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# There's More to Touch Than Meets the Eye: The Salience of Object Attributes for Haptics With and Without Vision

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## SUMMARY

The availability and salience of object attributes under haptic exploration, with and without vision, were assessed by two tasks in which subjects sorted objects that varied factorially in size, shape, texture, and hardness. In the *directed-discrimination* task, subjects were instructed to sort along a particular dimension. Although levels on all dimensions were easily discriminated, shape was relatively less so for haptic explorers without vision, as was hardness for those using vision and haptics. Size was least discriminable for both groups. In the *free-sorting* task, subjects were to sort objects by similarity. Three groups used haptic exploration only; these were differentiated by the experimenters' definition of object similarity: unbiased haptics (no particular definition of similarity), haptically biased haptics (similarity = objects feel similar), haptics plus visual imagery (similarity = objects' visual images are similar). A fourth group used vision as well as haptics, with instructions like those of the unbiased haptics group. Dimensional salience was measured by the extent to which levels on a dimension were differentiated in free sorting (more differentiation indicating higher salience). The unbiased haptics and haptically biased haptics groups were highly similar; both found the substance dimensions (hardness and texture) relatively salient. The haptics plus visual imagery group showed shape to be overwhelmingly salient, even more so when they were instructed to use two hands, but less so when they had just seen the objects. The haptics plus vision group showed salience to be more evenly distributed over the dimensions. Exploratory hand movements were videotaped and scored into four categories of *exploratory procedure* (Lederman & Klatzky, 1987): lateral motion, pressure, contour following, and enclosure (related to texture, hardness, shape, and size, respectively). The distribution of exploratory procedures was found to be directly related to both the designated dimension in the directed-discrimination task, and the salient dimension in the free-sorting task. The results support our contention that the haptic and visual systems have distinct encoding pathways, with haptics oriented toward the encoding of substance rather than shape. This may reflect a direct influence of haptic exploratory procedures: The procedures that are executed under unbiased haptic encoding are those that are generally found to be rapid and accurate (high "ease of encoding"), and the execution of these procedures determines which object properties become salient.

We invite you to take part in the following "thought" experiment. First, think of the attributes you would expect to see if you were *looking* at a cat. You would probably first think of the visible parts (e.g., four legs, tail, whiskers), perhaps imagining their particular shape or size. Next, suppose you were *touching* a cat without being able to see it. Which attributes now come to mind? You would be likely to think of the softness of the cat's fur, the warmth of its body, or its movement as it breathed. Our simple thought experiment suggests that object dimensions may be differentially salient for visual and haptic exploration.

This article addresses the cognitive representation of objects that are encoded through haptic exploration, both with and without vision. Haptics is defined as a perceptual system that incorporates inputs from cutaneous receptors and also from kinesthetic receptors embedded in muscles, joints, and tendons (Loomis & Lederman, 1986). (We include thermal sensing under the cutaneous system, although it was not specifically considered by Loomis & Lederman, 1986). Not only does the hand sense a wide variety of cutaneous primitives, but also its functional sensitivities are enhanced by the execution of very precise motor patterns that we call *exploratory procedures.* (The full description of these procedures and related empirical work can be found in Lederman & Klatzky, 1987; a reduced description which places the procedures in a general theoretical framework is in Klatzky & Lederman, 1987.) This system is therefore capable of encoding a number of object dimensions and properties: surface texture, internal substance, and thermal attributes (such as heat conductivity and absolute temperature), as well as the structural attributes of contour and size. Our research has demonstrated that haptic explorers can be remarkably fast and accurate at recognizing real objects (Klatzky, Lederman, & Metzger, 1985). We argue that these tasks are performed so well in part because haptics can encode many different object properties.

Why then is haptics usually not regarded as a viable perceptual system? The source of this negative view can be traced to earlier haptic literature that focused primarily on apprehension of contour (as did mainstream vision at that time) rather than on object processing per se. The earlier work used raised two-dimensional graphic displays or free-standing three-dimensional nonsense shapes in such tasks as matching, recognition, and reproduction (e.g., Bryant & Raz, 1975; Cashdan, 1968; Magee & Kennedy, 1980; see also Lederman, Klatzky, & Barber, 1985). However, most materials of this type are not ecologically valid: Either they fail to include haptically important properties such as texture, hardness, thermal conductivity, and absolute size when depicting real objects, or they do not vary these properties when using unfamiliar forms. Accordingly, these studies have failed to test the full capabilities of haptic encoding.

The focus on contour in previous research reflects adherence, whether implicit or explicit, to what we call an image-mediated model. This intuitively plausible model treats haptics as an inferior form of vision. It assumes kinesthetic information about local spatial position is integrated, usually over both space and time, to provide a representation of object contour. (Cutaneous information might also be integrated to provide a representation of texture, a dimension that is varied occasionally on raised graphics displays.) The resulting representation is converted to a visual image, which is then "reperceived" (cf. Kerst & Howard, 1978) by visual processors.

In striking departure from the image-mediation model, we assume that the haptic system has its own encoding processes and pathways, which may or may not be shared with vision. Even when representations achieved haptically and visually are held in common, the two domains are likely to give different weights to such codes. This assumption therefore leads us to consider which attributes are perceptually and cognitively important when an object is encoded by the haptic system, with and without vision. In other words, we are concerned with the "salience" of object attributes under haptic exploration.

At the outset, we can identify certain factors that might affect the salience of some dimension along which haptically explored objects vary. One is stimulus-specific discriminability, that is, the extent to which levels on the dimension can be differentiated within a particular stimulus set (as measured by accuracy or variability). This may be particularly important in limiting salience: If all stimuli have similar values along a dimension, it should not be highly salient.

A more general potential influence on salience is the intrinsic ease with which the perceptual system encodes distinctions along a particular dimension, over a lifetime of experience with typical variations. The dimensions studied by Klatzky and Lederman vary considerably in ease of haptic encoding, as indicated by the time spontaneously spent in executing the relevant exploratory procedures and by the resulting accuracy. In contrast, the visual system accurately computes many attributes with considerable speed (although exceptions may exist, such as with very large objects that require multiple fixations). A third factor that may strongly influence dimensional salience is the goals and expectancies of an explorer. This influence acts "top down," in contrast to the first two factors, which reflect more direct influences of the perceptual system.

In the present experiments, the principal concern was with dimensional salience and its relation to ease of encoding. Note that we wished to identify general characteristics of haptic processing, not stimulus-specific effects. Thus, the experimental objects were designed to have highly discriminable values within each of the varied dimensions. To verify that this was the case, directed-sorting tasks were used: Subjects were instructed to sort objects along a given dimension, and their speed and accuracy were measured. Given discriminable values within the particular set of stimuli, these tasks were further used to infer ease of encoding more generally.

To assess salience, a free-sorting procedure was used: Subjects placed objects perceived as "similar" into a common bin. A dimension was considered salient if it was used as a basis for judging similarity. An important aspect of the free-sorting task is that it pits dimensions against one another, with segregation along one dimension requiring that objects varying along others are not differentiated. This reduces the potential for compromise and makes favored dimensions readily apparent.

The salience of object attributes was compared under various conditions. One important comparison was between haptic exploration with and without vision. The intersensory integration literature has addressed the issue of differential weighting of tactual and visual inputs in a variety of perceptual tasks. Much of the evidence has been obtained using a discrepancy paradigm, in which conflicting information is presented simultaneously to a pair of modalities. The relative weighting can be observed by comparing performance in the discrepancy condition to either of the unimodal control conditions (for a review, see Welch & Warren, 1981). "Functional measurement" (Anderson, 1974; Jones, 1983; Lederman, Thorne, & Jones, 1986) has also been used to assess the relative weights applied by different modalities in nondiscrepant bimodal tasks.

The present studies also compared dimensional salience across conditions of solely haptic exploration with no modality-specific encoding bias, a bias toward using visual imagery, and a bias toward haptic encoding. If haptic exploration naturally gives rise to visual imagery, the unbiased and imagery conditions should be quite similar, and they should be different from a condition in which haptic explorers are urged to consider what

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objects "feel like." As our little thought experiment suggests, however, this is likely not to be the case.

The objects that were sorted in these studies varied factorially along four dimensions: texture (i.e., roughness), hardness, shape (two-dimensional), and size (also two-dimensional, because thickness was held constant). Texture and hardness are substance-related attributes that can be extracted locally (assuming homogeneous objects or regions); shape and size are global structural properties.

