

## Haptic Integration of Planar Size With Hardness, Texture, and Planar Contour

Catherine L. Reed, *University of California, Santa Barbara*

Susan J. Lederman, *Queen's University*

Roberta L. Klatzky, *University of California, Santa Barbara*

**ABSTRACT** Three studies investigate the role of size information in haptic classification of custom-made planar objects when size covaries with hardness, texture, or planar contour. The haptic exploratory procedure (Lederman & Klatzky, 1987) associated with size extraction is also sufficient for encoding shape, which should promote their integration. Experiment 1 showed substantial facilitation of classification by redundant size and shape cues, indicating the coprocessing of size and shape. Experiments 2 and 3 used a withdrawal paradigm: Classification trials began with two redundant properties, and one was then held constant (withdrawn). Experiment 2 showed that when size and shape were redundant, withdrawal of either impaired responses, whereas when size was redundant with texture or hardness, only size withdrawal had an effect. Experiment 3 demonstrated that this size weighting was not restricted to a single procedure for exploration. Size appears to be highly weighted in haptic classification and potentially integrated with other properties having compatible methods of extraction.

**RÉSUMÉ** Nous avons investigué dans trois expériences le rôle du paramètre grandeur dans la classification haptique d'objets tracés faits sur mesure, lorsque le grandeur covarie avec la dureté, la texture ou le contour tracé. La procédure exploratoire haptique (Lederman & Klatzky, 1987) associée à l'extraction de la grandeur est aussi suffisante pour coder la forme, qui devrait permettre leur intégration. L'expérience 1 a montré une facilitation substantielle de la classification par des indices redondants de grandeur et de forme, indiquant un co-traitement de la forme et de la grandeur. Les expériences 2 et 3 utilisaient un paradigme de retrait: les essais de classification commençaient par deux propriétés redondantes, et l'une d'elle était par la suite maintenue constante (retrait). L'expérience 2 a montré que lorsque la grandeur et la forme étaient redondantes, le retrait de l'une ou l'autre affectait les réponses alors que quand la taille était redondante avec la texture ou la dureté, seul le retrait de la taille avait un effet. L'expérience 3 démontrait que le poids attribué à la taille n'était pas restreint à une procédure unique d'exploration. La taille apparaît beaucoup plus importante dans la classification haptique et est potentiellement intégrée à d'autres propriétés ayant des méthodes d'extraction compatibles.

The human haptic system, on the basis of cutaneous and kinesthetic sensors, provides a remarkable ability to recognize objects by manual exploration alone (Klatzky, Lederman, & Metzger, 1985). We have previously suggested that rapid object identification is made possible, in part, because the hand extracts multiple object properties that provide convergent clues to category membership. This would require that

haptically extracted dimensions could be processed together or integrated. We have, in fact, found evidence for haptic integration in our previous work, which is described below (Klatzky, Lederman, & Reed, 1989). Whereas that work focussed on the integration of shape and attributes related to material substance, the present paper considers integration between size and other haptically accessible properties (texture, hardness, and planar contour).

There is a considerable body of theoretical and empirical work on the perceptual integration of stimulus dimensions. The term *integration*, according to Garner (1974), refers to a characteristic of an information processor, rather than stimulus dimensions per se; the individual can be said to integrate whenever two dimensions are processed together. Such dimensional coprocessing can occur at relatively early perceptual stages or at later decisional stages (see Ashby & Townsend, 1986, for a theoretical separation of such effects). The term *integral* has been used to characterize a perceptual level of integration that is beyond volitional control. It is clear, however, that various degrees of integration can exist (whether controlled by the stimulus or by the subject).

The earlier studies of Klatzky, Lederman, and Reed (1989) suggested, in fact, that there are asymmetries in integration of haptic properties. For example, when attending to shape information, subjects gave evidence of integration with implicitly redundant texture information, whereas the reverse was not observed; that is, texture variations affected shape processing, but shape did not affect texture. In contrast, texture and hardness each intruded significantly on the processing of the other. Although these studies were not specifically directed at discriminating levels at which integration occurs, texture and hardness appeared to be coprocessed even under manipulations that should have discouraged such effects. This combination may be a candidate for Garner's (1974) integral dimensions or Ashby and Townsend's (1986) perceptually dependent attributes.

Not all haptically available properties are integrated to the same extent. We suggested in our earlier paper (Klatzky, Lederman, & Reed, 1989) that there are several potential constraints on haptic integration. These constraints arise because the haptic system has optimal, or even necessary, motor patterns for extracting particular attributes. We have called these patterns *exploratory procedures* (Lederman & Klatzky, 1987). For example, the execution of *lateral motion* between the skin and object surface is optimal for extracting information about surface roughness.

The existence of exploratory procedures potentially constrains attribute integration. Procedures may determine not only which dimensions are integrated, but whether they influence one another symmetrically, that is, whether variations in each of two dimensions affect processing of the other. There are several ways in which procedures constrain processing. One is by motor compatibility: Attributes are more likely to be integrated when the optimal procedures for their extraction can easily be performed in tandem. For example, lateral motion with normal pressure can be used to extract texture and hardness information together. Another factor supporting integration is regional compatibility. For example, consider shape and texture information about planar objects (i.e., those varying in two dimensions while a third is held constant) of some uniform material. Shape is extracted at the edge of the object, whereas texture can be extracted over the entire surface and may be

The present research was supported by a contract from the Office of Naval Research and by a grant from the National Science and Engineering Research Council of Canada. Address reprint requests to any of the authors: Catherine Reed and Roberta Klatzky at Department of Psychology, UCSB, Santa Barbara, CA 93106, and Susan Lederman at Department of Psychology, Queen's University, Kingston, Ontario, Canada K7L 3N6.

optimally extracted away from the edge on the planar surface. Yet another constraint is that when a procedure directed toward one object property has the effect of deforming or altering another, the two cannot be readily integrated. For example, using *pressure* to detect hardness may inadvertently change shape. Finally, the sufficiency of exploratory procedures (Lederman & Klatzky, 1987) constrains integration: A procedure that is optimal for one object attribute may also provide discriminating information about another dimension (and in this sense, be sufficient to encode it), thus speeding classification. For example, enclosure, or molding to an object's contours, can be used to detect gross shape or size and is also sufficient to extract thermal (and other) properties.

Our previous work investigated the haptic integration of three object properties or dimensions<sup>1</sup>: texture, hardness, and planar shape. The studies adapted the classification paradigm developed by Garner (e.g., 1974). Subjects learned to classify a set of planar objects varying in texture, hardness, and shape into three classes. The classes could be defined by one dimension alone (e.g., all As are rough, all Bs are smooth, etc.), by two correlated dimensions (e.g., As are rough and hard, etc.), or by all three (e.g., As are rough, hard, and oval, etc.). Whereas a second correlated dimension speeded classification relative to the single-dimension condition, adding a third failed to reduce response time further. Analysis of videotaped exploratory behaviour suggested why there was no advantage for subjects in the three-dimension condition: They tended to perform only those exploratory procedures related to texture and hardness. Two subsequent experiments used a *withdrawal* paradigm, in which one of two initially correlated dimensions was held constant after a critical number of classification trials. When texture and hardness were initially correlated, withdrawal of either substantially disrupted performance. Further, exploratory procedures relevant to both texture and hardness were performed in the correlated condition, even when instructions emphasized just one, and even after the point where one of the two was withdrawn.

These findings suggested substantial and relatively nonlabile integration of texture and hardness, more so than either was integrated with planar contour. This is readily understood when one considers the constraints described previously: On objects of this given type, both hardness and texture are more readily extracted on relatively large, uniform surfaces than on edges. Further, the exploratory procedures associated with shape information tend to be incompatible with those used for hardness and texture. *Contour following*, used for precise shape encoding, and *enclosure*, used to extract gross shape, cannot be performed with substantial pressure or the object's edges will be deformed. As a result, hardness information (optimally extracted with the pressure procedure) is limited. Enclosure also requires that the hand be held relatively still, minimizing lateral motion (the procedure associated with texture).

