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Haptic Integration of Object Properties: Texture, Hardness, and Planar Contour

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Planar objects varying in shape, texture, and hardness were classified under haptic exploration. Classes were defined by values on one dimension, or redundantly, by two or three dimensions. Response times and exploratory procedures (Lederman & Klatzky, 1987) were recorded. Experiment 1 showed that a second dimension speeded responses for all combinations (redundancy gain), but a third dimension produced no further effect. In Experiments 2 and 3, classification trials began with two redundant dimensions, and subsequently one was withdrawn (held constant). When texture and hardness varied redundantly, withdrawal of either increased response time—even when subjects were initially instructed to focus on one dimension. Joint exploration for texture and hardness dominated whenever the two varied redundantly and persisted despite withdrawal. Redundancy gains (Experiment 1), but not substantial withdrawal effects (Experiments 2 and 3), were observed for combinations of texture or hardness with planar contour, indicating less integration than between substance dimensions. Compatibility of exploratory procedures appears to constrain dimensional integration.

There has been substantial interest in the integration of information over multiple stimulus dimensions, but largely this work has concentrated on visual displays. Our own recent research (Lederman & Klatzky, 1987) has described a number of stimulus dimensions that can be extracted haptically, by purposive touch. This raises the question of whether information integration occurs in haptics. The present article reports a series of studies investigating three questions: Does integration of distinct stimulus attributes occur under haptic encoding? Does such integration vary with the particular dimensions being encoded? What is the extent of such integration in terms of relative weighting of dimensions and flexibility of processing?

Haptics builds on a basic tactual system that incorporates information from cutaneous sensors in the skin and kinesthetic sensors in muscles, tendons, and joints. Its sensory primitives, therefore, include pressure, vibration, local position (skin, limb), and thermal properties. We have argued, however, that the functional sensitivities of haptics are considerably enhanced by motor capabilities, so that the system can quite directly extract properties pertaining to an object's substance (e.g., texture, hardness) and structure (planar and three-dimensional shape and size).

More specifically, we have proposed that the haptic perceptual system makes use of stereotyped motor patterns, which we call *exploratory procedures.* (A description and supporting research can be found in Lederman & Klatzky, 1987; a broader theoretical context for the procedures is in Klatzky & Lederman, 1987.) An exploratory procedure is a motor activity that is typically used for extracting a particular object property. In previous work, we have described the links between desired knowledge about object properties and specific exploratory procedures. We have also shown that the procedure that is typically performed to extract a property is generally the optimal one, in terms of accuracy and/or speed.

The procedures we have studied are *lateral motion* (a rubbing action) for encoding texture; *pressure* for encoding hardness; *static contact* for thermal sensing; *unsupported holding* for weight; *enclosure* for volume and gross contour information; and *contour following* for precise contour information as well as global shape. We have also considered procedures for encoding higher level object properties, such as functional uses based on structure, and the nature of part motion.

The existence of distinct motor patterns for encoding different object dimensions in haptics might be thought to indicate that the dimensions are treated separately, at least during early stages of haptic processing. Yet the subjective impression of a haptically explored object is that its attributes form a coherent whole. This makes the issue of information integration in haptics a particularly intriguing one.

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There are various approaches to the concept of information integration. On the one hand, it can be viewed as involving perceptual fusion at early stages of processing. Alternatively, integration might occur when discretely processed sources of information are pooled to arrive at a terminal decision. If multiple sources of information are not integrated, it may be because only one source was encoded or because they were all sampled but treated independently in processing. Such distinctions have been discussed by Ashby and Townsend (1986) and by Garner (1974). Our present concern is in demonstrating the existence of haptic integration and evaluating its extent for various dimensional combinations, rather than determining its precise processing locus. Aspects of the data do speak to processing distinctions, however, as will be discussed below.

Work on human haptics provides a unique means of addressing issues of information integration, because of the observability of distinct classes of exploratory hand movements (Lederman & Klatzky, 1987). Because haptic exploratory procedures are optimal for extracting particular dimensions, they can be used as a "window" to assess whether subjects are targeting specific stimulus attributes for encoding. Response-time data, in addition, can be used to provide indications of the costs and benefits of dimensional coprocessing.