Our a priori predictions were that haptic encoding without vision would most naturally focus on texture and hardness, whereas the addition of vision (imaged or real) would lead to greater emphasis on shape and to some extent on size. These predictions are based on evaluations of the ease with which the various dimensions are encoded, as indicated by the Lederman and Klatzky work on exploratory procedures and other research on encoding by vision and touch. We will now describe the implications of these data for ease of encoding and hence for the potential salience of each dimension. (For a review that treats sensory comparison more generally, see Marks, 1978.)

*Shape.* The dimension of shape is particularly problematic for haptics, both in an absolute sense and relative to vision. Our previous studies indicate that shape can be extracted grossly by the procedure of "enclosure": a static molding to the contours of an object. This is quick to perform but conveys only low-level information. In order to determine precise shape, it is necessary to use "contour following" (a dynamic movement along an edge), which is characteristically very slow to execute and therefore subject to inaccuracies due to memory and integration.

As indicated previously, there is evidence that the haptic system is limited in encoding precise shape even when contours are followed in detail. In contrast, contour information (or inferred volumetric structure) appears to be a primary avenue to object identification in vision (Biederman, 1987). This may well be because the visual system is extremely well equipped to perform fine spatial analyses of patterns both quickly and accurately over a broad range of viewing distances. It is perhaps not surprising, then, that the results of intersensory discrepancy studies involving judgment of macrospatial object properties (i.e., size, shape, depth, and spatial position) have consistently found that vision either completely or very strongly dominates touch (see Lederman et al., 1986; Welch & Warren, 1981).

*Size.* For similar reasons, the size of objects (at least hand sized, as in these experiments) appears to be more readily encoded by vision. In haptics, size is primarily extracted with the "enclosure" procedure, for objects within the span of the hands. This is quick to perform but appears to provide only relatively gross size information, as it does for contour. The effectors that are used to enclose (e.g., two fingers; full hand) may provide a natural measuring unit or "bandwidth," so that size discriminations are made easily only between objects that are enclosed differently. For larger objects, sequential contour following or a series of enclosures is likely, imposing memory and integration loads such as occur in shape encoding.

There is evidence that the visual system veridically represents one-dimensional size (i.e., length; Teghtsoonian & Teghtsoonian, 1965), as well as two-dimensional size when binocular depth cues are available (e.g., Holway & Boring, 1941); observers also readily adjust for viewing distance. There has been little formal experimental work on haptic evaluation of size, but some relevant studies suggest it is not performed particularly well. In the magnitude estimation task used by Teghtsoonian and Teghtsoonian, the length of rods statically grasped at both ends was also estimated. As in vision, the exponent of the power function was close to unity. However, we have more recently demonstrated considerable distortion in haptic length perception of triangular and curved raised lines when traced with a finger or when fingers statically anchor each end (Lederman et al., 1985; Lederman, Klatzky, Collins, & Wardell, 1987). Millar (1986) has shown that subjects of all ages found the size of small raised-dot surfaces (less than 1 cm on a side) particularly difficult to discriminate haptically. Finally, McColm (1979) found exponents of approximately .7 in tasks requiring the magnitude estimation of haptically perceived volume (cubes), indicating once again a lack of 1:1 correspondence between physical and perceived size.

*Texture.* Both vision and haptics encode texture well. This dimension is haptically extracted by the "lateral motion" procedure, a rubbing movement that is quick to perform and does not require an extended surface sample. Evidence for haptic salience of texture was provided by Lederman and associates (Lederman & Abbot, 1981; Lederman et al., 1986). Using a discrepancy paradigm, they found that when instructions referred merely to "texture," vision and touch weighted the inputs about equally. An instruction to treat texture as "spatial density" led to visual dominance, and an instruction to treat it as "roughness" led to dominance by touch. Where the microspatial distribution of surface elements is not obvious, and especially when a single object is being perceived at one time, as in the present studies, we might expect texture to be more relevant to haptic exploration than to vision. In contrast, vision is thought to use texture variation primarily to segment the visual field into distinct objects, to judge depth, and to judge microspatial patterns within homogeneous surfaces.

*Hardness.* This is commonly defined in several different ways, for example, by the distance an object such as the finger penetrates a surface when applying a normal force, by the force required to break through a surface (brittleness), and even by elasticity (the rate or extent to which a surface recovers its previous position after deforming under force). Instructions to judge hardness lead to the exploratory procedure called "pressure," which expends normal force into the surface of the object. (Torque is also possible.) Like the lateral motion procedure used for texture, pressure is rapid and can be executed locally on a homogeneous object.

There is little work on hardness perception by either haptics or vision. Harper and Stevens (1964) used direct magnitude estimation tasks and cross-modal matching to scale hardness and softness by touch alone. The judgments generally followed a power function, with exponents of about .8 for magnitude estimation and .7 and .6 from matching with handgrip and loudness, respectively. There was an upper threshold on hardness, above which there were no further variations in subjective magnitude given differing stimulus values. Thus, these results suggest systematic, if nonveridical, haptic judgments of hardness. As for vision, it is obvious that within the range of hardness values of rigid objects, there are virtually no visual cues. Even when objects become so soft that their contours are deformed by their own weight, the visual cues may not be substantial.

Thus, hardness appears to be more readily encoded by haptics than by vision.

In addition to assessing salience under haptic exploration, the current study also focuses on the exploratory procedures themselves. Klatzky and Lederman previously linked haptic exploratory procedures to encoded object attributes by observing hand movements made when objects were matched along experimenter-specified dimensions. However, in less directed tasks (such as free sorting), exploratory activities may not be as closely related to the encoded attributes. For example, a single enclosure, which was previously shown to be sufficient for crudely apprehending a number of attributes simultaneously, may be the only exploratory procedure performed. To address this issue, hand movements were videotaped during the sorting tasks and subsequently related to dimensional salience.

There is another issue related to exploratory procedures: We note informally that during spontaneous exploration, people almost invariably use both hands to execute a contour-following procedure. This two-handed search is not nearly so apparent when the substantive dimensions of texture and hardness are extracted. This probably occurs because both lateral motion and pressure procedures may be executed competently with either one or two hands. Given the apparent connection between two-handed search and contour following, we assessed whether the salience of shape could be augmented by requiring two-handed exploration, and conversely, suppressed by allowing only one-handed haptic exploration. Together, the free- and constrained-sorting (i.e., directed one- and two-handed) tasks were intended to confirm and further extend our understanding of the relation between object knowledge and purposive hand movements.

## Experiment 1: Ease of Encoding Object Dimensions by Using Haptics With and Without Vision

The purpose of this study was to verify that values on four object dimensions were highly discriminable, and under these conditions, to assess relative ease of encoding by measures of time and accuracy. The objects were initially designed to have dissimilar dimensional values, so that variations on these measures could be generalized beyond the restricted stimulus set. The dimensions were explored either by haptics alone or by haptics and vision together. Two—texture (roughness) and hardness—were substance-related, and two—shape and size—pertained to structure. Analysis of hand movements during the directed-sorting tasks was also performed and related to the dimension being sorted.

### *Method*

*Stimuli.* The final set of custom-prepared stimuli used in the following experiments was chosen on the basis of preliminary haptic scaling of each dimension by 10 raters. Each of the four stimulus dimensions was evaluated in isolation (e.g., texture, by fabric samples). Raters ordered the levels on the dimension and assigned each a value, anchoring the low end at 10. The three levels ultimately selected for the stimulus set were chosen to make the scaled range and intervals along each dimension relatively comparable. The procedure was also intended to achieve high discriminability across dimensions. The selected levels (and average scale values) for each dimension are presented in Table 1.

Table 1

*Description of Stimuli and Average Scale Value: Experiment 1*

| | Dimension level | | |
|---|---|---|---|
| Dimension | 1 | 2 | 3 |
| Texture | satin | thin-wale corduroy | rough metallic knit |
| | 10.0 | 22.4 | 40.7 |
| Hardness | foam rubber | polyfoam | wood |
| | 10.0 | 36.0 | 53.5 |
| Shape | oval | hourglass | three lobed |
| | 10.0 | 26.0 | 39.5 |
| Size (in $\text{cm}^2$) | 17.4 | 32.9 | 52.9 |
| | 10.0 | 25.7 | 47.3 |

*Note.* Subjects assigned the number 10 to Level 1 of each dimension; Levels 2 and 3 were assigned larger numbers that reflected the perceived distance along the specified dimension.