In the present studies, we extend our previous work with planar objects to include the structural attribute of size. We are particularly interested in the integration of

size with shape, relative to its integration with substance dimensions (texture and hardness). There are several reasons for considering size and shape to be likely candidates for integration in haptic classification. First, with planar objects both types of information are carried in the same region, the edge. Also, the procedure associated with precise shape information (contour following) is sufficient to extract size, and the procedure associated with size (enclosure) is sufficient to extract gross shape information. In fact, substantial spontaneous enclosure is found during exploration for both size and gross shape. There may also be a habitual tendency to treat size and shape information together. Lederman and Klatzky (in press) found that when people ranked object attributes according to their importance for categorizing a series of objects, size and shape both tended to be given either high or low ranks for the same objects, suggesting a natural correlation in their salience for object categorization.

As noted above, we use size and substance integration as a comparison for the combination of size and shape. We predict that some integration will occur between size and texture or size and hardness, but it should be to a lesser extent, based on the constraints described above. In fact, evidence exists for the integration of size with substance properties. Millar (1986) found that discrimination of outline size for raised braille patterns was improved when size was correlated with texture. The relationship was asymmetric, in that simple texture judgements were not improved by correlated size cues. This is likely to reflect not so much a general limitation as differences in baseline discriminability of the dimensions, because influences of texture on haptic length judgements have also been reported (Corsini & Pick, 1969; Hammen, 1970). Schiff and Isikow (1966) also reported evidence for integration of texture with length of raised histograms. However, McColm (1979) did not find integration between texture and three-dimensional volume when subjects evaluated cubes of various sizes. This may be because subjects performed enclosure with the fully three-dimensional objects, but used contour following (which also induces lateral motion and thus provides texture information) with the linear segments and histograms. Comparison of these studies, therefore, suggests a critical role of exploratory procedures in determining when haptic integration occurs.

In the first two studies, we used two different paradigms to provide converging measures indicating the extent of integration between size and other object dimensions (shape, texture, and hardness). The constraints described above led to the specific hypotheses that correlated size and shape would produce faster response times than either dimension alone (Exp. 1) and that the withdrawal of either dimension would produce a substantial increase in response time (Exp. 2). In Experiment 3, we investigated whether haptic coprocessing of size and shape would generalize when subjects were constrained to use a different exploratory procedure than the one they executed spontaneously.

## EXPERIMENT 1

<sup>1</sup>Like Treisman and Gormican (1988), we define a dimension as a set of mutually exclusive values for a single stimulus. Although we will use general dimension labels such as *shape*, clearly many such partitions are possible. Our stimulus construction instantiates the partitioning of current interest.

Experiment 1 compared classification performance with a redundant combination of size and shape to classification with each dimension in isolation. Subjects were asked to classify a set of multidimensional stimuli into three distinct classes. The stimuli

varied on the dimensions of size, shape, texture, and hardness, and values on one or more dimensions determined the class of a given stimulus. Without explicit instruction from the experimenter, subjects ascertained the dimension(s) of variation and determined a classification rule from preliminary exposure to the stimuli.

We hypothesized that redundant size and shape classification information would produce faster response times than either dimension alone, producing a redundancy gain. In particular, we intended to demonstrate that redundancy of the shape and size dimensions would produce classification times equivalent to those of texture and hardness, constituting evidence for substantial integration. Hand movement data should provide converging evidence for such integration.

### Method

**Subjects:** In all three experiments, subjects were college students who were paid or participated as partial fulfillment of a course requirement. In this experiment, 15 subjects were assigned to each of four groups on a rotating basis.

**Stimuli:** The stimuli were 81 custom-made objects, constructed by factorially combining three levels on each of four dimensions. The interior of each object was constructed from a material that determined its hardness (compliance: foam rubber, polystyrofoam, or balsa wood), was cut into a particular planar shape (oval, hourglass, three-lobed), and was covered with black fabric of a particular texture (satin, medium-wale corduroy, metallic polyester). The stimuli were black walters of a uniform 1.25-cm thickness; the size of the two-dimensional planar surface varied (area: 17.4, 32.9, or 52.9 square cm). A thin, raised seam from the covering fabric ran along the narrow contour edge and was smoothed with glue. The four dimensions of variation had previously been found to be nearly equal with respect to discriminability, but size variations were slightly less discriminable. (For an assessment of dimensional discriminability, see Klatzky, Lederman, & Reed, 1987.)

**Design and Procedure:** Each subject was assigned to one of four groups, as schematized in Figure 1. For two of the groups, a single dimension of either size or shape determined classification. For the other two groups, two redundant dimensions of either size and shape or texture and hardness permitted classification. Variation in other dimensions was irrelevant (orthogonal) to the response decision; thus, all three levels of each dimension were represented in the stimulus set. The assignment of dimensional levels to classes was counterbalanced across subjects.

Each subject was exposed to 9 of the 81 stimuli, divided into three categories (A, B, and C) of three stimuli each. The classes could be differentiated by the level of the classifying dimension(s). For example, the As might be small objects, the Bs might be medium-sized objects, and the Cs might be large objects.

Subjects were blindfolded and wore noise-reduction earphones. Initially, the subject was handed the nine objects in sets of three. The experimenter indicated the class of each triad (A, B, or C), but did not reveal the relevant dimension partitioning the set. Each subject was allowed to explore the full set of stimuli freely and was given a brief test to ensure correct classification of each object before proceeding. Subsequently, 144 speeded trials began. In each trial, the subject was presented with an object (by touch alone) and was to classify it vocally as an A, B, or C as quickly as possible.

To measure classification time, a force-sensitive board with a piezoelectric sensor was interfaced with an IBM-AT computer. (For a more detailed description, see Klatzky, Lederman, & Reed, 1989.) On each trial, the experimenter placed a randomly selected object on the board and prepared the computer. A tone signalled that the object was in position. The subject's first manual contact with the stimulus produced a signal from the board to start the clock, and the subject's vocalization of the stimulus class produced a signal from a collar microphone to stop the clock. Response times were recorded to millisecond accuracy, and classification

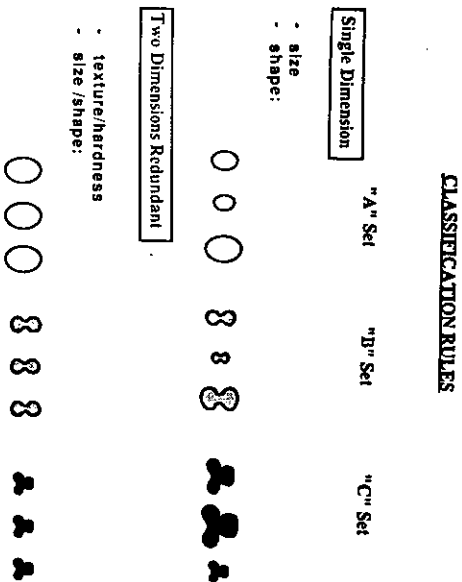


Figure 1. Schematic representation of redundancy paradigm and group assignment for Experiment 1. Subjects classify stimuli into three classes (A, B, C) by single dimensions or redundant combinations. Texture is indicated by shading.

errors were noted. To record hand movements, a videotape camera was placed behind the subject's right shoulder. At the end of the experiment, subjects were asked what dimension(s) they used to classify the objects and what hand movements or rule they used to discriminate between classes.

### Results and Discussion

**Response Times:** Response times from the 144 trials, errors, and hand movements classified as exploratory procedures were the dependent measures. Response times greater than three standard deviations above the subject's mean were eliminated, and those trials in which the subject obviously fumbled the stimulus object were repeated. In addition, times below 450 ms were considered to be ambient noise triggering the microphone response, and were eliminated from the analysis.

In all the analyses reported, the criterion for statistical significance was set at .05. Also, a priori comparisons between paired conditions used an error term based only on those conditions and were two-tailed, unless specified otherwise.

Errors ranged from 0-8% over subjects, with an average of 1.7%. Most of the errors were made by subjects in the size group (an average of 3.4%); however, this is not surprising given that size discrimination with these objects has been found to be slightly worse than discrimination based on the other dimensions (Klatzky et al., 1987). An analysis of variance on error data over groups indicated a main effect,  $F(3, 56) = 6.55$ .

