, which might be not so much exploratory as a form of task maintenance (positioning the object in preparation for exploration by another EP or simply pausing to process previously obtained information). We do note that there was little evidence of an effort to mold to the object in this situation, suggesting that the subject was not trying to extract information about its external envelope or volume. In short, one should be cautious in assuming that the enclosure (body) observed in Stage 2 has an exploratory function.

To determine whether exploration was responsive to diagnostic properties, we next examined the frequency with which each EP occurred, within objects having each MDA. Table 6 shows a normalized matrix of frequencies, in which the total number of occurrences of each EP at a given level of MDA is divided by the number of objects having that MDA (excluding objects for which no exploration at Stage 2 occurred). This EP-per-object matrix is shown for data from the basic and subordinate

Table 4
Correlations Among Stage 1 Confidence and Accuracy and the Proportion of Trials in Which Subjects Proceeded to Stage 2, by Classification Level and Correct Response

Classification Level and Correct Response	Confidence/ Accuracy	Proceed/ Confidence	Proceed/ Accuracy
B+	.78	−.86	−.66
B−	.81	−.92	−.77
SB+	.93	−.90	−.80
SB−	.66	−.85	−.64

Note—All *ps* < .0001. B = basic, SB = subordinate.

Table 5
Frequencies of Exploratory Procedures in Stage 2 of the Current Study Compared with Lederman and Klatzky (1990b)

Exploratory Procedure	Stage 2	1990 Results	Ratio (Adjusted)
Lateral Motion	96	344	.31
Pressure	91	414	.24
Static Contact	2	34	.06
Unsupported Holding	168	2,121	.09
Enclosure (Body)	722	2,251	.35
Enclosure (Part)	762	1,099	.76
Contour Following	1,376	1,949	.78
Part Motion	108	223	.53
Total	3,325	8,435	

Note—Ratio is adjusted for difference in number of subjects between the two studies.

levels, which were very similar. The asterisks in the matrix indicate combinations in which the given EP is predicted for the given MDA (see Table 1); thus, these entries would be expected to be relatively high. These results are discussed below.

A final analysis on the exploratory procedure data examined the sequential positions in which EPs tended to occur during Stage 2. Figure 2 shows the cumulative proportion of an EP's total observations that occurred at each position in the EP sequence for a trial. It can be seen that there is a tendency for enclosure (body) to occur first, followed by unsupported holding. Pressure and part motion are relatively late. These trends are similar to those obtained from our earlier study (Lederman & Klatzky, 1990b).

DISCUSSION

The present results generally confirm predictions from the two-stage model of exploration, in which broadly sufficient EPs (grasp and lift) are initially executed to extract a number of object properties at a coarse level, followed by optimal EPs guided by expectations about the object's diagnostic properties. That the initial stage is sufficient to form a strong hypothesis about the correct identification response is indicated by the above-chance accuracy

Table 6
Number of Occurrences of Each Exploratory Procedure for Objects with a Given MDA, Divided by the Total Number of Objects Having That MDA and Undergoing Exploration in Stage 2

	Exploratory Procedure								
MDA	Contour Following	Enclosure (Body)	Enclosure (Part)	Lateral Motion	Part Motion	Pressure	Static Contact	Unsupported Holding	No. Objects
				Subordinate					
Motion	7.40	2.80	7.00*	0	2.80*	.40	0	.20	5
Part	9.07*	2.21	9.57*	.28	3.43	.86	0	.28	14
Shape	6.60*	4.13*	2.93*	.07	0	.53	0	1.00	15
Size	8.43	4.03*	5.40	.20	.43	.50	0	1.23	30
Temperature	7.40	5.60	2.00	0	.20	1.00	0*	1.60	5
Texture	5.58	4.58	1.08	1.96*	.25	.67	.04	.75	24
Weight	7.11	4.33	2.56	0	.11	.67	0	2.78*	9
Hardness	3.83	1.42	2.50	.08	0	.42*	0	.25	12
				Basic					
Motion	9.00	2.00	6.50*	0	1.50*	0	0	0	2
Part	7.67*	4.00	4.00*	.17	1.50	.17	0	.33	6
Shape	6.04*	3.00*	3.26*	.16	.19	.09	.02	.44	57
Size	5.83	2.75*	2.83	.08	0	.42	0	1.25	12
Temperature	6.00	3.00	3.00	0	0	1.00	0*	0	1
Texture	3.68	2.59	1.36	1.14*	0	.41	0	.64	22
Weight	3.50	2.00	2.00	.25	.50	.25	0	.25*	4
Hardness	(No objects)								

*Predicted by MDA (most diagnostic attribute). Data are shown for each level of classification (basic vs. subordinate).