The stimuli were constructed by factorially combining all the dimension levels. With 3 shapes, 3 sizes, 3 hardness values, and 3 textures, there were 81 stuffed forms. Each object was a black "wafer" approximately 1.25 cm thick, cut in a particular shape and size from material of a given hardness, and covered with fabric of a given roughness. The seams of the covering fabric lay along the outer contour and were smoothed with glue after stuffing and sewing.

*Subjects.* The subjects were students from an introductory psychology class, participating as part of a course requirement. There were 20 subjects in the haptic (blindfolded) sorting condition and 10 in the haptic plus visual sorting condition; these latter subjects saw as well as touched the objects.

*Procedure.* In the first part of the session, all 81 objects were sorted four times, once for each target dimension. Three bins were arranged on a table before the subject at 30°, 90°, and 150° (relative to 0° right horizontal); a tray was positioned directly in front. Before each sort, a target dimension was designated, and one bin was assigned to each of its levels. This assignment was random and varied over subjects. The subject practiced finding the bins and was then given samples of the dimensional levels in isolation.

During the sorting test trials, an object was placed in the tray by the experimenter, and the subject placed it into the bin designated as target for that level of the given dimension. Subjects were told to be as fast but as accurate as possible. As each object was removed from the tray, the next object was put into position. The order in which dimensions were sorted was counterbalanced by a Latin square over subjects.

Response time (in milliseconds) was measured from the beginning to the end of each 81-object sort. Errors were recorded after each sort. In addition, after completing the sort on a given dimension, the subject rated the task difficulty on a 10-point scale. The hand movements of the haptic subjects were videotaped, and frame numbers (30/s) were overlaid on the tape for analysis.

After performing three-level sorts on each dimension, the subject sorted all pairs of levels on each dimension, that is, 12 more two-level sorts by using the right and left bins. The order of the sorts was random, except that the same dimension was never designated twice in succession. Response times and errors were recorded as before, but task difficulty was not rated.

### *Results*

Table 2 presents the mean number of errors and response time for each of the 16 sorting tasks, by instruction. The difficulty-rating data generally correlated with errors and will not be reported. In all analyses in this paper, unless otherwise indi-

Table 2
*Mean Error Rate and Response Time in Seconds by Dimension, Sorting Task, and Group: Experiment 1*

| | Haptic plus vision | | Haptic | |
|---|---|---|---|---|
| Task | Error | Time | Error | Time |
| Texture | | | | |
| 3-level | 0.9 | 86.4 | 2.3 | 149.2 |
| Level 1 vs. $2_a$ | 0.0 | 48.9 | 0.1 | 83.7 |
| Level 2 vs. $3_b$ | 0.8 | 49.2 | 0.3 | 86.4 |
| Level 1 vs. $3_c$ | 0.0 | 49.5 | 0.2 | 78.4 |
| Hardness | | | | |
| 3-level | 4.3 | 105.5 | 3.5 | 150.9 |
| Level 1 vs. $2_d$ | 1.9 | 55.6 | 0.4 | 84.6 |
| Level 2 vs. $3_e$ | 0.4 | 52.4 | 0.0 | 80.5 |
| Level 1 vs. $3_f$ | 0.0 | 50.4 | 0.0 | 76.6 |
| Shape | | | | |
| 3-level | 1.6 | 82.8 | 0.7 | 160.7 |
| Level 1 vs. $2_g$ | 0.3 | 49.1 | 0.6 | 85.2 |
| Level 2 vs. $3_h$ | 0.1 | 48.8 | 0.4 | 93.9 |
| Level 1 vs. $3_i$ | 0.0 | 48.4 | 0.2 | 87.1 |
| Size | | | | |
| 3-level | 4.4 | 90.8 | 6.7 | 154.6 |
| Level 1 vs. $2_j$ | 1.1 | 49.5 | 1.1 | 84.2 |
| Level 2 vs. $3_k$ | 1.7 | 52.6 | 3.4 | 92.6 |
| Level 1 vs. $3_l$ | 0.0 | 48.8 | 0.1 | 78.3 |

*Note.* Subscripts refer to the following significant comparisons. Haptic–time: c < a < b; f < e < d; g, i < h; l < j < k (error: l < j < k). Haptic plus vision–time: d < f; j, l < k (error: l < k).

cated, alpha was set at .05, and any stated comparisons between levels of a factor are significant by Scheffé test.

The haptics and haptics plus vision conditions differed with respect to the ordering of dimensional difficulty. Response times for the three-level sorting were analyzed with a 2 × 4 analysis of variance (ANOVA) on instruction and dimension. The effect of instruction was significant, $F(1, 28) = 93.4$, indicating that haptics plus vision was much faster. There was also a significant interaction, $F(3, 84) = 7.4$: This reflects the fact that hardness was significantly slower in the haptics plus vision condition than the other dimensions, $F(3, 27) = 14.4$, whereas shape was slowest (though not significantly so) in the haptics condition. The error data showed no effect of instruction but a significant effect of dimension, $F(3, 84) = 18.8$. Within the haptics group, size produced more errors than all other dimensions; within haptics plus vision, size and hardness had higher errors than texture. Errors tended to be confusions between adjacent levels on a dimension.

An overall ANOVA on the two-level sorting with variables instruction, dimension, and cutpoint (i.e., the two levels being discriminated: 1/2, 1/3, or 2/3) indicated trends that were similar to the three-level sorting and hence will not be reported in detail. Table 2 indicates the significant post hoc differences between the levels of the cutpoint variable, for each dimension and group. In general, the 1/3 cutpoint differentiating the extremes of the dimension was always processed with either the least error or greatest speed or both (with exceptions small in magnitude), thus validating the dimensional ordering. The two cutpoints between adjacent levels varied in difficulty within and between dimensions, however.

*Videotape data.* Ten subjects were randomly chosen from the taped record of the three-level discrimination task in the haptic condition only. For each subject and each target dimension, the sorting period for 10 objects (every 8th one, starting with the first) was analyzed. The period beginning with the subject's first contact with the object and ending with its placement in a bin was examined for the presence of four exploratory procedures: lateral motion, pressure, contour following, and enclosure. These procedures are associated with apprehending texture, hardness, shape, and both size and shape, respectively. Both the presence of a procedure and its duration were recorded, as was the number of objects (out of 10) explored with two hands. Reliability of scoring such exploration has previously been assessed at 80%; we report reliability checks with the present stimuli for Experiment 2A. Scoring details are available on request.

Table 3 shows the mean frequency of each procedure (averaged over subjects, summed over 10 objects) and the number of objects undergoing two-handed exploration for each target dimension. (The duration data generally paralleled the frequencies and therefore are not reported here.) A 4 × 4 ANOVA was conducted on the frequency data, with the variables dimension and procedure. As expected, this produced an interaction, $F(9, 81) = 91.2$. In addition, there was a main effect of procedure, reflecting the general use of enclosure to initiate exploration, $F(3, 27) = 604.4$.

On the whole, the effects were as predicted. Enclosure was high for all conditions. With texture targeted, lateral motion was also higher than the other procedures; with hardness, pressure was higher. Contour following had its highest value for shape (not significantly so), but enclosure was nonetheless highly dominant for both shape and size. For these hand-size objects with only moderately complex contours, enclosure appears to be reasonably sufficient for shape discrimination.

An ANOVA was conducted on the measure of two-handed use, with one variable, target dimension. A significant effect, $F(3, 27) = 10.0$, reflected greater use of two hands for shape discrimination than for size and hardness. (The contour following procedure is generally performed with both hands.) Texture also led to substantial use of two hands. Observation of the tapes indicates that the second hand was used to stabilize the object for lateral motion, the procedure associated with texture encoding.

## *Discussion*

A necessary initial step in investigating dimensional salience under haptic exploration is to create stimuli that are reasonably easy to discriminate on the dimensions. The present study generally verifies that this was the case; errors were quite low in all

Table 3
*Frequency of Exploratory Procedures and Two-Handed Exploration by Dimension (Haptic Condition): Experiment 1*

| Procedure | Texture | Hardness | Shape | Size |
|---|---|---|---|---|
| Lateral motion | 9.3 | 0.2 | 0.7 | 1.0 |
| Pressure | 0.0 | 10.0 | 0.0 | 0.3 |
| Enclosure | 10.0 | 10.0 | 7.7 | 8.9 |
| Contour following | 0.8 | 0.0 | 2.4 | 0.1 |
| Two Hands | 2.6 | 0.1 | 5.3 | 0.3 |

conditions. With such highly differentiable values, speed effects and any errors that are observed can be taken to indicate general ease of encoding the dimensions rather than stimulus-specific findings. As we have noted, there are few studies of haptic encoding of dimensions other than contour, and those usually do not compare haptics alone to haptics with vision.