Concerned with the larger number of errors in the size group and the possibility that subjects might be compromising accuracy for speed, we eliminated those subjects with high error rates (i.e., > 5%) and performed the analysis described below on the remaining data. The same effects were found, indicating that the high error

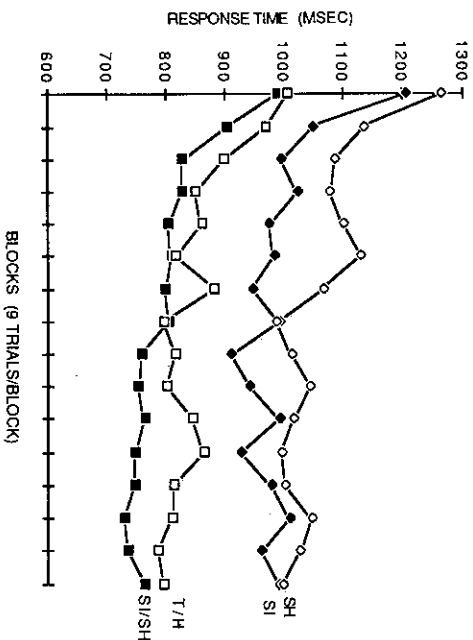


Figure 2. Mean response time in Experiment 1 by group and block of trials. SI, SH, T, and H abbreviate size, shape, texture, and hardness, and abbreviations separated by slashes are redundant dimensions for the indicated group.

rates did not reflect speed/accuracy trade-offs. In addition, we found no significant correlation between mean response time and error rates. Thus, we accepted the fact that our stimuli were subject to a certain level of size discrimination errors and included all subjects.

The 144 trials were divided into 16 blocks of nine trials each. Figure 2 shows the mean response times by group over blocks. The figure shows an overall practice effect, but, more notably, there are effects of classification structure. As we predicted, the two groups classifying by a single dimension perform at approximately the same rate, as do the two redundant-dimensions groups. Clearly, classification based on a single dimension is slower than that based on redundant dimensions. This redundancy gain or reduction in classification time is evidence that size and shape information are integrated during haptic encoding, potentially at either perceptual or decisional levels.

An ANOVA was performed on response time data for group (4) and period (defined by thirds of trials: Period 1 = Trials 1-48, Period 2 = 49-96, Period 3 = 97-144). Thirds were chosen because an initial comparison of the response times by blocks indicated asymptotic performance during the last third of trials (all blocks statistically equivalent); an ANOVA on group and blocks shows the same effects as group and thirds). Main effects were found for group,  $F(3, 56) = 5.25$ , and period,  $F(2, 112) = 30.12$ . The period effect reflects a significant decrease in response time between the first third and the last 2 thirds, indicating that learning occurred.

More importantly, the group effect arose because the redundant-dimension groups were significantly faster than the single-dimension groups. Response times for the two single-dimension groups did not differ significantly, nor did those for the two

redundant-dimension groups. Not only was the size/shape group faster than either of its constituent dimensions (the expected redundancy gain), it was as fast as the texture/hardness group, which our previous work found to give the strongest evidence of integration.

**Hand Movements:** Hands movements were scored for nine randomly chosen subjects in each group on Trials 1-20, 65-84, and 125-144, thereby sampling from each third. We focussed initially on the exploratory procedures of lateral motion, contour following, pressure, and enclosure associated with encoding texture, exact shape, hardness, and size/global shape, respectively. There is high interrater reliability for identifying these four procedures (Klatzky et al., 1987; Klatzky, Lederman, & Reed, 1989).

Enclosure occurred on virtually all of the trials within the size, shape, and size/shape groups. This procedure, as previously defined, is a relatively gross category that includes molding between part or all of the hand and the object surface. It was clear from observation that subprocedures can be defined within the enclosure category, using variations in the details of the hand configuration. These subprocedures appeared to be related to the group variable and, therefore, to the dimension of relevance in classification.

For these reasons, two subcategories were defined. The *enclosure-grasp* (grasp) procedure involves using the whole hand, typically with the palm on the upper surface and the fingertips on the edge, to engulf the object. It is relatively imprecise, in that no obvious effort is made to contact features on the edge that are clues to exact shape. With the *enclosure-mold* (mold) procedure, there is discernible effort to contact the edge. Typically, the approach to the object is along the side so that the fingers (and often palm) wrap around the informative edge. Clearly, grasp does not provide as much shape information as mold, but grasp may provide more information about the object's size. Accordingly, these two procedures were scored in lieu of enclosure. (Enclosures that did not fall in these categories were assigned to an *other* category which constituted less than 1% of the enclosures.) To assess the reliability of these new exploratory procedures, a second rater scored 40 of the scored trials for three subjects in both the size and size/shape groups. Interrater agreement was a reasonable 93%.

Videotape data were scored for the presence of lateral motion, pressure, contour following, mold, and grasp. For each block, the proportion of trials where each exploratory procedure was observed is shown in Figure 3.

An ANOVA performed on the proportion of trials where a procedure occurred with factors group (4), period, and procedure (5) revealed main effects of group,  $F(3, 32) = 9.78$ , and procedure,  $F(4, 128) = 6.00$ , as well as interactions between group and period,  $F(6, 64) = 4.71$ , and between group and procedure,  $F(12, 128) = 6.26$ . As can be seen in Figure 3, groups differed markedly in the procedures they used. As expected, lateral motion and pressure were found to predominate in the texture/hardness group. The size group mainly showed use of grasp, but with some molding. In contrast, the shape group primarily used mold, with some contour following and relatively little grasping. The size/shape group used both versions of enclosure, with a small amount of contour following. Thus, as expected, enclosure

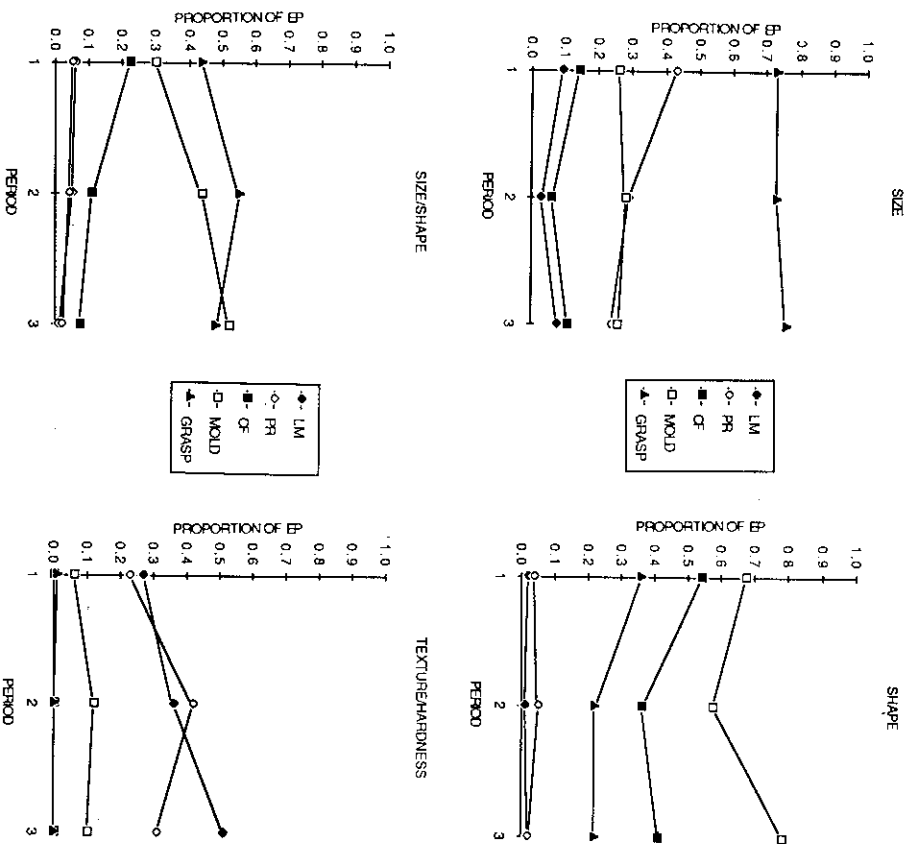


Figure 3. Proportion of trials in Experiment 1, where each exploratory procedure was observed by group and period (third) of trials. LM = lateral motion, PR = pressure, CF = contour following, MOLD = enclosure/mold, GRASP = enclosure/grasp.

was adapted to the relevant dimension. These effects led to the group by procedure interaction. The other interaction reflects the fact that certain procedures drop out over time, particularly contour following which has been found to be relatively slow to execute (Lederman & Klatzky, 1987) and appears unnecessary for the present shape discriminations.