There are several a priori reasons to propose that dimensional integration does occur in haptics. First, although exploratory procedures tend to be optimal for particular dimensions, most are broadly sufficient on several dimensions. Thus execution of one procedure may allow encoding and integration of multiple attributes. For example, a simple grasp (i.e., enclosure, potentially with pressure) allows for at least coarse information about all the attributes studied by Klatzky and Lederman. Another reason is the possibility that exploration could be adapted specifically for simultaneous extraction of multiple attributes. The limits on such "hybrid" exploratory procedures would be placed by the compatibility of their motor components and by the extent to which different tactual receptors reside in common surfaces of the hand. Finally, our previous work has established that the haptic system has capabilities for rapid and accurate object recognition, and we have suggested that information from multiple dimensions converges to determine the object category, at least at a decision level (Klatzky, Lederman, & Metzger, 1985).

We predicted that integration would occur in haptics, the extent of integration depending on the dimensions being processed. We propose certain general principles that would tend to influence haptic integration. One is motoric compatibility; dimensions extracted by procedures that can be executed simultaneously would tend to be integrated more than dimensions with motorically incompatible exploratory patterns. For example, it is difficult both to enclose an object (for global shape, size) and to rub it (for texture) at the same time. On the other hand, rubbing and pressing (for texture and hardness) are capable of being executed in one motion.

Another principle that might determine integration is compatibility in terms of explored regions on an object. Consider planar objects, that is, those having variation in two dimensions and relatively narrow sides of constant thickness. For such objects, information about the contour of the object "envelope" can be obtained only by exploration at the edges of the plane, through contour following or possibly enclosure (for gross shape). In contrast, information about substance properties such as apparent temperature, texture, and hardness can be extracted more locally. Integration may be promoted for dimensions that can be extracted without selective exploration in a particular region; this would favor combinations within the substance category. Conversely, to the extent that the edge limits the availability of substance information, integration of substance with contour may be reduced.

There are other principles potentially governing integration as well. Consider that some exploratory incompatibilities may be related to the encoded attributes rather than being motoric in nature. In particular, pressing on a contour to determine hardness may deform its shape. Another influence on integration may be natural covariation in object properties. In work in progress we have gathered ratings of the importance of dimensions for categorizing common objects by touch. Texture and hardness ratings strongly covary, and those for shape and size do so even more. Positive relations for pairs comprising a substance and a structure dimension are evident, but consistently lower. This suggests natural tendencies to treat certain dimensions together.

This study focused in particular on integration of the dimensions of texture, hardness, and contour within homogenous planar objects. We chose to use these stimuli as a first step in addressing issues of integration, both because of past work on their properties and because they clearly involve issues of regional compatibility, as described above. For such stimuli, we predicted that texture and hardness would tend to be integrated more than either would be combined with contour information.

This prediction follows from the principles described above, as well as from previous work. Procedures for extracting texture and hardness are motorically compatible and do not disturb one another's effects, as might the combination of hardness- and shape-extracting procedures. The texture or hardness of a surface is typically encoded haptically through restricted local exploration by use of lateral motion and pressure procedures, rather than edge following. In addition, our previous work (Klatzky, Lederman, & Reed, 1987) with multiattribute planar objects demonstrated that texture and hardness information were both highly salient to haptic explorers. Two-dimensional shape variations were less so, and planar size was particularly low in salience. These salience effects suggest that the shape and substance dimensions of objects were differentially weighted, if not actually segregated.

In the present research, integration of haptic dimensions was assessed with a paradigm based on work of Garner and associates (summarized in Garner, 1974). The basic task is one in which stimuli are to be assigned to distinct categories on the basis of some dimensional value(s). One common indication that two dimensions are processed together is facilitation of performance when their values are correlated in defining the category (redundancy gain). For example, if colored chips are to be classified as *A* or *B*, performance is faster when each category represents a particular value and chroma than when only one of these dimensions is relevant to classification (Garner & Felfoldy, 1970). A second indication of nonindependence is interference due to orthogonal variation: When two dimensions vary simultaneously in such a way that values on one dimension do not predict values on the other, discrimination and classification should be slowed. Dimensions that show no redundancy gain or interference from orthogonal variations have been called *separable.* Those dimensions that show effects of redundant and orthogonal variation (along with other converging indications) are said to be *integral.*