Size was found to be less discriminable than the other dimensions, both with and without vision. Although this might be dismissed as stimulus specific, note that the present sizes were dictated by the size of the hand. The objects were intended to be capable of exploration by even a fairly small adult hand; yet they were to be large enough that contour variations were readily apparent. These constraints establish nonarbitrary boundary conditions on the present size effects.

The differences observed between haptic exploration with and without vision are consistent with our original hypotheses about the relative ease of encoding substance and shape information for haptics versus vision. Contour information was discriminated relatively slowly by haptic exploration (although accurately, for the present objects). Hardness was both less discriminable and slower to encode than other dimensions when vision and haptics were used together. Although caution must be used in generalizing these results, two findings support their generality. First, these contrasting trends were obtained with the same set of objects; only the modality of exploration was changed. Second, the same trends are apparent even when the extremes of the dimensions were being discriminated. Thus, the present pattern does not appear to be dictated by biases in these particular stimuli; we infer more general differences in ease of encoding.

The study also confirms and extends the relation between desired knowledge about object attributes and the nature of haptic exploration. In the current experiment, when a particular dimension was targeted for discrimination, haptic observers tended to use specialized procedures for extracting targeted information, as described above. The slowness of contour following, in particular, accounts for the speed disadvantage for shape sorting in the haptic condition.

## Experiment 2A: Haptic Salience As Revealed by Free Sorting Under Four Instructions

In this study, a free-sorting task was used to assess relative dimensional salience under four instructional conditions: unbiased haptics, haptically biased haptics, visual-imagery biased haptics, and haptics with vision.

### *Method*

*Subjects.* A total of 80 undergraduates participated for partial credit in an introductory psychology class. They were assigned in rotation to four groups of 20 persons, with each group varying in instructions.

*Procedure.* The stimulus objects and experimental apparatus were as described in Experiment 1, except that there were four bins arranged in a diamond configuration so that their positions could easily be discriminated. The subject's task was to sort the 81 stimuli into bins, so that similar objects were placed in the same bin. Initially, the experimenter gave all objects to the subject, one at a time, for familiarization. Each subject then sorted three times, once using two bins, once three, and once four, in counterbalanced order. Each time, the experimenter handed every object in turn to the subject, who placed it into the desired bin. Corrections were permitted. At the end of the session, subjects were asked if they had noticed the dimensions along which stimuli varied, and they rated the importance of each dimension on a 5-point scale.

The instructions were as follows: (a) Unbiased haptics subjects were blindfolded and told that objects that "go together" or are "similar" should be placed in the same bin; no further interpretation was given. (b) Haptically biased haptics subjects were blindfolded and told that subjects go together if they *feel* similar. (c) Haptics plus visual imagery subjects were blindfolded and told that objects go together if their visual images are similar; that is, if the objects could actually be seen, they would look like one another. (d) Haptics plus vision subjects were not blindfolded, but were otherwise like unbiased subjects.

### *Results*

The principal expected result in this experiment was an interaction indicating that the salience of an object dimension varied over the instructional conditions. We consider first the measure of salience and then evaluate its pattern over dimensions, instructions, and number of bins used in the sort.

*Scoring.* The sorting data were converted to "salience" scores, one for each pair of levels or cutpoint—1/2, 2/3, 1/3—within each object dimension. The score for a given cutpoint was computed as follows: For each bin used during a sort, the number of objects representing each of the cutpoint's two levels was determined, and the absolute value of the difference between these numbers was determined. For example, on the size dimension, if a subject sorted 2 small (Level 1) and 5 large (Level 3) objects into a common bin, the score for the 1/3 cutpoint within size for that bin would be 3 (5 − 2). These values were summed over bins, producing the salience score for a cutpoint.

Each score indicates how well people discriminate between the two levels that constitute the cutpoint. The scores range from zero, which results when values are equally mixed within bins, to 54, which results when objects with the two dimensional levels under scrutiny are never placed in a common bin. In the two-bin sort, only two cutpoints can attain maximum scores for some dimension (in which case the other scores zero), whereas in the three- and four-bin sort, all three can score 54.

The anticipated effect—differences in the relative salience of dimensions across instructional conditions—was expected to vary across the sorts and cutpoints. The two-bin sort would indicate if subjects selected a particular value on a dimension as the basis for differentiating objects. In this case, two of the cutpoints for that dimension would have high salience scores and one low (e.g., if the most distinctive level was the first, the 1/2 and 1/3 cutpoints would have high scores and the 2/3 low), and scores for other dimensions should be essentially zero. In the three-bin sort, subjects were expected to select a dimension and distinguish among each of its levels, in which case salience scores for that dimension would be uniformly high, and for other dimensions, low. This would provide the most direct indication of overall salience and its interaction with instruction. In the four-bin sort, subjects must distinguish among more values than are available within a dimension, providing high salience scores for secondarily important dimensions but diluting instruction effects.

In Table 4, the salience scores are presented by sort (two, three, and four bins), dimension, and cutpoint, for each instruction group. The average scores (over all cutpoints) for the three-

Table 4
*Salience Scores by Sort, Dimension, Cutpoint, and Instruction: Experiment 2*

| | Two-Bin Sort | | | Three-Bin Sort | | | Four-Bin Sort | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Dimension | 1/2 | 2/3 | 1/3 | 1/2 | 2/3 | 1/3 | 1/2 | 2/3 | 1/3 | *M* |
| Size | | | | | | | | | | |
| H | 0.7 | 4.8 | 5.3 | 2.5 | 1.8 | 2.7 | 11.6 | 6.8 | 16.1 | 5.8 |
| HH | 2.4 | 3.2 | 5.4 | 0.8 | 0.4 | 0.6 | 2.2 | 2.4 | 2.8 | 2.2 |
| HVI | 5.5 | 5.5 | 8.1 | 2.8 | 3.0 | 3.1 | 6.4 | 2.4 | 7.8 | 5.0 |
| HV | 0.7 | 12.8 | 13.3 | 0.0 | 0.0 | 0.0 | 11.0 | 9.6 | 15.3 | 7.0 |
| Hardness | | | | | | | | | | |
| H | 7.4 | 22.8 | 27.3 | 19.8 | 21.0 | 21.0 | 7.0 | 19.0 | 19.6 | 18.3 |
| HH | 8.3 | 17.2 | 25.5 | 11.5 | 11.7 | 13.5 | 11.0 | 22.9 | 27.1 | 16.5 |
| HVI | 2.7 | 5.4 | 5.4 | 2.6 | 4.1 | 4.1 | 10.5 | 16.7 | 21.0 | 8.0 |
| HV | 0.8 | 10.9 | 11.7 | 5.4 | 6.8 | 6.8 | 6.7 | 12.5 | 12.8 | 8.3 |
| Texture | | | | | | | | | | |
| H | 5.6 | 9.0 | 11.7 | 18.0 | 16.5 | 18.3 | 20.2 | 25.0 | 25.3 | 16.6 |
| HH | 12.4 | 6.9 | 10.9 | 19.3 | 20.9 | 20.9 | 31.5 | 30.5 | 34.8 | 20.9 |
| HVI | 5.4 | 13.5 | 10.8 | 5.8 | 10.7 | 10.2 | 14.3 | 20.6 | 19.5 | 12.3 |
| HV | 8.8 | 8.5 | 5.6 | 24.3 | 24.3 | 24.3 | 18.3 | 17.1 | 19.9 | 16.8 |
| Shape | | | | | | | | | | |
| H | 5.7 | 3.0 | 8.3 | 13.7 | 13.8 | 14.0 | 18.5 | 22.3 | 20.7 | 13.3 |
| HH | 8.5 | 0.4 | 8.3 | 21.8 | 21.9 | 21.9 | 10.4 | 16.0 | 16.1 | 13.9 |
| HVI | 29.7 | 8.1 | 32.4 | 41.2 | 40.8 | 41.1 | 27.8 | 29.3 | 29.7 | 31.1 |
| HV | 16.6 | 3.3 | 13.9 | 24.3 | 24.3 | 24.3 | 31.1 | 27.6 | 28.1 | 21.5 |

*Note.* H = unbiased haptics; HH = haptically biased haptics; HVI = haptics plus visual imagery; HV = haptics plus vision.

bin sort, which most directly indicates the overall dimensional salience, are shown in Figure 1, by instruction and dimension.