The analyses described so far indicate a substantial redundancy gain for the correlated dimensions of size and shape, along with variations on the enclosure procedure that seem adapted for each of these two dimensions. An additional point must be addressed, however, before concluding that subjects process multiple dimensions in the redundant conditions. An alternative interpretation is that each subject processes

a single dimension, but is aided in the redundant condition by selecting whichever of the dimensions he or she processes faster (Biederman & Checkosky, 1970). The hand movement data allow us to address this possibility directly. Previously, we found that when people were given pairwise redundant combinations of texture, shape, and hardness, they showed purposive exploration for both dimensions (Klatzky, Lederman, & Reed, 1989); that is, a given individual exhibited exploratory procedures relevant to both dimensions in a single trial, often in a hybrid form. The present data may be different, however, because the two exploratory procedures scored — grasp and mold — are, by definition, mutually exclusive at any one time. Hence, people are likely to exhibit only one on a given trial. This does not mean, however, that only one dimension is processed: It is quite likely that each type of enclosure is sufficient to obtain information about both size and shape, although it is preferred for just one of these dimensions.

To address this issue in the present experiment, we first examined individual subjects' data to determine whether they preferred a particular exploratory procedure. In the texture/hardness group, consistently with our previous work, most subjects exhibited exploratory procedures for both dimensions on the same trial, usually simultaneously. However, the remaining groups showed clear single-procedure preferences. If use of a procedure on at least 80% of trials over the last third of trials is the criterion for single-procedure selection, all of the scored subjects within those groups selected either grasp or mold. Most subjects used just one of the two procedures on virtually every trial by the last third.

Although there were clear preferences for one or the other versions of enclosure, the verbal reports suggested that both dimensions were processed. For the redundant-dimension groups, 80% of the size/shape group and 73% of the texture/hardness group noticed both dimensions. This suggests that the redundancy effect reflects dimensional coprocessing. Experiment 2 clarifies this matter by inducing subjects to focus on a particular dimension and by determining the effects of withdrawing a second one.

## EXPERIMENT 2

The second experiment was conducted to provide converging evidence for size/shape integration, using the withdrawal paradigm. This directs the subject to a particular dimension (the *focal* dimension), instead of allowing a preferred one to be selected. Subjects classified stimuli that could be distinguished by two redundant dimensions; however, one of the dimensions was specified as the classification rule. There was no mention of the other, redundant dimension. After a series of speeded classification trials, subjects were switched without pause or warning to a second set of nine objects, where the dimension that had previously been implicitly redundant was now held constant.

If information from the withdrawn dimension was used to determine classification previously, we would expect an increase in response time at the point of withdrawal. Classification time would be expected to increase (a) because a relevant source of information had been eliminated and (b) because of the possible costs of learning to focus exclusively on the single, relevant dimension. The magnitude of the withdrawal effect reflects the previous dependence on withdrawn information and the amount

of new learning needed. If both dimensions are weighted equally, withdrawal effects should be the same, regardless of which is explicitly named in the instructions and which is implicit and withdrawn. At the other extreme, if the implicit dimension is ignored, its withdrawal should have no effect on response time. Between these extremes, asymmetric withdrawal effects suggest that one of the dimensions carries greater weight in classification, when it varies implicitly, than does the other.

Based on the results from Experiment 1 and our a priori hypotheses, we predicted a greater withdrawal effect for size/shape combinations than for either texture or hardness when paired with size. Furthermore, we predicted that when shape and size were redundant, withdrawal of either should produce about the same effect. This need not be the case for the other pairings, where implicit variations in one of the dimensions might carry greater weight than implicit variations in the other.

### Method

**Design and Procedure:** There were 12 participants in each of six groups, defined as follows. The notation A/B → A refers to a group that begins the task with A and B as redundant dimensions, following which B is withdrawn. The six groups are: size/shape → size (S/SH → SI), size/shape → shape (S/SH → SH), size/texture → size (S/T → SI), size/texture → texture (S/T → T), size/hardness → size (S/H → SI), and size/hardness → hardness (S/H → H).

The stimulus objects were the same as those used in Experiment 1. However, in this experiment two sets of nine objects were selected for each group. The initial set of objects was constructed so that two properties defined each category, as in Experiment 1. The second set of objects maintained only one of the previously redundant dimensions; the withdrawn dimension was held constant. (It was not varied orthogonally to the classification decision, which might produce confusion.) The specific stimulus levels assigned to a particular class (A, B, C) and the level at which the withdrawn dimension was held constant were randomly chosen for each subject.

The experimental procedure was similar to that of Experiment 1, except for two important changes:

1. Subjects were told that the objects could be classified by a simple rule, e.g., "All As are small, all Bs are medium, and all Cs are large." They were not told about the redundant dimension of variation. Subjects were given only one sample object from each set while the rule was explained, so they would not initially notice the redundancy.
2. The implicit, redundant dimension was withdrawn without pause after 117 trials (assumed to be sufficient for performance to reach asymptote), and subjects were then given 45 trials with the new set of objects. At the end of the experiment, subjects were asked whether they noticed a second classifying dimension and whether they noticed a change in the objects during the trials.

### Results

Errors, fumbles, and abnormal response times were eliminated as in the first experiment. The mean percentage of errors was 2.4%. An ANOVA on the error data, shown in Table 1, for group (6) and period (pre- and postwithdrawal) found an effect for group,  $F(5, 66) = 8.43$ . The S/T → SI group had significantly more errors than all other groups, and the S/SH → SH group had significantly fewer errors. There was also an effect of period,  $F(1, 66) = 26.82$ , with most groups showing fewer errors after withdrawal, suggesting an increase in accuracy due to learning. The interaction,  $F(5, 66) = 5.33$ , arose because the learning effects varied with group.

TABLE 1  
Mean Number of Errors in Experiment 2

Group	Period	
	Prewithdrawal (117 trials)	Postwithdrawal (45 trials)
S/SH → SH	0.25	0.50
S/SH → SI	2.25	1.83
S/H → H	1.25	0.83
S/H → SI	3.50	0.83
S/T → T	3.17	1.33
S/T → SI	5.75	1.50

**Response Times:** The data were first partitioned into 18 nine-trial blocks and then into six periods. Blocks 1–13 were prewithdrawal and Blocks 14–18 were postwithdrawal. Three pre- and postwithdrawal periods were defined as follows. The *prewithdrawal asymptote* period was defined as blocks 11–13 because the differences in mean response times over these blocks were not even marginally significant. The other prewithdrawal trials were divided into two *learning* periods of 45 trials each. The 45 postwithdrawal trials were divided into three periods of 15 trials each: *withdrawal, relearning, and asymptote* (although subjects might not have reached stable RTs by the last 15 trials).

Figure 4 shows the response time data by group for these six periods. As predicted, both groups with initially redundant size and shape showed an increase in response time at the point of withdrawal. The effect was greater for size withdrawal than for shape withdrawal. The other groups showed a substantial asymmetry; there was an effect only when size was withdrawn.

These observations were confirmed with an ANOVA on response time by group (6), defined by redundant and withdrawn dimensions) and period (6). It produced effects of period,  $F(5, 330) = 23.32$ , and a group by period interaction,  $F(25, 330) = 3.23$ , reflecting learning and withdrawal effects of varying magnitude for the different groups.

Additional analyses explored for effects of withdrawal (the difference between the prewithdrawal asymptote and the withdrawal period). This difference was significant for both the S/SH groups: 230 ms (or an increase of 30.8%) for S/SH → SH and 108 ms (13.8%) for S/SH → SI; the comparable increases for texture and hardness in the Klatzky, Lederman, and Reed (1989) integration study were 159 ms (20.1%) for T/H → T and 219 ms (29.1%) for T/H → H. The S/SH → SH effect was significantly greater than that of the S/SH → SI effect,  $F(1, 22) = 10.66$ . Within the other groups, only the withdrawal of size produced a significant increase: 107 ms (11.7%) in S/T → T and 54 ms (6.8%) in S/H → H. Thus, all three pairs showed greater effects when size was withdrawn.

We also tested for potential differences between the prewithdrawal and postwithdrawal asymptotes, which reflect long-term effects of losing a redundant dimension (although these differences may be weakened by competing effects of overall learning). The S/SH → SH group showed a substantial and significant asymptotic difference (162 ms), reflecting a redundancy gain that overrode learning, as did the difference for S/H → H (47 ms).