The use of this paradigm in the present context has several attractive features. One is that exploratory hand movements can be analyzed under conditions of redundant and orthogonal variation to investigate what information enters into classification. The introduction of redundant information allows us to consider the extent of focus on the various redundant dimensions. Conversely, orthogonality allows us to determine whether dimensions of stimulus variation that are irrelevant to classification are purposively extracted or, in contrast, avoided. Other valuable aspects of the task are that redundancy invites encoding of multiple dimensions and that response times provide a means of assessing the extent of the resulting integration.

There has been some previous work using the redundancy/orthogonality approach in haptics, but with raised two-dimensional patterns rather than free-standing objects. This work provides some evidence for integration. Taylor (1977) found the predicted pattern for intensity and frequency (loudness and pitch) of a simple vibrotactile stimulus. Millar (1986) found effects of both orthogonal and redundant variations in shape and texture, using Braille-like displays. Shape was defined by entries in a matrix of dots (3 × 3 square vs. 3 × 5 rectangle), and texture was defined by dot size.

In the present experiments, both response-time and exploration data were collected as participants classified haptically explored objects. The classes varied in the number of redundant dimensions, although subjects were never told about the dimensional composition. Experiment 1 was intended to determine whether any integration among the dimensions of texture, shape, and hardness would occur in haptics, and if so, what combinations would be integrated. The extent to which redundant dimensions were all purposively sampled was assessed through analysis of hand movements. If a dimension was not redundant, it varied orthogonally to the decision. Avoidance or incorporation of orthogonally varying dimensions could thus be similarly assessed. The simultaneous manipulation of redundancy and orthogonality also maximized the potential for observing integration effects on response time.

Experiment 2 assessed the weighting of redundant dimensions with a *dimension withdrawal* paradigm: After a series of classification trials involving objects with two redundant dimensions, a new set of objects that could be classified only on one of the dimensions was introduced. Subjects were given the opportunity to explore the new set and to infer a new rule. If they chose to process both dimensions during the prewithdrawal phase, there should be an increase in response time regardless of which dimension was withdrawn. However, focus on one dimension prior to withdrawal would lead to an asymmetric withdrawal effect; performance would be slowed only when the focal dimension was withdrawn.

Experiment 3 provided an even stronger test of integration. It investigated whether subjects would process two redundant dimensions even when specifically instructed, during the prewithdrawal phase, to focus on a particular one. (No such instruction occurred in Experiments 1 and 2.) Without informing the subject or breaking the trial sequence, the second, redundant dimension—about which the subject had not been informed—was withdrawn. (This contrasts with Experiment 2, where subjects were informed of a stimulus change.) If subjects were using only the instructed dimension prior to withdrawal, the withdrawal manipulation should have no effect. But if the implicitly redundant dimension had been used, response time should increase at the point of withdrawal. Exploratory data were used as converging evidence of the degree to which the implicit dimension was processed, both before and after withdrawal.

Experiment 1

The first experiment was intended to demonstrate that the dimensional composition of classes would affect haptic classification time and exploration. We asked subjects to classify a set of multidimensional stimuli that varied on the dimensions of hardness, texture, and shape. They were told about neither the dimensions of variation nor the classification rule, which had to be inferred from exposure to the stimuli. (Size also varied, but orthogonally to the classes. We excluded this dimension because it was minimally salient in previous work—Klatzky et al., 1987.) Seven groups of subjects took part, representing different degrees of redundancy—either one dimension, two, or all three provided cues to the class of the stimulus. When a dimension was not redundant, it varied orthogonally to the decision. Our interest was in whether additional redundant and fewer orthogonal dimensions would speed classification, which would constitute evidence for integration. We further used exploration data to investigate which dimensions were explicitly sampled.

Method

Subjects. Participants in this and all experiments were college students whose participation served as partial fulfillment of a course requirement or who were paid. There were 15 subjects in each of seven groups; assignment rotated over consecutive subjects.