An omnibus ANOVA on all variables confirmed the critical prediction about interactions involving instruction and dimension. It showed higher order interactions among instruction, dimension, and cutpoint, $F(18, 456) = 2.0$, and dimension, sort, and cutpoint, $F(12, 912) = 7.2$). Given the results of Experiment 1 (which showed shape and texture to be somewhat more discriminable than hardness and size), effects of dimension might be expected on the basis of discriminability alone. None-

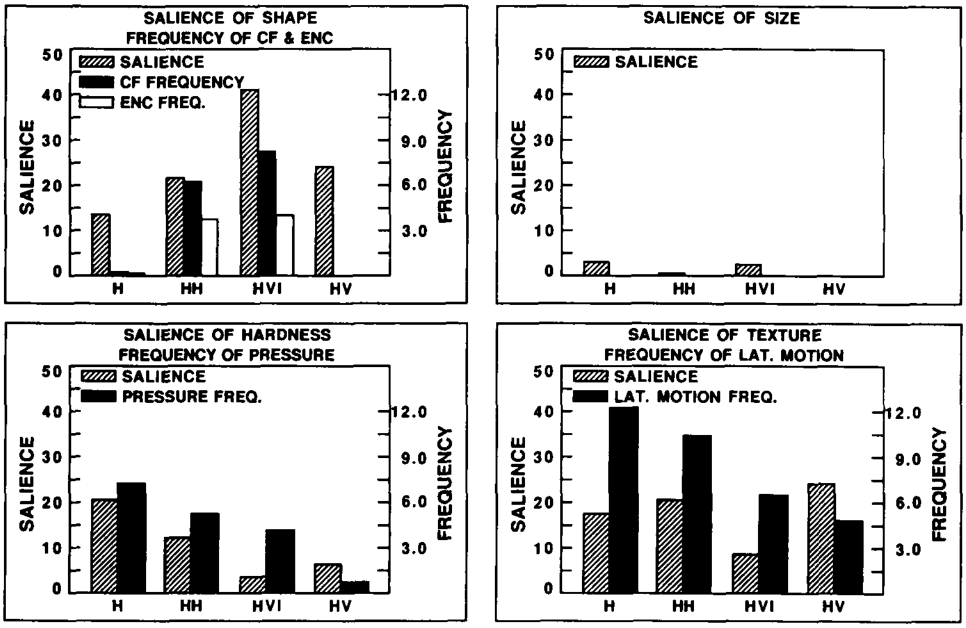

*Figure 1.* Salience scores for each dimension, by group (H = unbiased haptics; HH = haptically biased haptics; HVI = haptics plus visual imagery; HV = haptics plus vision), together with the frequency of the relevant exploratory procedures for the dimension (CF = contour following; ENC = enclosure; LAT = lateral). (Note that no salience score for size significantly differs from zero and therefore no procedure is displayed.)

Table 5
*F Values for Significant Effects in Analysis on Instruction and Cutpoint*

| Dimension and sort | Instruction: $F(3, 76)$ | Cutpoint: $F(2, 152)$ |
|---|---|---|
| Shape | | |
| Two-bin | 5.4 | 17.1 |
| Three-bin | 4.0 | |
| Hardness | | |
| Two-bin | 3.7 | 15.6 |
| Three-bin | 3.0 | 3.2 |
| Four-bin | | 16.4 |
| Texture: | | |
| Four-bin | | 3.4 |
| Size | | |
| Two-bin | | 7.1 |
| Four-bin | 3.1 | 7.4 |

*Note.* For the interaction of instructions and cutpoint on the shape dimension, $F(6, 152) = 2.2$.

theless, the three-way interaction among instruction, dimension, and cutpoint, and a significant instruction by dimension interaction, $F(9, 228) = 5.1$, indicate that discriminability did not force a common pattern on all instruction groups. (This interaction was also significant within each sort.)

The sorts were expected to reveal different patterns and total scores, for reasons described earlier. In general, these expectations were confirmed: The three-bin sort showed one dimension to be highly salient; the two-bin sort revealed the important level within that dimension (via cutpoint effects); and the four-bin sort established secondary dimensions. Often, the pattern of four-bin sorting within individual subjects suggested two dimensions were favored, but variations in these dimensions over subjects produced fairly uniform scores.

The effects involving cutpoint indicate that only the texture dimension approximated equal subjective spacing between adjacent values. The salience scores on the other dimensions indicate that a major distinction was made between one value and the other two, which were treated as more similar. The oval shape was differentiated from the two lobed ones, the hardest object from the two compliant ones, and the largest objects from the two smaller. As expected, these trends were minimized when subjects sorted into three bins.

Given these patterns, subsequent analyses within each level of the dimension and sort variables were used to isolate the effects of interest. The main interest was in the effects of instruction, but the ANOVAs included the cutpoint variable as well. (Although some cutpoint effects were observed, they were generally as described earlier and will not be discussed further.) Planned comparisons were used to compare each of the haptics plus vision and haptics plus visual imagery groups, on the one hand, to the unbiased and haptically biased haptics groups, on the other. Table 5 reports the *F* values of significant effects.

*Shape dimension.* Shape gave the overall highest salience scores, but there were dramatic differences in its salience depending on instructions. In both the two- and three-bin sorts, the hypothesis that shape would be more salient to the haptics plus vision and haptics plus visual imagery groups than to the unbiased haptics and haptically biased haptics groups was supported. The effect was particularly strong for the haptics plus visual imagery group, which had higher scores than any other. (The comparison of haptics plus visual imagery to haptics plus vision was significant in the three-bin sort by a priori test, but not Scheffé.) The effects of instruction were diluted ($p < .10$) in the four-bin sort, indicating that all groups used shape as at least a secondary dimension of similarity.

*Hardness.* Again, there were substantial instruction differences. In the two- and three-bin sorts, the comparisons showed the unbiased haptics group to have higher scores than either haptics plus vision or haptics plus visual imagery. In the two-bin sort, the haptically biased haptics group also had higher scores than the haptics plus visual imagery group.

*Texture.* There were no significant main effects of instruction, although planned comparisons showed that on the four-bin sort, the haptics plus vision and haptics plus visual imagery groups had lower scores than the haptically biased haptics group. In the three-bin sort, almost all salience scores were significantly greater than zero, indicating that texture was used to some extent to determine similarity, but about equally so for all groups.

*Size.* Size was the least discriminable dimension according to Experiment 1, and it was also minimally salient to all the instruction groups. In the four-bin sort, size was apparently brought into secondary consideration, particularly by the haptics plus vision group, which had higher scores than the haptically biased haptics group. In the two-bin sort, the only values significantly above zero were again in the haptics plus vision group. In the three-bin sort shown in Figure 1, no score was significantly above zero.

*Correlations between instruction groups.* The 36 cutpoint scores over all dimensions and sorts were used as the basis for intergroup correlations, as is shown in Table 6. As expected, the unbiased haptics and haptically biased haptics groups were highly correlated, as were the haptics plus vision and haptics plus visual imagery groups. The haptics plus visual imagery group correlated minimally with the unbiased haptics and haptically biased haptics groups; however, haptics plus vision did show a positive correlation with those latter groups. Thus, vision seems to be a middle ground between haptics without imagery and haptics with imagery. It is less extreme in its reliance on shape than the imagery condition, making use of dimensions that are important to haptics, such as hardness and texture.

*Ratings of dimension importance.* In general, subjects noticed that objects varied on all four dimensions, and they seemed substantially aware of the dimensions underlying their similarity judgments. An instructions by dimension ANOVA on the ratings produced a main effect of dimension, $F(3, 228) =$

Table 6
*Correlations Among Groups on Cutpoint Scores*

| Group | Unbiased haptics | Haptically biased | Haptics plus vision |
|---|---|---|---|
| Haptically biased | $.749_a$ | | |
| Haptics plus vision | $.457_{a,b}$ | $.504_{a,b}$ | |
| Haptics plus imagery | $.152_b$ | $.308_b$ | $.692_a$ |

*Note.* Critical $r = .279$, alpha $= .05$, $df = 34$. Values that share a common subscript do not differ significantly.