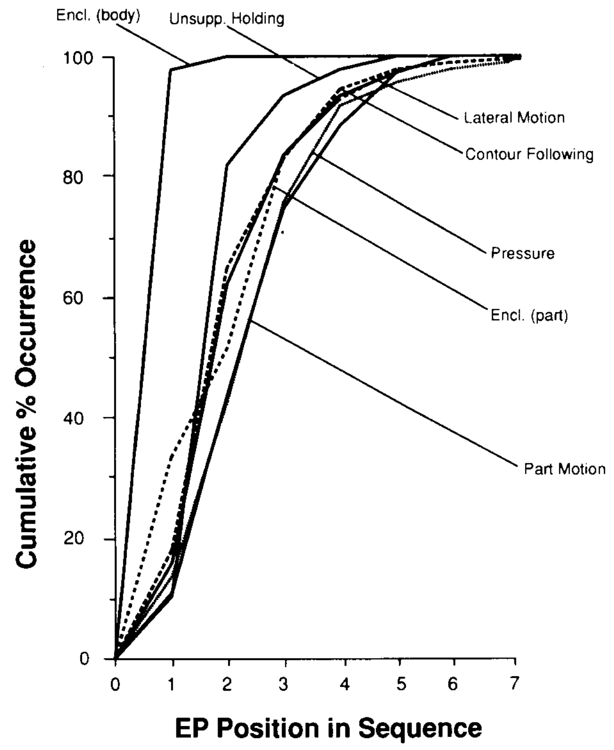


Figure 2. Cumulative percentage of an EP's total occurrences in Stage 2 as a function of position within the EP sequence. Static contact is not shown because of the small number of observations.

that followed the imposed Stage 1. Performance at this point was lowest for the subordinate negative questions, which require finding a discrepancy between properties of the object named and those of the object actually handled (e.g., a dessert fork is presented, but a dinner fork is named). When distinctions are made at the subordinate level, the properties that determine category membership are not readily obtained from Stage 1 exploration, because members of contrasting categories at the subordinate level tend to be relatively similar.

A number of findings confirm our hypothesis that the purpose of Stage 2 is to compensate for inadequacies of the initial general exploration. The subjects were more likely to proceed to explore, the less their accuracy and confidence after Stage 1. They were also more likely to go on to Stage 2 when objects were to be identified at the subordinate level, where more difficult discriminations must be made, and there was more exploration (i.e., a greater number of EPs) with the subordinate-level discriminations. Clearly, the second phase of exploration was effective in significantly increasing accuracy and confidence.

We next consider the specific nature of exploration in Stage 2. We initially predicted that the subjects would follow the grasp and lift with those EPs that were associated with the object's MDA. Looking across each row of Table 6 tells us which EPs were most prevalent for a given MDA. It is clear that contour following, enclosure (body), and enclosure (part) predominated in exploration at both levels of classification, regardless of the MDA. [Note from above, however, that enclosure (body) may not be exploratory in this context.] These EPs are all used to extract geometric properties of an object. In this sense, one could say that Stage 2 exploration is not driven by an object's diagnostic properties, but rather is directed toward extracting information about precise shape and body/part distinctions. However, looking down a column of Table 6 tells a somewhat different story, that is, which MDAs tended to elicit the most frequent occurrences of a given EP. Considering the subordinate level of classification, in the case of contour following, part enclosure, lateral motion, and unsupported holding, the MDA eliciting the most frequent occurrence is one that is predicted to be associated with the given EP. Static contact was simply too infrequent ($n = 2$) for any assessment to be made. Part motion has its highest frequency with the MDAs of motion (which was predicted) and part. At the basic level of classification there is a small number of objects for some MDAs (shape generally being most diagnostic at this level), but the appropriate MDAs elicit relatively frequent occurrences of contour following, enclosure (part), lateral motion, and part motion. Thus, there is evidence of a linkage between the nature of exploration and the object's diagnostic attributes. However, this is overlaid by a tendency to execute procedures that deliver information about an object's shape and part structure.