Stimuli. A detailed description of these stimuli and the assessment of dimensional discriminability can be found in Klatzky et al., 1987. Each stimulus was a 1.27-cm thick wafer, of a particular planar shape and size, constructed of an internal material that determined hardness and covered with a black fabric that determined surface texture (roughness). A raised seam ran along the thin edge. Eighty-one individual objects resulted from factorially combining three values on each dimension (*hardness*: wood, polyfoam, soft foam rubber; *texture*: satin-poly fabric, thin-wale corduroy, metallic knit; *shape*: oval, hourglass, three-lobed; *size*: three sizes within the range of the hand—17.4, 32.9, and 52.9 cm^2 area of planar surface). The objects had been constructed so that the single dimensions were approximately equivalent when scaled psychophysically. They were also intended to be equally discriminable, and tests of sorting time along each dimension validated this goal (except for size, as mentioned above). (Scale values and sorting times are reported in Klatzky et al., 1987.)

Design and procedure. Subjects were assigned to seven groups. Each subject was exposed to only 9 of the 81 objects, 3 in each of three categories, called *A*, *B*, and *C*. In three of the groups, the classification decision was made on the basis of only one dimension (shape, hardness, or texture). Each level of this dimension defined a different class. For example, all round objects might be *A*, all hourglass shapes *B*, and all clover shapes *C*. In another three groups, either of two redundant dimensions was sufficient for classification (shape/hardness; shape/texture; hardness/texture). For example, the *A* class might be round hard objects, and so on. In a final group, the three dimensions were redundant indicators of the stimulus class. If a dimension was not redundant, it varied orthogonally to the response decision, so that all subjects experienced all three levels on each of the dimensions, including size. The assignment of dimensional levels to classes was counterbalanced across subjects.

Each subject was blindfolded. He or she was handed the nine objects in sets of three, with the experimenter indicating the class of each triad (*A*, *B*, or *C*) but not what dimension(s) was relevant to the partitioning. The subject was allowed to freely explore the full set of stimuli before proceeding. Next, the subject was required to correctly classify each object in turn. Speeded trials then began. There were 144 trials, in which an object was explored by touch and classified vocally as *A*, *B*, or *C*, as quickly as possible.

The speeded trials used a force-sensitive board with a piezoelectric sensor, interfaced to a computer. The board measured 33 × 60 cm, and the sensor was mounted beneath a cut-out disc of 5.2-cm radius. The disk did not move observably, but contact was sufficient to cause the sensor to emit a signal. An adjustable hardware filter was set to eliminate false signaling due to environmentally produced vibrations. On each trial, the experimenter placed one of the nine objects (selected at random by the computer) on the board and then readied the computer, which emitted a tone to signal that the object was in position. Upon the subject's first manual contact with the stimulus, a signal from the board started a clock, and when the subject vocalized the stimulus class, a signal from a collar microphone stopped the clock. The response times were recorded to millisecond accuracy. A videotape was placed behind the subject's right shoulder, recording the hand movements.

Results and Discussion

The dependent variables are response times from the 144 trials and hand movements, classified as exploratory procedures. Error trials were eliminated. (Errors ranged from 0% to 7% over subjects, with an average of 1.2%. An analysis of variance on the error data over groups indicated a main effect, $F(6, 98) = 6.83$, with the hardness-only group making more errors [3.0%] than the others.) Response times greater than 3 SDs above the subject's mean were eliminated, as were those where the subject obviously fumbled the stimulus. In addition, times less than 500 ms were dismissed from the analysis as due to ambient noise triggering the response key. Times below this were very infrequent (0.7%), and pretesting indicated it took about 300 ms just to pick up an object and immediately speak into the microphone.

In all analyses reported, alpha was set at .05. Also, a priori comparisons between paired conditions use an error term based only on those conditions and are two-tailed, unless specified otherwise.

Figure 1 shows the mean response times by group over blocks of 12 trials each. The figure shows an overall practice effect, but more important, there are effects of the classification structure. The groups with one relevant dimension are about equal, as we expected, given our construction of the dimensions to be about equally discriminable. One-dimension classification is slower than two, but three dimensions clearly does not produce a gain over two. Among the two-dimensions groups, there is an apparent tendency for texture/hardness to be fastest. (This did not reach significance in these data, but did in Experiments 2 and 3.)