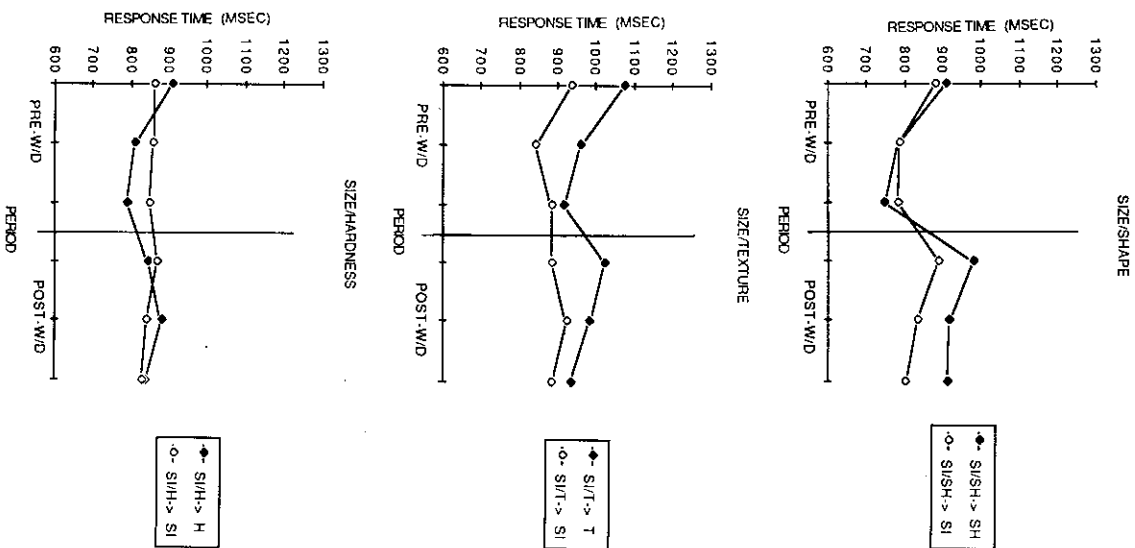


Figure 4. Mean response time in Experiment 2 by group and period (Pre-W/D = prewithdrawal period, Post-W/D = postwithdrawal period). Groups having initially redundant dimensions in common are shown together.

**Hand Movements:** To determine how exploration responded to withdrawal of the implicitly redundant dimension, we turned to hand movement data. We sampled 20 trials prior to withdrawal, 20 after withdrawal, and the last 20 trials for each

of the six groups (all subjects in each group but S/SH-SH, where camera error eliminated two subjects' data). The proportion of trials on which each procedure appeared at least once is shown in Figure 5.

Prior to withdrawal, subjects generally used the procedure(s) relevant to the instructed dimension, although execution of the procedure relevant to the redundant dimension was also evident. By the last 20 trials sampled, most groups were using exclusively the procedure(s) relevant to the single predictive dimension. Thus exploration responded to withdrawal. It is noteworthy that the S/SH-SI group predominantly used the grasp procedure, as is consistent with the results of Experiment 1. The substantial effect of shape withdrawal for this group, despite their using the size-relevant version of enclosure, supports our argument that a preference for one type of enclosure over the other does not preclude dimensional coprocessing.

These patterns were confirmed in an overall ANOVA with the factors period (pre- and postwithdrawal), procedure (5), and group. There were significant effects of period,  $F(2, 128) = 21.24$ , procedure,  $F(4, 256) = 29.16$ , and group,  $F(5, 64) = 3.73$ , procedure by group,  $F(20, 256) = 21.69$ , group by period,  $F(10, 128) = 2.16$ , procedure by period,  $F(8, 512) = 5.07$ , and a three-way interaction,  $F(40, 512) = 2.79$ .

Answers to the postexperimental questions indicated that only 25% of subjects told to focus on a substance dimension (texture, hardness) noticed that size was redundant, although most noticed that something had changed. In contrast, 50% of subjects told to classify objects by shape noticed redundant size. These results suggest that the two redundant structural dimensions are more related in conscious perception than the combination of a structural dimension (i.e., size) with substance. Previously (Klatzky, Lederman, & Reed, 1989), we found a corresponding effect for substance: Redundancy between two substance dimensions was more likely to be noticed consciously than redundancy between substance and structure (in this case, shape). These reports agree with the response time data in which size withdrawal had a greater negative effect than withdrawal of other dimensions. By both verbal and response time measures, then, it appears that changes in the size of experimentally familiarized stimuli are quite powerful, even when the contribution of size to classification is not explicitly acknowledged.

#### Discussion

Experiment 2 provides converging evidence for the processing of size and shape information together in classification. Evidence for dimensional coprocessing was found even under instructions that emphasized just one dimension. An effect of withdrawing redundant size information was found when subjects were initially focused on shape, and vice versa. The effect of size withdrawal was, however, substantially greater than that of shape withdrawal, suggesting a differential weighting of information from the two dimensions. This effect cannot be attributed to greater discriminability of the size differences because our previous discriminability measures have shown the two dimensions of variation to be essentially equal (with, if anything, an advantage for shape).

Experiment 2 thus clarifies the nature of the redundancy gain observed in Experiment 1. Observation of hand movements in that study showed that each individual

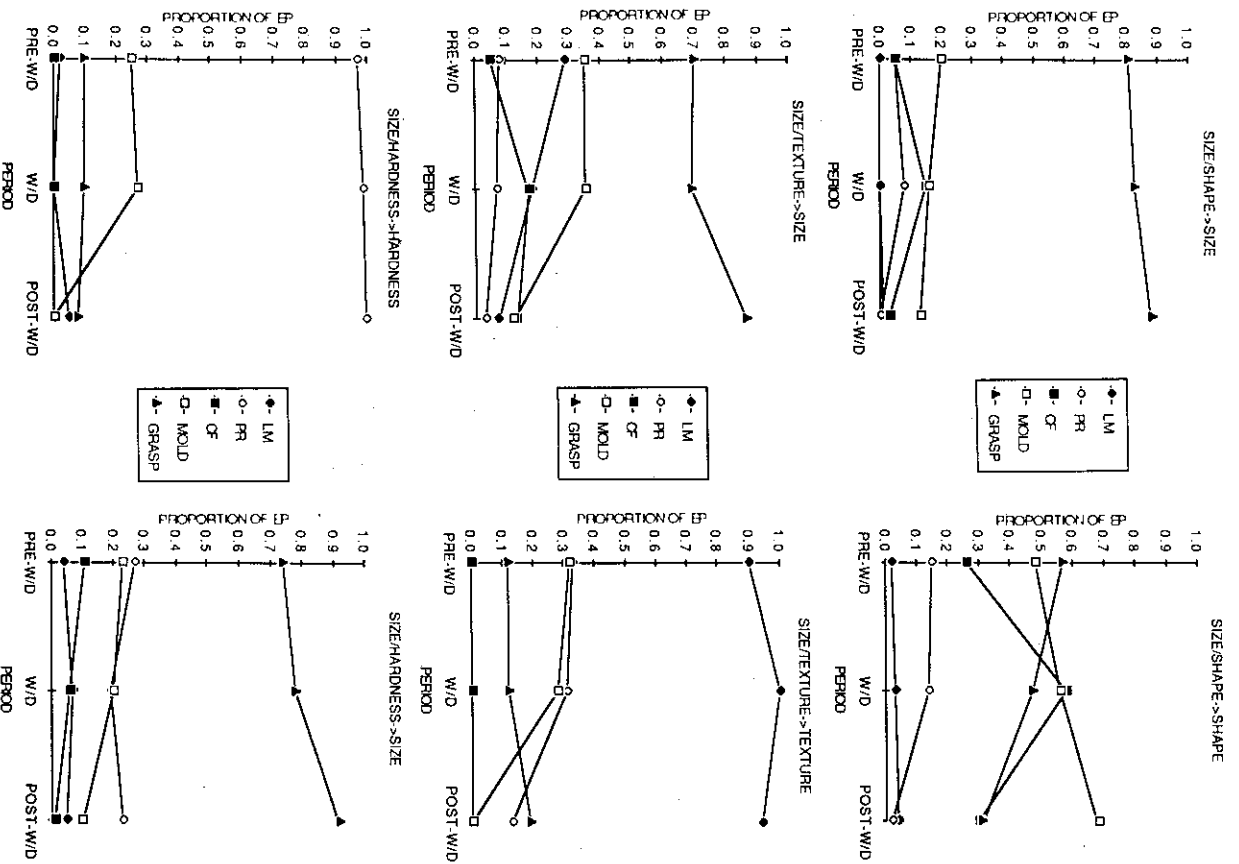


Figure 5. Proportion of trials in Experiment 2 where each exploratory procedure was observed before, during, and after withdrawal (Pre-W/D, W/D, and Post-W/D), by group.

had a clear preference for a particular exploratory procedure, with size and shape classification distinguished by the preferred type of enclosure (grasp or mold). It appeared, then, that redundant dimensions might facilitate classification because they allowed subjects to select a single preferred dimension, rather than simultaneously processing two dimensions. Experiment 2, however, provides evidence against the single-dimension argument by controlling the dimensional focus and assessing withdrawal effects: If subjects were processing just one dimension (presumably, the one about which they were instructed), there should be no effect of withdrawal.