Table 7
*Frequency of Exploratory Procedures and Two-Handed Exploration by Instruction and Sort: Experiment 2*

| | Group | | | |
|---|---|---|---|---|
| Procedure | HVI | HH | H | HV |
| Two-Bin | | | | |
| Lateral motion | 6.0 | 5.4 | 9.6 | 3.2 |
| Pressure | 6.0 | 16.2 | 9.6 | 0.8 |
| Enclosure | 4.4 | 1.2 | 0.2 | 0.0 |
| Contour following | 3.4 | 1.4 | 0.0 | 0.0 |
| Two Hands | 10.0 | 9.6 | 5.8 | 0.2 |
| Three-Bin | | | | |
| Lateral motion | 6.6 | 10.4 | 12.2 | 4.8 |
| Pressure | 4.2 | 5.2 | 7.2 | 0.8 |
| Enclosure | 4.0 | 3.8 | 0.2 | 0.0 |
| Contour following | 8.4 | 6.2 | 0.4 | 0.0 |
| Two Hands | 12.8 | 14.4 | 6.0 | 0.0 |
| Four-Bin | | | | |
| Lateral motion | 10.2 | 15.2 | 10.4 | 4.2 |
| Pressure | 8.2 | 15.6 | 5.8 | 1.2 |
| Enclosure | 6.2 | 3.0 | 4.0 | 0.0 |
| Contour following | 5.8 | 2.6 | 7.2 | 0.0 |
| Two Hands | 11.8 | 13.8 | 12.6 | 0.0 |

*Note.* Initial enclosures were not counted. HVI = haptics plus visual imagery; HH = haptically biased haptics; H = unbiased haptics; HV = haptics plus vision.

21.2, and an interaction, *F*(9, 228) = 5.0. Overall, the ratings increased from size (2.1), to hardness (2.7), to texture (3.5), to shape (3.7). The interaction reflects the fact that haptics plus visual imagery rated shape most important (4.4), as did haptics plus vision (4.0); haptically biased haptics rated texture most important (4.1) and hardness only third (3.1); and unbiased haptics favored hardness (3.8) and then texture (3.6). All but the haptics plus vision group gave size the lowest rating; it rated hardness lowest (1.9).

*Videotape data.* Five subjects in each group were videotaped during sorting, and from these tapes, 17 objects per subject (the 1st, 8th, and every 4th thereafter) were examined in each of the three sorts. The analysis was as in Experiment 1, except that because the object was initially placed in the hands, enclosure was not scored unless it recurred within a trial, following some intervening activity. The data are shown in Table 7, which indicates the frequency of each procedure and of two-handed exploration for each group, summed over 17 objects, by sort and instruction.

Reliability of scoring was assessed by having Roberta Klatzky score seven objects for each of 16 subjects (constituting over 10% of the scored objects). Samples were drawn equally over instructions and the different sort conditions; scoring was performed without knowledge of the conditions. Agreement was measured as twice the total number of procedures scored by both scorers in common divided by total number of procedures scored by either. If no procedure occurred other than initial enclosure, a single "null" procedure was tallied. The resulting reliability was 90%. In general, the exploratory procedures were quite clear and discriminable. Where confusion occurred, it tended to be because a hybrid procedure was performed (especially lateral motion and pressure), or because a procedure was executed with minimal external signals (most prevalent in the visual group, where exploration was rapid and minimal).

An overall analysis on the procedure data revealed effects of instruction, *F*(3, 16) = 12.3, sort, *F*(2, 32) = 8.3, procedure, *F*(3, 48) = 10.3, sort by procedure, *F*(6, 96) = 2.4, and instruction by sort by procedure, *F*(18, 96) = 1.8. There were significantly fewer procedures executed by the haptics plus vision group than by the others. The four-bin sort—where secondary dimensions were assumed to emerge—yielded more procedures than the others. And lateral motion and pressure were used more than enclosure and contour following (note, however, that this discounts the initial enclosure).

Supplementary analyses revealed that for contour following, there were effects of instruction, *F*(3, 16) = 6.2, sort, *F*(2, 32) = 4.3, and an interaction, *F*(6, 32) = 3.1. The contour-following procedure was used more under haptics plus visual imagery than haptics plus vision, and was used least in the two-bin sort, where only a crude discrimination between oval and lobed shapes was made. For enclosure, there was a main effect of instruction, *F*(3, 16) = 8.6, with the haptics plus visual imagery group using it more than the unbiased haptics and haptics plus vision groups. For lateral motion, no effects were significant (and texture salience had not differed substantially over instruction). For pressure, there were effects of instruction, *F*(3, 16) = 3.3, and sort, *F*(2, 32) = 3.6. There was more use of pressure under haptically biased haptics than haptics plus vision; no comparisons between sorts reached significance. The frequency of each exploratory procedure for the three-bin sort is shown by instruction in Figure 1, together with the salience of the dimension with which the procedure is closely linked.

The analysis of the number of objects explored with two hands, with variable sort and instruction, showed a significant effect of instruction, *F*(3, 16) = 7.9, and of sort, *F*(2, 32) = 3.7. There was significantly less two-handed exploration (and activity in general) by the haptics plus vision group. There was no evidence that the haptics plus visual imagery group was particularly prone to use two hands, as one might expect if this were needed to encode shape information, which that group found most salient. In fact, the greatest use of two hands was by the group instructed to consider how the objects felt (haptically biased haptics). The sort effect reflects more use of two hands on four-bin sorting than two-bin, which is consistent with the assumption that more refined discrimination is necessary in the four-bin case.

## *Discussion*

The present results reveal substantial differences in the salience of object attributes under haptic exploration with and without vision. Furthermore, they indicate that attribute salience can be manipulated within the haptic system. In general, the data confirmed the prediction that when participants judged similarity by haptics alone, they would tend to base their responses on the material substance of which the objects were composed. Hardness was very salient to haptic explorers under unbiased or haptically biased instructions. All groups used texture at least to some extent, but there was somewhat less use in the groups with vision and visual imagery. When participants used both haptics and vision, all object attributes were used to judge similarity, although shape was emphasized the most. This was the only group that demonstrated much use of the size dimension (and then not in the three-bin sort shown in Figure 1). Finally, when participants were denied sight but told to form a visual image of the judged object, they heavily favored shape cues, virtually excluding all other dimensions from consideration.

There appears to be a close correspondence between the salience of object dimensions and the occurrence of related exploratory procedures. As can be seen in Figure 1, the ordering of salience values over groups is generally mimicked by the ordering of the use of the relevant procedure. Thus, when haptic explorers were biased toward using visual imagery, the procedures relevant to contour extraction (i.e., contour following and enclosure) were used most frequently. (Enclosure might also be evaluated in relation to size, but the salience values constitute a floor effect.) The haptically biased and unbiased groups most frequently used pressure, the procedure associated with hardness. Although the effects did not reach significance, Figure 1 shows trends toward greater salience of texture among the unbiased and haptically biased groups, along with greater use of lateral motion by these groups. Furthermore, patterns of hand movement were sensitive to the precision of discrimination required. The use of specialized procedures and two-handed exploration tended to be less in the two-bin sort, where only crude discriminations were necessary, and more in the four-bin, where secondarily salient dimensions had to be assessed. However, these trends were eliminated when vision was permitted. With vision, exploration was brief and tended to be primarily manipulatory; that is, the objects were simply grasped with one hand and placed into a bin.

## Experiment 2B: One- Versus Two-Handed Object Exploration

Experiment 2A was equivocal about whether two-handed activity was used to encode shape in the free-sort task (compare the results of the directed-sort task of Experiment 1). There was substantially greater two-handed exploration with imagery instructions than in the unbiased haptic condition, and correspondingly, there was much greater salience for shape in the former condition. But there was also frequent use of two hands in the haptically biased condition, without a concomitant high salience for shape. This second effect may be misleading, because the instructions to consider how objects felt may have generally increased exploratory activity.

Accordingly, a supplementary study was performed to investigate further the relation between two-handed haptic exploration and shape salience. Subjects were directed to keep one or two hands on the objects. There were 10 subjects in each of four groups, representing the crossing of the hand factor (one vs. two hands) with sorting instruction (unbiased haptics and haptics plus visual imagery, both as in Experiment 2A). The question of interest was whether shape would be more salient under two-handed exploration.