An analysis of variance (ANOVA) was performed on group (7) and third of trials (Third 1 = Trials 1–48; Third 2 = 49–96; Third 3 = 97–144). Thirds were used because an initial comparison of the response times by blocks as in Figure 1 indicated asymptotic performance during the last third (all blocks statistically equivalent). (Also, an ANOVA on group and block shows the same effects as group and third.) This ANOVA

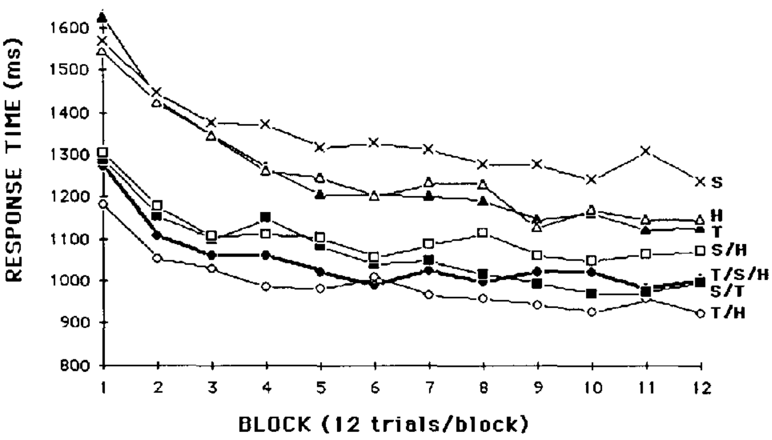

Figure 1. Mean response time (in milliseconds) in Experiment 1, by group and block of trials. (*T*, *H*, and *S* abbreviate texture, hardness, and shape, and abbreviations separated by slashes were redundant dimensions for the indicated group.)

revealed main effects of group, $F(6, 98) = 3.94$, and third, $F(2, 196) = 91.34$. The interaction was marginal, $F(12, 196) = 1.75$, $p < .06$, reflecting a slight tendency for the relative positions of the groups to change over thirds. The effect for third reflects a significant decrease in response time between each third. One-tailed tests were used to compare conditions with redundant dimensions to their fewer-dimensions-redundant counterparts (e.g., texture/hardness to texture only or hardness only). The two-dimensions groups were significantly faster than either of the component one-dimension groups, except that the shape/hardness group was not significantly faster than the hardness-only group (significance was reached in the first third alone, however). The three-dimensions group was not faster than any of the two-dimensions groups, although it was faster than each one-dimension group. Thus a third redundant dimension produced no further facilitation, even when it replaced an orthogonally varying one.

We turn now to the data on the hand movements of subjects in the various groups. These were examined for 7 subjects (randomly chosen) in each of the groups, for Trials 1–20, 65–80, and 129–144, thus sampling from each third. For each trial, the presence of lateral motion (linked to texture encoding), pressure (hardness), enclosure (gross shape), and contour following (exact shape) was recorded, and the proportion of trials where each exploratory procedure was observed at least once was determined (by the third author). Figure 2 shows these proportions. (Reliability of scoring was assessed by having the first author score 1 subject per redundant-dimension group; the percentage of total procedures agreed upon by the two scores was 91%. Because reliability had also been high in previous studies, it was not determined for subsequent experiments.)

An analysis of variance on group (7), third, and procedure (4) revealed main effects of procedure, $F(3,126) = 6.21$, and third, $F(2, 84) = 19.58$, and two-way interactions between procedure and third, $F(6, 252) = 2.28$, and procedure and group, $F(18, 126) = 11.19$. This complex of interactions reflects the facts that different procedures were used to explore the objects by the various groups, and there were changes over time. Essentially, each one-dimension group executed the appropriate procedure(s), and the two-dimensions groups executed procedures related to both relevant dimensions. However, the three-dimensions group followed the texture/hardness pattern.