The asymmetry in effects of withdrawing size, as compared with shape, was mimicked in the data from conditions where size was redundantly combined with texture or hardness. Our previous studies (Klatzky, Lederman, & Reed, 1989) found that when shape was redundantly combined with either texture or hardness, there were effects of withdrawing the latter two dimensions, but not of withdrawing the shape information, suggesting that processing of substance information could be done with little regard for planar contour. One might expect that these effects would generalize to another structural dimension, so that texture and hardness classifications would be minimally impaired by the withdrawal of redundantly varying size. Somewhat surprisingly, withdrawal of size information affected classification by substance, whereas the reverse did not hold.

On the whole, Experiment 2 points to a *size weighting* effect: Variations in size that are relevant to stimulus classification are highly weighted, even when they are implicit, in comparison to variations in other dimensions. One potential account of such asymmetries attributes them to differences in dimensional processing speed; that is, the faster classification is done by some focal dimension, the less processing time can accrue to other, implicit dimensions. This would produce asymmetries such that implicit variations in the faster dimension impinged on others more than the reverse. Although size was somewhat (not significantly) faster than shape in Experiment 1, this argument receives little support from the Experiment 2 data because response times are not consistently fastest when size is focal. In fact, the prewithdrawal response times for the shape- and size-focussed groups are virtually identical. Thus, it is not obvious that size weighting should be attributed to the speed of size-based classification.

We propose a more substantive account of this result, based on the potential importance of size for object manipulation. In a more extended discussion to follow, we will argue that the size of an object (within the range studied here) is critical to manipulation because it provides powerful constraints on the way an object is contacted for a stable grasp. Conversely, gross manipulatory activity such as grasping is highly informative about object size, potentially more so than about texture, hardness, or shape (Lederman & Klatzky, 1987). The idea that manipulatory activity enhances the weighting of size information during classification motivated Experiment 3.

### EXPERIMENT 3

Experiment 3 was intended to provide a discriminating test of three hypotheses about size weighting. The hypotheses differ with respect to the level of generality at which manipulation affects the haptic representation of size information. To address

this issue, the experiment constrained the extent to which manipulatory activity could be used during exploration. Subjects were instructed to use a particular exploratory procedure, either grasp (as in Experiment 1) or contour following (as described below). Incidental manipulatory support that might contribute to classification was eliminated. The question of interest was whether under such constrained conditions size weighting would occur, that is, whether there would be a greater effect of size withdrawal than shape withdrawal.

The first hypothesis suggests that size weighting might reflect the availability of additional information about an object's size (more than other dimensions), due to incidental manipulation that occurs during exploration. In these studies, subjects typically grasp and orient the object with one or both hands, rather than merely probing its upper surface as it rests passively on the table top. (Similar manipulatory support for exploration was called *task maintenance* by Lederman & Klatzky, 1987.) Thus, size information could accrue from two sources: feedback from the motor activities that support purposive exploration and feedback from the purposive exploration per se. If so, size weighting should be eliminated when ancillary manipulatory movements are precluded.

Second, the effect might reflect dual coding of size information from two representational systems: manipulatory and exploratory. This hypothesis is analogous to the one proposed by Paivio (e.g., 1971) regarding dual contributions of imaginal and verbal coding to verbal recall. It is plausible, we feel, because of the different motoric characteristics of manipulatory and exploratory activity (as described in Klatzky, Lederman, Pellegrino, Doherty, & McCloskey, 1989). A separate, manipulatory representation for size information would not necessarily rely on incidental manipulation that occurs during exploration. It could be activated whenever exploratory activity is similar to manipulatory activity. In particular, to the extent that the grasp procedure for exploration is similar to manipulation, size weighting might still occur when exploration is constrained to that procedure. In contrast, we assume that contour following would be less likely to produce such a manipulatory code.

The third hypothesis assumes a general weight ordering of object dimensions, which determines their relative contribution to haptic object classification. Size is assigned a higher weight, presumably because of its importance to object manipulation. In this case, size cues would play a greater role in classification, regardless of the exploratory or manipulatory activity that occurred with any one object. Size dominance, therefore, should generalize to forms of exploration other than grasping, as long as those procedures were sufficient to extract size information.

Contour following is sufficient for the encoding of size, but there is some reason to expect its use to reduce or eliminate size weighting, if the effect is not a highly general one. The procedure is strongly associated with shape extraction, in that it is the only one that suffices for precise shape discriminations, and it is the preferred procedure for such tasks (Lederman & Klatzky, 1987). Thus, one might expect the procedure to be biased toward a higher weight for shape.

To summarize, this experiment addresses the generality of size weighting. Evidence for size/shape integration is expected for both exploratory conditions, because the grasp and contour following procedures are sufficient to extract both dimensions. However, size weighting might not be found in all conditions. If the effect arises from the joint contributions of exploratory and manipulatory activity during

TABLE 2  
Mean Number of Errors in Experiment 3

Group	Period	
	Prewithdrawal (117 trials)	Postwithdrawal (45 trials)
SHAPE/EN	0.67	1.08
SHAPE/CF	0.42	0.92
SIZE/EN	1.83	1.58
SIZE/CF	3.67	4.75

the same period, it should be eliminated when incidental manipulation is precluded. If the effect is due to a second, manipulatory code, it should be reduced or eliminated when contour following is used instead of the grasp procedure. But if the effect is due to a general weighting that favours size information in haptic classification, it should persist despite variations in exploration or elimination of initial manipulation.

#### Method

*Design and Procedure:* The withdrawal paradigm of Experiment 2 was used again. The participants were 48 college students who were assigned to four groups determined by the classification instruction and by the assigned exploratory procedure. Groups will be referred to by their focal dimension (size or shape) and exploratory procedure, enclosure/grasp or contour following (EN or CF, respectively).

The same stimuli and response time apparatus were used as in previous experiments. In addition, stimulus holders were designed to guide exploration. For those using contour following, a wood trough was mounted onto the touch-sensitive disc, and an object was placed in it so that the edge was on top. For the grasp conditions, the object was placed flat on a wooden block that was mounted on the disc.

Subjects were given explicit object handling instructions. Those in the enclosure conditions were instructed simply to grasp the object (the experimenter demonstrated a typical grasp from the top) and not to move the hand or fingers along the edge. The contour following subjects were instructed to pick up the object from the side, pinching the flat surfaces of the object with one hand (note this gives no size information) while tracing its outline with the index finger of the other hand. Tracing started with the two hands together, which precluded measuring size by the initial distance between the two hands. Subjects were discouraged from tracing with more than one finger and from stopping at any point. Each group was given practice at exploring in the appropriate manner on a larger, differently constructed, practice object.