The main finding from this additional study was that the instruction to use two hands increased the salience of the shape dimension, but only for haptics plus visual imagery, not unbiased haptics. The mean salience scores for the two-bin sort for shape were 7.6, 4.4, 14.5, and 28.8 for the conditions: unbiased touch, one hand; unbiased touch, two hands; visual imagery, one hand; visual imagery, two hands, respectively. The difference between hand conditions for the haptics plus visual imagery group was significant, $t(18) = 1.9$. For the three-bin sort, effects were similar but reached ceiling. The corresponding means were 33.1, 32.1, 43.4, and 54 (the maximum possible).

## Experiment 3: Salience of Attributes When Size Is Biased

In Experiment 2A, there was little evidence for the use of size as a basis for comparing objects, except by visually guided subjects. This result, together with our introductory observations and the results of Experiment 1, suggest that the haptic system is not well developed to differentiate size within the limited range of hand-size objects. Given such a general restriction on ease of encoding, we may fail to find size a salient dimension even when its values are very discriminable.

Experiment 3 tested this hypothesis by using the free-sorting task from Experiment 2A; this time, however, we deliberately increased the discriminability of size by including only the two extreme values—previously shown to be highly discriminable in Experiment 1. If its discriminability over a particular set of objects dictates whether size is used as a basis for assessing similarity, we should now find it is used extensively. The increased salience of size should be particularly evident in the two-bin sort, which lends itself to discrimination along a two-level dimension.

Experiment 3 also determined whether there were sequential dependencies among the various instructions for sorting. For example, seeing the objects prior to haptic sorting with visual imagery might change the imaged properties so that visible dimensions other than shape (particularly texture) would be included. Similarly, visual imagery prior to unbiased haptic sorting might leave a residual effect, so that shape would be used more. A within-subjects design was used to determine such dependencies; all subjects sorted under three of the instructions used in Experiment 2A (the haptic bias instructions were excluded).

### Method

*Subjects.* The subjects were 48 students in introductory psychology who participated as a course requirement. They were assigned equally to six different groups, who received the three sets of instructions in all possible orders.

*Procedure.* The stimuli and sorting instructions were identical to those of Experiment 2, with the following exceptions: (a) Only 54 stimuli were used; the 27 mid-size objects were excluded. (b) The haptic bias instructions from Experiment 2 were eliminated. Thus, there were unbiased haptics, haptics plus visual imagery, and haptics plus vision conditions. (c) Each subject sorted under three instructions, completing all sorts (two, three, and four bins) before moving to the next instruction. Subjects were told to treat each instruction as if they were just beginning the experiment; that is, they should not take their previous sorting behavior into account (nor should they try to avoid doing so).

### Results

*Adjustment of scoring.* The data were converted to salience scores as in Experiment 2. However, the highest possible score was 54 for size and only 36 for the other dimensions, because one third of the objects at each level had been excluded by discarding the mid-size objects. Thus, to allow comparisons, the

Table 8
*Normalized Salience Scores for 1/3 Cutpoint on the Shape Dimension for the Haptics plus Visual Imagery Group: Experiment 3*

| | Order | | | |
|---|---|---|---|---|
| Sort | First | After haptics plus vision | After haptics | Third |
| Two Bin | 0.69 | 0.01 | 0.52 | 0.50 |
| Three Bin | 0.94 | 0.49 | 0.76 | 0.94 |
| Four Bin | 0.60 | 0.46 | 0.56 | 0.71 |

scores were normalized by dividing each one by the maximum possible value; the resulting values were all then between zero and one.

*Sequential effects.* Each instruction was presented in three orders: first, second after one alternative, second after the other alternative, and third. This constitutes an order variable that was used in analyses. The normalized scores from the 1/3 cutpoint were the only ones to allow examination of all four dimensions (there was no Level 2 for size). Analyses of variance were performed on these scores within each instruction, with dimension and instruction order as variables. Thus, for example, for the analysis within haptics plus visual imagery, the order variable included: that instruction first, second after unbiased haptics, second after haptics plus vision, and third. These analyses aggregated the data over number of bins sorted, because preliminary examination showed the trends were similar.

The only significant effect of instruction order was with the haptics plus visual imagery instruction. This was revealed by a dimension by order interaction, $F(9, 132) = 2.7$. When imagers sorted immediately subsequent to using vision, the salience of shape decreased significantly. Table 8 shows the 1/3 cutpoint salience scores for shape under this instruction, by order and number of bins sorted. The shift away from shape-based sorting was distributed to all other dimensions, especially size (from .18 in the imagery-first condition to .41 when imagery followed haptics plus vision) and texture (from .11 to .26); hardness also gained slightly (.11 to .15). Given the diffusion of the effect, none of these increases reached significance.

*Comparison with Experiment 2A.* For reasons explained in Experiment 2A, data from each dimension and sort were examined separately. The analysis included instruction and cutpoint (for size, only instruction because there was just one cutpoint), but as cutpoint effects were generally redundant with Experiment 2A, only the instruction effects will be noted. Given the minimal effects of instruction order except on the shape dimension, the data were pooled over order for all but shape, which used data from the first-instruction conditions only. Table 9 shows the mean scores for this analysis.

For texture, there were no significant effects, although the haptics plus visual imagery group had the lowest score for each sort. There was also no effect in the size analyses. For hardness, there were effects of instruction for the two- and four-bin sorts, where unbiased haptics was greater than haptics plus visual imagery, and the three-bin effect was marginal ($p < .075$), $Fs(2, 141) = 3.4, 3.2$, and 2.8, respectively. For the shape dimension, there was an effect of instruction in the two- and three-bin sorts, $Fs(2, 45) = 5.0$ and 5.2, with haptics plus visual imagery showing the highest scores.

## Discussion

The main finding from this study was a general replication of Experiment 2A with respect to the relative importance of object dimensions under various instructions, despite biasing the stimulus set in favor of size. Haptics plus visual imagery instructions overwhelmingly led to using shape as the basis for similarity judgments. Unbiased haptics instructions induced the greatest use of hardness. And under haptics plus vision instructions, subjects used more of a mixture of dimensions.

The use of just two highly discriminable size values did not markedly change the results, as has been noted. In particular, size did not dominate similarity judgments, even when subjects sorted into two bins. However, some more subtle changes appeared to result from this manipulation. First, size was more salient than before, virtually equally for all groups. Second, the increased salience of size appears to have been more at the expense of the material-substance dimensions than of shape. The salience scores for shape were higher in this study than before, particularly so for the unbiased haptics group.

These results suggest that high discriminability of size values in a particular set of objects is not sufficient to make the dimension a salient one. Any context-specific discriminability of size may be overriden by a more general tendency to discount size differences within the range of hand-size objects, as was suggested earlier.

Why should the salience of substance dimension decrease in this study, relative to Experiment 2? Although hand movements were not recorded, the previous analysis of exploratory procedures suggests that substance dimensions may have been less salient because haptic explorers used fewer procedures specialized for these attributes. Specifically, subjects may have made more use of the enclosure procedure at the beginning of the trial, prompted either by greater awareness of size (which this procedure would be sufficient to ascertain) or because the extreme difference in sizes changed the way they made initial contact with the objects. In either case, the enclosure procedure would provide information about contour, more than texture or hardness. If exploration ceased there, these substance dimensions might not be extracted, and hence could not be salient.

Also worthy of note are the effects of prior visual experience on visual imagery during haptic encoding. Without having seen the objects, subjects given visual imagery instructions used shape to judge similarity, virtually excluding any other dimension. However, actual visual experience caused them to consider other, visually salient dimensions: texture and size.