The following description of trends indicates effects found significant within the various groups. The one-dimension groups concentrated almost exclusively on the relevant procedure, except that some enclosure accompanied pressure in

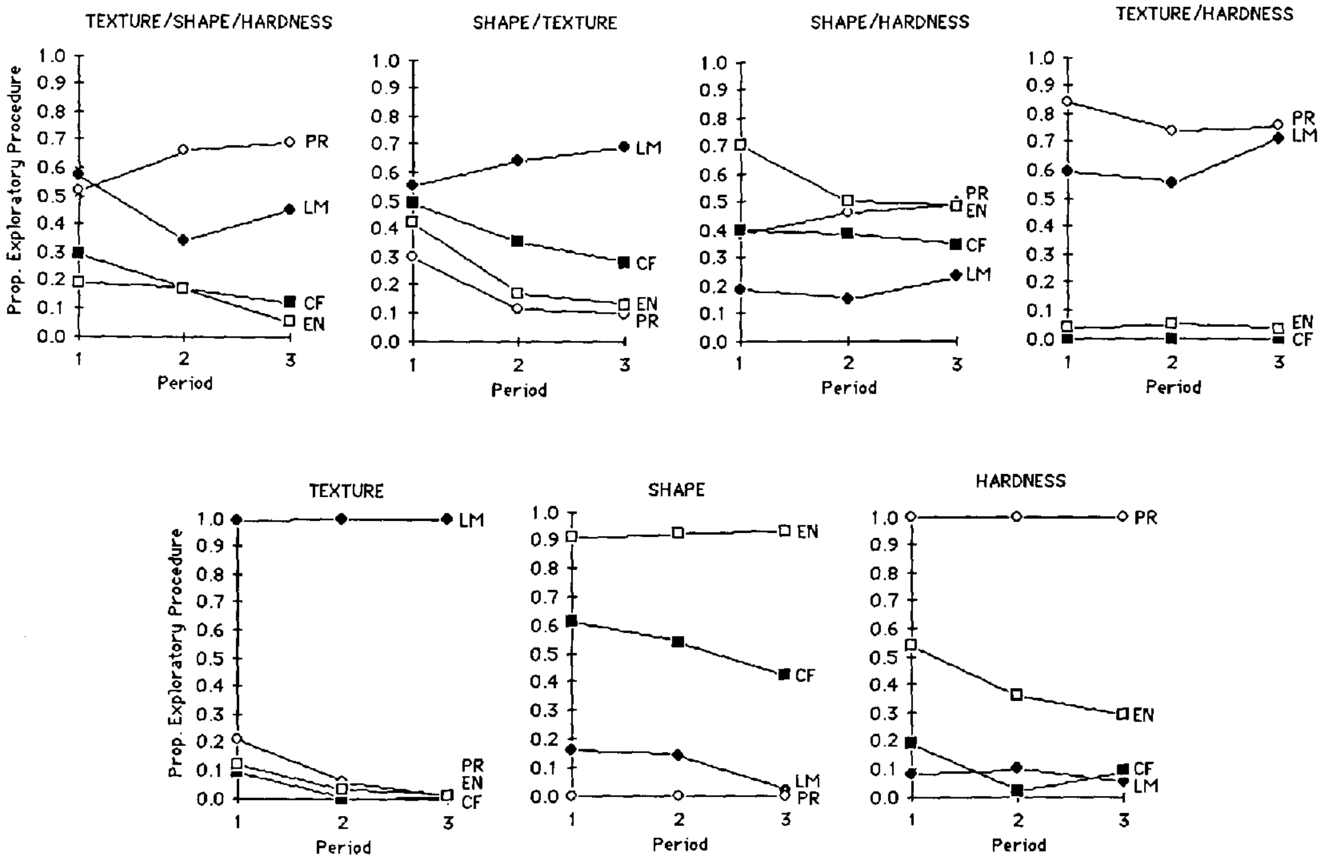

Figure 2. Proportion (prop.) of trials in Experiment 1, where each exploratory procedure (PR = pressure; LM = lateral motion; CF = contour following; EN = enclosure) was observed, by group and period (third) of trials.

the hardness group (i.e., subjects squeezed on the edges). There was a marginal tendency for irrelevant procedures to be used initially but to be eliminated over trials.