#### Results

Errors, fumbles, and extreme response times were eliminated as before. Because the holder reduced the initial contact time, the minimum response time (below which the trial was rejected as reflecting ambient noise) was reduced to 300 ms. Errors ranged from 0-8% over subjects with a mean of 3%, as shown in Table 2. An ANOVA performed on error data for exploratory procedure by focal dimension by period (pre- and postwithdrawal) produced effects for exploratory procedure,  $F(1, 44) = 10.63$ , dimension,  $F(1, 44) = 38.76$ , and the exploratory procedure by dimension interaction,  $F(1, 44) = 14.85$ . The dimension effect showed that the focal-size groups made more errors than the focal-shape groups. The interaction and the procedure main effect resulted because the Size/CF group made relatively more errors. In short, errors suggest that size encoding is relatively difficult, especially under

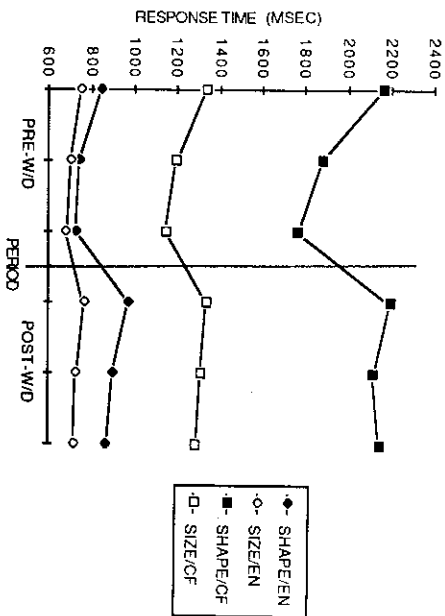


Figure 6. Mean response time in Experiment 3 by group (defined by focal dimensions: either size or shape), exploratory procedure (CF = contour following, EN = enclosure/grasp) and period.

contour following, which clearly indicates any size weighting effect is not due merely to stimulus discriminability.

An ANOVA comparing response times for exploratory procedure by focal dimension by period (6, as defined for Exp. 2) produced all effects except for the three-way interaction. Means for these effects are shown in Figure 6. The period effect,  $F(5, 22) = 14.63$ , is attributable to general practice and withdrawal. The exploratory procedure effect,  $F(1, 44) = 83.31$ , indicates that contour following was significantly slower than enclosure, as expected. The effect of dimension,  $F(1, 44) = 21.89$ , indicates that exploration for shape information was slower than exploration for size information. This was particularly true when exploration was by contour following, interaction  $F(1, 44) = 11.85$ . An interaction between procedure and period,  $F(5, 220) = 2.36$ , indicates that the slowness of contour following was exacerbated after withdrawal. Finally, a dimension by period effect,  $F(5, 220) = 2.79$ , arose because size withdrawal had a larger effect than shape withdrawal. Lack of a further qualifying three-way interaction indicates that the withdrawal asymmetry was substantially the same regardless of the nature of imposed exploration.

Analyses within each group probed further for withdrawal effects. All four conditions showed significant effects. The magnitudes for the enclosure (249 ms, 34.3% increase, for size withdrawal; 82 ms, 12.1%, for shape withdrawal) and contour following (426 ms, 24%, and 193 ms, 16.9%, respectively) conditions were similar to those of Experiment 2 — the withdrawal of size produced a greater effect. Furthermore, most groups (only Size/EN was not significant) showed higher postwithdrawal than prewithdrawal asymptotes, suggesting long-term repercussions from the elimination of previously redundant information.

Verbal reports again suggested that there can be substantial withdrawal effects of a dimension without awareness of its redundancy. This was particularly evident in the contour following groups, where 42% of the subjects failed to notice the

implicit, redundant property, whether it was size or shape. (In the enclosure/grasp groups, 75% noticed the redundant dimension.)

#### Discussion

Experiment 3 was conducted to determine whether the pronounced effects of redundancy varying size observed in Experiment 2 would occur in the absence of free manipulation and would generalize when exploration was constrained to a mode of exploration other than grasping. We found that the greater withdrawal effect of size (size weighting) was maintained for both the contour following and enclosure conditions. This result suggests that size weighting is intrinsic to the representation developed for classes of planar objects over a range of exploratory activities. Still, withdrawal effects were found for both focal dimensions under both methods of exploration, providing further evidence for dimensional coprocessing.

Of the three hypotheses considered initially to explain size weighting, the data support the third, which proposed a generally higher weighting for size information in classification. The effect does not simply reflect greater availability of size information during incidental manipulatory activities, as proposed by the first hypothesis, because incidental manipulation was precluded here. The asymmetry between shape and size withdrawal also does not depend on a manipulatory code formed from exploration by grasping, as suggested by the second hypothesis. Exploration by contour following as well as by enclosure produced the asymmetry.

As was indicated after Experiment 2, size weighting also does not appear to be due to intrinsically faster classification by size, resulting in relatively little information being coded about other dimensions. For the grasp conditions in this experiment, as before, the size-focus group was essentially no faster than the shape-focus group. However, the magnitude of the asymmetry found in the contour following conditions may reflect a temporal advantage for size encoding. Not only was the size-focus group faster within these conditions, but we have also informally observed that subjects exploring for size often terminated relatively early, before a distinctly shaped segment of contour was completely explored. Although early termination of exploration would limit shape encoding, there are still substantial effects of shape withdrawal.

Overall, this study supports the hypothesis of a general emphasis on size while ruling out several other possible explanations of the size weighting effect. Below, we develop the argument that such an emphasis could be related to the role of size in manipulation.

#### GENERAL DISCUSSION

The experiments presented in this paper confirm our prediction that information about planar size and shape is integrated in object classification. Relative to our comparison combination of texture and hardness, planar size and shape showed equivalent indications of integration based on measures of redundancy gain and effects of information withdrawal. Combinations of size with texture or hardness produced less evidence for integration. The data further indicated that the contribution of size information to classification dominates over that of other object properties (hardness,

texture, and planar shape) that are at least as discriminable and that are equivalent in predictive value for classification.

Our analysis of factors that constrain dimensional coprocessing in haptics points to the critical role of haptic exploration. In our previous work on texture and hardness, integration was made possible partly because the relevant exploratory procedures, lateral motion and pressure, are motorically compatible and hence can be executed together. The present investigation of size and shape differs in that the single procedure of enclosure can be used to extract both types of information. Although two variants of enclosure emerged, each clearly preferred for a specific property, Experiments 2 and 3 demonstrated that either version was sufficient to provide information about both size and shape.

Integration effects for shape and size contrasted with those of size and two substance-related dimensions, texture and hardness, again for predictable reasons. The exploratory procedure associated with texture judgements, lateral motion, is not particularly compatible with the enclosure procedure, although some texture information is no doubt gained from the initial stages of grasping. Also, unlike size and shape, these size/substance combinations do not share regional compatibility. It was therefore expected and confirmed that texture redundancy would be used minimally when subjects classified by size. One might expect somewhat greater evidence for integration of size and hardness on the basis of motoric compatibility: Normal pressure can be combined readily with enclosure. However, these dimensions conflict, in that the pressure needed to judge hardness may deform a compliant object, distorting its size. Accordingly, there was also no effect of redundant hardness variation when subjects classified by size. On the whole, then, our assumptions about the existence of dimensional coprocessing and its basis in exploration were confirmed from observation of exploratory activity and reaction time data.

It was further found in Experiment 2 that size withdrawal impeded performance substantially more than shape withdrawal, suggesting more processing of implicitly redundant size cues than of shape cues. The same dominance of size was found when it was combined redundantly with texture or hardness; in both these cases, only size withdrawal had a significant effect on response time. This occurred despite relatively few reports of consciously noticing the size variation.

There is good ecological reason for size evaluation to be of primary importance to the haptic system. Size constrains an important component of manipulation, the grasp; conversely, manipulation provides substantial information about size. During grasping, the fingers close in until they are stopped by the object's surface. The hand configuration at which stabilization occurs is substantially determined by the object's size and thus provides size information for perceptual purposes. In fact, grasping instantiates the exploratory procedure of enclosure, which we have found to be spontaneously chosen when planar or three-dimensional size is to be encoded (Klatzky et al., 1987; Lederman & Klatzky, 1987). Of course, shape also constrains the final geometry of the hand during grasping, but shape features of high spatial frequency may be irrelevant and unnoticed because of the limited area contacted by the fingers. As this argument implies, the enclosure procedure has been found insufficient to provide precise shape information. Surface texture constrains manipulatory forces (Johansson & Westling, 1984). However, grasping extracts fine textural

details only to the extent that the fingers move laterally on the object's surface. Finally, within the range of objects that maintain their shape under typical grasping forces, hardness will have little effect on simple manipulatory acts, nor will such acts convey hardness information.