This tendency raises the issue of why exploratory patterns were so similar over the two levels of classification. Differentiation of objects at the basic level is known to depend primarily on shape and part structure (Rosch, 1978; Tversky & Hemenway, 1984), whereas at the subordinate level, other properties become more relevant to categorical discriminations. One might, then, expect greater use of EPs associated with geometric properties, particularly contour following, when questions are posed at the basic level. It is important to note, however, that contour following is also a broadly sufficient means of exploration, having been found to produce above-chance performance in matching for all the dimensions studied by Lederman and Klatzky (1987). Its predominance at the subordinate level here may reflect this general sufficiency. That is, contour following offers a second-stage broad "glance" at many object properties, which could be used to reassess earlier hypotheses.

The sequencing of EPs, shown in Figure 2, is strikingly similar to the sequence we obtained when no preliminary grasp/lift stage was imposed (Lederman & Klatzky, 1990b). There is a strong tendency for enclosure (body) to occur early and for unsupported holding to occur in the second position. Lateral motion and contour following have very similar profiles that rise sharply after the second position. Part enclosure is somewhat similar to these two EPs, but a bit flatter, with slightly more early and late occurrences. Finally, pressure and part motion have relatively greater representation at late positions in the sequence. (Again, static contact is too infrequent to consider here.)

Although the sequencing of EPs was very similar to our earlier results (Lederman & Klatzky, 1990b), their frequency was not. As Table 5 shows, the occurrence of Stage 1 generally reduced the use of subsequent EPs, relative to our earlier study in which no initial stage was enforced. A possible explanation for the reduction in Stage 2 exploration is that Stage 1 processing was more exhaustive under the present instructions, due to the need to make at least a preliminary response. Although all aspects of exploration were reduced somewhat by the initial enforced routine, contour following showed the least reduction. As was discussed above, this makes sense, in that we know that contour following is necessary to obtain precise shape information, and it is also sufficient to provide at least coarse information about the other object properties considered here.

The overall pattern of exploratory behavior observed in yes/no haptic object identification seems to maximize what is learned while minimizing the effort given to exploration. Grasping and lifting an object provides coarse information about many object properties very quickly. This information is frequently enough for identification, possibly because it provides redundant category cues, which have been shown to facilitate haptic classification (Klatzky et al., 1989; Reed et al., 1990). However, the information from Stage 1 fails to provide precise information about an object's geometry. In the face of uncertainty, subsequent exploration is substantially dedicated to contour following and molding to parts. In those cases where information other than geometry is critical to the object's identity, the second stage of exploration also appears to invoke the relevant optimal EPs.

One important issue is whether the exploratory sequence observed here would generalize beyond the yes/no identification task. A critical aspect of this task is that it specifies in advance a target categorical identity, to which the given object is to be compared. This information appears to direct exploration "top down," toward diagnostic properties. Advance categorical information is also likely to speed haptic identification and improve its accuracy (see Heller, 1986, 1989). Even in an identification task without a specified target category, subjects will no doubt generate hypotheses. At that point, their task becomes similar to yes/no identification, and we might expect similar processes to apply. However, the generality of the two-stage model beyond yes/no tasks remains to be tested empirically.

Yes/no identification of objects by touch occurs frequently in everyday activities, in which the potential pool of candidates is small and the objects tend to be familiar (e.g., searching for the car keys in a pocket or purse). In such cases, grasping and lifting will frequently be sufficient. Manipulatory acts as well often begin with grasping and lifting; this is necessary to orient an object with respect to tools and other spatially constrained targets. In this sense, the combination of grasp and lift plays a dual role; this commonplace and efficient motor behavior is a particularly elegant vehicle for achieving symbiosis between the exploratory and manipulatory functions of the hand. It also minimizes error in that the cutaneous and kinesthetic sensors used to guide motor control are very closely situated to the site of action by the hand.

The results of our haptics research program collectively indicate the importance of several constraints on the selection and sequencing of exploratory procedures during the extraction of object properties for object classification. Elsewhere, we have argued that many of these issues are also relevant to achieving efficient robotic haptic performance within highly unpredictable ("unstructured") environments (e.g., servicing the space center, underwater recovery and servicing, handling radioactive waste). Bajcsy (1989) has argued that within such environments, active robotic haptic exploration becomes critical for extracting object properties useful for both perceptual and manipulatory tasks. In keeping with this approach, both Stansfield (1988) and Allen and Michelman (1990) have implemented robotic versions of some of the human exploratory procedures. Just recently, we (Lederman, Klatzky, & Pawluk, in press) have suggested how roboticists might adapt the scientific method used in our human research to their own domain, for purposes of selecting effective sequences of exploratory procedures during manual robotic exploration.

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