Addressing the two-dimensions groups next, within the texture/hardness condition, the relevant procedures of lateral motion and pressure dominated from the beginning of the task, and shape-related procedures were completely excluded. The proportions indicate that often, both relevant procedures occurred on the same trial. In fact, 6 of the 7 scored subjects used both procedures on at least 15% of sampled trials. Frequently this took the form of a single hybrid "smear" (a lateral movement with observable normal force). The shape/texture group executed both lateral motion, relevant to texture, and the shape-related procedures of contour following and enclosure. However, exploration for texture dominated by the last third of trials. The shape/hardness condition exhibited less procedure specialization, although the least appropriate procedure, lateral motion, did receive minimal use.

The three-dimensions group was very much like texture/hardness, except that exploration for shape was present at first and dropped over time. The similarity between the texture/hardness and three-dimensions groups is indicated by a correlation, over the 12 recorded proportions (3 periods; 4 procedures), of $r(10) = .90$ (cf. $r = -.06$ and $-.24$ for the correlations of the three-dimensions group with texture/shape and hardness/shape, respectively).

A critical issue is whether individual subjects in redundant-dimensions conditions sampled more than one dimension, or whether the observed redundancy effect in response time reflects subjects' encoding their single preferred dimension (Biederman & Checkosky, 1970). Examination of individual subjects in the redundant-dimensions groups indicated that most showed substantial use of two redundant dimensions, although some appeared to be focusing on a single dimension, in that they overtly explored another redundant one on less than 10% of the scored trials. No subject in the three-dimensions group showed substantial exploration for more than two dimensions. (One who exhibited exploration for all three actually changed over the three periods, exploring for no more than two at a time.)

On the whole, the data provide evidence for integration of dimensions in haptic classification—but only to a certain point. A second redundant dimension facilitated responses, but a third produced no further effect. The exploratory data indicate why this pattern occurs: Given all three redundant dimensions, exploration for shape (i.e., two-dimensional contour) is virtually dispensed with by most subjects, and exploratory procedures for texture and hardness are executed. Accordingly, the redundant shape information produces no facilitation of response times relative to the texture/hardness condition.

Experiment 2

Our next study was intended to provide converging evidence of integration and also to assess the relative weightings of integrated dimensions. Subjects were trained with stimuli that could be classified by two redundant dimensions. The names of the dimensions were never mentioned; rather, subjects were merely introduced to nine stimuli, each designated as *A*, *B*, or *C*. After a number of classification trials, sufficient to approach asymptotic performance, they were introduced to a new set of nine stimuli, again partitioned into classes called *A*, *B*, and *C*, but—unannounced to the subject—now defined by only one of the previously relevant dimensions. The other, withdrawn dimension was held constant at an arbitrary value.

If information from the withdrawn dimension had previously been used to determine classification, we would expect to see an increase in response time. We call this increase the *dimension withdrawal effect.* Classification time would be expected to increase because a relevant source of information has been lost and because there are potential costs of learning to focus entirely on the now single relevant information source while ignoring the previously relevant one. The magnitude of the withdrawal effect reflects the previous dependence on withdrawn information and the amount of new learning needed. To the extent relearning occurs, it should decrease response time only to the single-dimension asymptote. (However, if additional learning goes on over the experiment, a learning function will be superimposed on these predictions, which may reduce differences between the pre- and postwithdrawal asymptotes.)

On the basis of Experiment 1 and our a priori hypotheses, we predicted a greater withdrawal effect for texture/hardness pairings than for the pairing of either with shape. Moreover, we predicted that withdrawal of either texture or hardness should produce about equal effects, whereas in the other pairings, asymmetries might be observed because of differential focus on one of the two dimensions.

Method

There were 15 participants in each of six groups, defined by the combination of two dimensions drawn from texture, hardness, and shape.