We are suggesting, then, that size information might acquire perceptual importance because of its fundamental relation to the grasp. Moreover, grasping is an exceedingly common behaviour in both exploration and manipulation. In a haptic discrimination task with small objects, initial object contact was generally grasping (Roland & Mortensen, 1987); in an object identification task with common objects, static enclosure and lifting (or unsupported holding) were typically the first exploratory activities (Lederman & Klatzky, in press). Further, during functional interaction with objects, they must be picked up and/or oriented, which requires grasping.

One might think, from the foregoing arguments, that size weighting should be found only when objects are manipulated by grasping. This would occur if manipulatory activity became tuned to size and the resulting kinesthetic afference offered an additional cue to an object's class. Although a motor level code remains a possibility, Experiment 3 demonstrated that the higher weighting of size over shape was apparently not restricted to the enclosure mode of stimulus exploration. Essentially, size seems to be highly weighted in the representation of the object class, even when subjects are focussed on some other defining dimension.

Evidence for a similar effect has been found in visual shape matching (although there is also some evidence that size and shape are not strongly integrated in vision, e.g., Attneave, 1950). When subjects are told to match stimuli on the basis of shape, independent of size, they nevertheless show performance decrements due to size variations. This occurs both when shapes are presented in immediate succession and response time is measured (e.g., Larsen & Bundesen, 1978) and when a longer interval separates them and recognition memory is tested (Jolicoeur, 1987). These results indicate that size-specific representations for visually presented shapes are encoded even when size is irrelevant to the task.

The diagnostic value of stimulus size would be expected to be even more critical to the haptic system. Visual processes have developed to accommodate for changes in retinal size in identifying objects because such changes might reflect stimulus distance. In contrast, the distance of a haptically explored object from the sensors in an exploring effector is constant (and is zero).

The present size weighting effect contrasts markedly with a phenomenon we have reported previously (Klatzky et al., 1987). In an unsped task, subjects were instructed to sort the present set of objects in its entirety into classes having "similar" members. As the number of sorted classes was limited by the experimenter, a decision to sort on one dimension meant that objects varying on another had to be aggregated. When dimensions were pitted against one another in this fashion, size was the least frequent basis for sorting. Subjects sorting without vision tended, instead, to emphasize texture and hardness.

Similarly, subjects in the sorting study showed no difficulty in evaluating shape independent of size. This was particularly true when instructions defined similarity in terms of visual images. In one condition with imagery instructions, virtually every

subject sorted exclusively by shape. This contrasts with the strong evidence for size/shape integration in the present classification task.

In understanding the discrepancy between these (1987) results and the present ones, it is important to note that the similarity sorting task required subjects to evaluate the relative importance of object properties. The properties did not differentially define membership in some a priori class, nor were they differentially discriminable. Thus, unlike the present task, there was no prior designation of certain dimensions as particularly diagnostic. Under the circumstances, subjects may have emphasized those dimensions that were extracted most efficiently. In contrast, the current task involved classification of objects by predetermined dimensions as defined by a specific redundancy rule. Weighting of dimensions in these two tasks appears to be quite different. Smith and Medin (1981) have made a similar distinction between the *core* properties of categories, those that one spontaneously associates with the category when asked to describe its members, and those properties used in perceptually identifying an exemplar. The role of size in the haptic system appears to be substantially different in these two contexts.

It should be noted that our results are at present restricted to planar objects having sizes within the range of the adult hand and having multiple dimensions scaled for virtually equal discriminability. An important issue is whether the effects for planar size and shape will generalize to the domain of three-dimensional objects, particularly those offering redundant shape and size information over the object's surface (e.g., cubes, ellipsoids). The extension of shape information to the entire surface of the object would provide regional compatibility with texture and hardness information and would therefore promote integration. However, we would still expect the same exploratory constraints to apply. In particular, if size and shape are global structural properties which the enclosure procedure is sufficient to encode, we would expect substantial integration. Again, we would expect size and hardness or shape and hardness to be less integrated due to the potential deformation of the surface under pressure. There should be greater integration between texture and these structural properties because the surface texture is now part of the outer envelope that defines an object's shape.

Thus, there is reason to expect that the proposed constraints to haptic integration for planar objects would generalize to three-dimensional objects. The issue of asymmetries, particularly size weighting, remains a more open question. The generality of the size weighting asymmetry under different modes of exploration in Experiment 3 suggests that it might occur over a broader domain of objects for such a classification task.

The present findings may contribute to the development of computational models of exploration and object identification (e.g., Stansfield, 1988). Klatzky and Lederman (1990) have described a set of constraints that potentially guide the ongoing course of human object exploration and that can be implemented in algorithms that guide exploration by sensate robotic effector systems. Constraints arise at multiple levels in the processing system: from conceptual knowledge about objects, from knowledge about links between exploration and perception, and from the exploratory procedures themselves. Sufficiency is one such constraint, and the present data indicate that it is a useful one: When there are redundant cues to category membership, as

is the case with most common objects, the use of multiply sufficient procedure for exploration speeds haptic classification.

#### References

- Attneave, F. (1950). Dimensions of similarity. *American Journal of Psychology*, *63*, 516-556.
- Asby, F.G., & Townsend, J.T. (1986). Varieties of perceptual independence. *Psychological Review*, *93*, 154-179.
- Biederman, I., & Cheekosky, S.F. (1970). Processing redundant information. *Journal of Experimental Psychology*, *83*, 486-490.
- Bundesen, C., & Larsen, A. (1975). Visual transformation of size. *Journal of Experimental Psychology: Human Perception and Performance*, *1*, 214-220.
- Corsini, D.A., & Piek, H.L., Jr. (1969). The effect of texture on tactually perceived length. *Perception and Psychophysics*, *5*, 352-356.
- Garner, W. (1974). *The processing of information and structure*. Hillsdale, NJ: Erlbaum.
- Hanninen, K.A. (1970). The effect of texture on tactual perception of length. *Exceptional Children*, *36*, 655-659.
- Johansson, R.S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, *56*, 550-564.
- Jolicoeur, P. (1987). A size-congruency effect in memory for visual shape. *Memory and Cognition*, *15*, 531-543.
- Klatzky, R.L., & Lederman, S.J. (1990). Intelligent exploration by the human hand. In S.T. Venkataraman & T. Iberall (Eds.), *Dextrous robot hands* (pp. 61-81). New York: Springer-Verlag.
- Klatzky, R.L., Lederman, S.J., & Metzger, V.A. (1985). Identifying objects by touch: An "expert" system. *Perception & Psychophysicists*, *37*, 299-302.
- Klatzky, R.L., Lederman, S., Pellegrino, J., Doherty, S., & McCloskey, B. (1989). Procedures for haptic object exploration vs. manipulation. In M. Goodale (Ed.), *Vision and action: The control of grasping*. Norwood, NJ: Ablex.
- Klatzky, R.L., Lederman, S., & Reed, C. (1987). There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *Journal of Experimental Psychology: General*, *116*, 356-369.
- Klatzky, R.L., Lederman, S., & Reed, C. (1989). Haptic integration of object properties: Texture, hardness, and planar contour. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 45-57.
- Larsen, A., & Bundesen, C. (1978). Size scaling in visual pattern recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *4*, 1-20.
- Lederman, S.J., & Klatzky, R.L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*, 342-368.
- Lederman, S.J., & Klatzky, R.L. (in press). Haptic classification of common objects: Representation driven exploration. *Cognitive Psychology*.
- McColem, K. (1979). *The effect of texture on the haptic judgement of three dimensional size*. Undergraduate honours Psychology Thesis, Queen's University, Kingston, Ontario.
- Millar, S. (1986). Aspects of size, shape and texture in touch: Redundancy and interference in children's discrimination of raised dot patterns. *Journal of Child Psychology and Psychiatry*, *27*, 367-381.
- Roland, P.E., & Mortensen, E. (1987). Somatosensory detection of microgeometry, macrogeometry and kinesthesia in man. *Brain Research Reviews*, *12*, 1-42.
- Schiff, W., & Istikow, H. (1966). Stimulus redundancy in the tactile perception of histograms. *The International Journal for the Education of the Blind*, *16*, 1-11.
- Smith, E.E., & Medin, D.L. (1981). *Categories and concepts*. Cambridge, MA: Harvard University Press.
- Stansfield, S. (1988). A robotic perceptual system utilizing passive vision and active touch. *International Journal of Robotics Research*, *7*, 138-161.
- Trisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, *95*, 15-48.

First received 31 October 1989

Revision received 7 March 1990

Accepted 7 March 1990