# General Discussion

These experiments support our initial contentions that the haptic system maintains its own specialized pathways for encoding objects and that ease of encoding is a strong influence on the salience of object attributes. Performance of constrained discrimination and free-sorting tasks indicates that the availability and salience of object properties differ under haptic exploration with and without vision. Equally important, the rep-

Table 9
*Normalized Salience Scores by Sort, Cutpoint, Dimension, and Instruction: Experiment 3*

| | Texture[a] | | | Hardness[a] | | | Shape[b] | | | Size[a] |
|---|---|---|---|---|---|---|---|---|---|---|
| Sort | 1/2 | 2/3 | 1/3 | 1/2 | 2/3 | 1/3 | 1/2 | 2/3 | 1/3 | 1/3 |
| Two Bin | | | | | | | | | | |
| H | 0.08 | 0.13 | 0.17 | 0.02 | 0.29 | 0.29 | 0.07 | 0.19 | 0.25 | 0.27 |
| HVI | 0.07 | 0.05 | 0.07 | 0.02 | 0.08 | 0.10 | 0.54 | 0.16 | 0.69 | 0.32 |
| HV | 0.09 | 0.11 | 0.11 | 0.05 | 0.14 | 0.19 | 0.19 | 0.07 | 0.26 | 0.36 |
| Three Bin | | | | | | | | | | |
| H | 0.30 | 0.30 | 0.29 | 0.09 | 0.11 | 0.11 | 0.63 | 0.60 | 0.63 | 0.03 |
| HVI | 0.13 | 0.13 | 0.13 | 0.00 | 0.00 | 0.01 | 0.93 | 0.94 | 0.94 | 0.04 |
| HV | 0.28 | 0.27 | 0.27 | 0.04 | 0.05 | 0.05 | 0.47 | 0.44 | 0.47 | 0.04 |
| Four Bin | | | | | | | | | | |
| H | 0.39 | 0.32 | 0.39 | 0.13 | 0.30 | 0.34 | 0.48 | 0.44 | 0.42 | 0.39 |
| HVI | 0.26 | 0.20 | 0.26 | 0.04 | 0.15 | 0.16 | 0.63 | 0.62 | 0.60 | 0.44 |
| HV | 0.28 | 0.27 | 0.32 | 0.08 | 0.21 | 0.24 | 0.40 | 0.35 | 0.43 | 0.42 |

*Note.* H = unbiased haptics; HVI = haptics plus visual imagery; HV = haptics plus vision.
[a] Averaged over all orders. [b] First instruction only.

resentation of an object that is naturally encoded by haptics alone appears to be substantially different from a visual image. In fact, haptically biased and unbiased haptic conditions were highly similar, indicating that haptic encoding has an inherent bias toward the way objects feel, and not toward how they might look.

These results also support the more specific hypothesis that substance information would be relatively important under purely haptic exploration, whereas structure would be more significant when vision was also allowed. Under haptic exploration without vision or imagery bias, the dimensions of hardness and texture were found to be encoded readily and particularly salient. In contrast, when both vision and haptics were available, shape—and to some extent, size—became more easily encoded and more salient (although size was not used extensively under any condition, especially the three-bin sort shown in Figure 1). Visual imagery instructions led to an overwhelming emphasis on shape, to the exclusion of virtually every other property of the objects explored.

Contour information proved to be particularly important when subjects were asked to image objects they had not previously examined visually; only when visual exposure immediately preceded visual imagery did the salience of texture and size increase. This is not surprising, in that inclusion of contour in visual imagery is certainly paramount. Although there is evidence that relative size is maintained in imagery (e.g., Kosslyn, 1975), there are also limitations which preclude full imaging of large objects or detailed imaging of small ones (Finke & Kurtzman, 1981). Presumably, texture can be included in visual images. But there is no compelling reason to do so unless it is an important attribute (e.g., of a corduroy shirt); moreover, it would probably require considerable processing capacity to imagine texture over the entire surface of an object, if it were possible at all. Whatever the general relevance of texture and size in images, haptic exploration alone seems insufficient to motivate their inclusion in images of the present objects. It is hardly surprising, then, that hardness is also excluded, despite its being an important property for haptics.

The present experiments verify and extend previous findings linking haptically encoded attributes to the execution of particular exploratory hand movements. Klatzky and Lederman's previous demonstrations of such connections used a match-to-sample task in which some specific dimension was designated for matching. Similarly, Experiment 1 designated an object attribute for discrimination and confirmed the exploration–attribute connection. Experiment 2A advanced beyond such constrained tasks to free exploration, where no particular object dimension was targeted by the experimenter. As in the previous studies, the exploratory procedures of lateral motion, contour following, and pressure were found to be closely associated with the object dimensions of texture, shape, and hardness, respectively. In contrast, enclosure appears to be a more general-purpose activity in both the current and previous studies: It is used motorically to manipulate and balance objects (Klatzky, McCloskey, Doherty, Pellegrino, & Smith, 1987) as well as to obtain sensory information concerning shape (and presumably size, to the extent it was encoded here).

We initially considered whether the salience of some object attribute under haptic exploration would be dictated by perceptual discriminability within a particular set of stimuli, by ease of encoding, or by exploratory goals. The results of the current experiments lead us to conclude that stimulus-specific discriminability, in particular, is not an important determinant of dimensional salience (although it could certainly limit salience when very low). This can be seen from the substantial variation in salience scores under different instructions, while discriminability is high for all dimensions (Experiments 2A and 3). The unimportance of this factor is further indicated by the finding that size remained low in salience even when its discriminability was increased so as to virtually eliminate error (Experiment 3).

By ease of encoding, we mean the readiness with which dimensional values can generally be differentiated by a perceptual system. The speed and accuracy of directed discrimination in Experiment 1, together with the analysis of associated hand movements, provide indications of differential ease of encoding for haptics with and without vision. From Experiments 2A and 3 on free sorting, the salience of an object dimension appears to be strongly influenced by this factor, along with exploratory goals.

Consider in particular the shape dimension. Contour following is necessary to acquire exact shape haptically. However, it is a procedure that is relatively slow and complex (usually performed with two hands). Not surprisingly, then, haptic explorers (without imagery bias) tended to perform other procedures more than contour following, and the salience of shape was also relatively low. This procedure was used more extensively when instructions biased the extraction of shape information (haptics plus visual imagery condition). But even then, contour following occurred primarily when fine distinctions were necessary (three- and four-bin sorting); for less precise distinctions, enclosure would (and apparently did) suffice. In contrast, subjects with visual information did not need to use contour following to extract shape, nor did they do so; its salience thus could be and was relatively high.

Consider also the encoding of hardness. The directed-discrimination data indicate that this dimension is relatively slowly encoded by joint haptic and visual exploration. It is relatively available haptically, but visual explorers tended to perform minimal manual exploration, relying instead on visual cues. Accordingly, hardness was also low in salience under this condition. It was also rated as less important than the others in the free-sorting task with vision, and it had the least carryover from vision to visual imagery.

These patterns suggest that encoding procedures not only facilitate acquisition of object properties but also control which ones are apprehended. More specifically, haptic exploratory procedures can be said to control object processing in two ways: top down and bottom up. Top-down control occurs when instructions direct explorers to learn about a particular object dimension. As our work demonstrates (Lederman & Klatzky, 1987; the present Experiment 1), this elicits the particular exploratory movements that are necessary or optimal to extract the desired information. Top-down direction can specifically name a dimension or it can be more general. For example, instructions to use visual imagery apparently motivated subjects to encode precise contour, leading to more use of the contour following procedure.

In contrast, exploratory movements act bottom up when they induce explorers to encode particular object attributes. For example, when subjects were directed to use two hands rather than one, the salience of shape increased (for subjects who were already biased toward encoding shape). Directing exploration apparently affected the object representation. And instructing subjects to think about what objects "feel like" produced more exploratory activity and hence, the data suggest, made texture and shape more salient. But bottom-up control need not be explicitly directed; it may result because of the characteristics of the procedures themselves. That is, procedures may be executed because of their ease of execution and accuracy of discrimination.

We suggest that the salience of object dimensions under haptic exploration, with and without vision, reflects such bottom-up control. Haptic explorers, quite reasonably, appear to execute hand movements that are "economical," in that they produce the highest return for the least cost. This in turn influences which object dimensions are found salient. When visual input is excluded, texture and hardness are such dimensions. They are acquired by exploratory procedures that are relatively fast and accurate. Shape is not such a dimension, however. Information about this attribute can be acquired by the procedure of enclosure, which is fast to execute but produces only crude information (not only about shape, but presumably about size within the range of the hand). The alternative to enclosure, contour following, is slow to execute, imposes memory problems, and still has substantial limitations in accuracy. Ultimately, then, in the absence of biasing instructions, haptics may "highlight" those dimensions that it achieves with maximum efficiency and validity, producing an emphasis on substance over structure.

From this perspective, in some cases where vision appears to dominate touch, it may reflect not so much a competition between perceptual modalities as a control issue (cf. Posner, Nissen, & Klein, 1976). In the perceptual literature on visual dominance, subjects are usually specifically instructed to encode information haptically; in such cases, it is not surprising that the data indicate that both modalities are encoded (with different weightings). But with less directed encoding, as in the present studies, the availability of vision may substantially reduce hand movements and thus severely decrease the data available to the haptic modality. The result would be to make object salience primarily dependent upon vision. Such interactions between the haptic and visual systems merit exploration in future research.

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