The stimuli and procedure were like those of the two-dimension groups in Experiment 1, except for the withdrawal manipulation: After 108 trials in the initial task with two redundant dimensions, speeded trials terminated, and subjects were introduced to a new set of nine stimuli. (The decision to use 108 trials prior to withdrawal was based on the fact that subjects in Experiment 1 had essentially reached assymptote by this point, although some further nonsignificant reduction in response time was observed.) This new stimulus set represented withdrawal of one of the previously redundant dimensions—that is, where that dimension had previously varied so as to predict the classification decision, it was now held constant at one of the three possible values (the particular value being counterbalanced across subjects within the group—this was done rather than introducing orthogonal variation so that subjects would not attempt to learn a new classification rule involving the withdrawn dimension). The remaining two dimensions varied orthogonally, as before, but their assignment was changed so that all nine stimuli were novel and had not been used in the first part of the study. Subjects were given the nine stimuli just as at the start of the study, were told their labels, and were allowed to explore them freely. Then they were given nonspeeded classification trials until they classified all nine without error, at which point they began 99 speeded trials with the new set.

Results and Discussion

The data were response times and videotaped exploratory procedures from the entire experiment, including the exposure to and practice on the second set of stimuli. Response times 3 *SD*s from the subject's mean were truncated as before, and any trial was repeated if it had a time less than 450 ms (dismissed as ambient noise) or if the object was fumbled. Errors were not repeated and not included in the analysis; these constituted 1.4% of observations and did not differ by group. In the following discussion, *T*, *H*, and *S* refer to texture, hardness, and shape, respectively, and the designation A/B→B refers to a group for which dimensions *A* and *B* were at first redundant, and *A* was withdrawn, leaving *B* as the basis for classification.

The speeded trials were divided initially into 23 blocks of 9 trials. Blocks 1–12 were prewithdrawal and 13–23 were postwithdrawal. Four prewithdrawal periods and four postwithdrawal periods were then defined as follows. (See abscissa of Figure 3.)

The four periods within the prewithdrawal interval were three periods of initial learning, followed by a *prewithdrawal asymptote*, where performance should be essentially constant. This asymptotic period was designated as Blocks 11 and 12, because the difference in response time was not even marginally significant, and increases in response time over successive blocks in the 10–12 range were observed for all but one group (T/H→H). The initial learning periods were then formed by dividing the remaining prewithdrawal trials into thirds.

The first period within the postwithdrawal interval was *withdrawal*, where effects of the manipulation were presumably greatest. It was designated as the last five trials in Block 13 (the first four were eliminated as motor practice) and all of Block 14, because these two blocks did not differ significantly, whereas Block 13 was slower than Block 15. The last period, the postwithdrawal *asymptote*, was designated as Blocks 21–23, because there were no significant differences overall in this region. (It should be noted, however, that some groups clearly had not reached a flat asymptote.) The remaining postwithdrawal trials were divided into two *relearning* periods (27 trials each).

The response times by paired subgroups (those starting with the same pair of dimensions) are shown over the eight periods in Figure 3. The T/S and S/H groups exhibit an asymmetric pattern that shows dominance by one dimension. In this case, shape appears to be given higher weight in classification, because its withdrawal produces a substantial increase in response time. In contrast, the T/H groups show a symmetric pattern of impairment that indicates both dimensions contributed to classification; withdrawal of either texture or hardness increased response time.

Separate ANOVAS were conducted on the prewithdrawal data and the periods from the prewithdrawal asymptote to the postwithdrawal asymptote. The prewithdrawal analysis simply tests the replication of Experiment 1, for the two-dimensions groups. An analysis on group (T/H, S/H, T/S), and period (4, as defined above) revealed effects of period, $F(3, 261) = 66.60$, and group, $F(2, 87) = 7.65$, but no interaction. The group effect reflects a significant advantage for the T/H group, which had been marginal in Experiment 1. The period effect simply reflects the decrease in response time with practice.

The second ANOVA was concerned with the effects of withdrawal. Its variables were group (6, as defined by the combination of dimensions before withdrawal and the dimension remaining after withdrawal) and period (5—prewithdrawal asymptote, withdrawal, Relearning 1, Relearning 2, and postwithdrawal asymptote). There was the expected effect of period, $F(4, 336) = 8.39$, and a Group × Period interaction, $F(20, 336) = 2.48$. Subsequent tests probed for effects of the withdrawal, defined as a response time difference between the prewithdrawal asymptote and withdrawal periods. As pre-

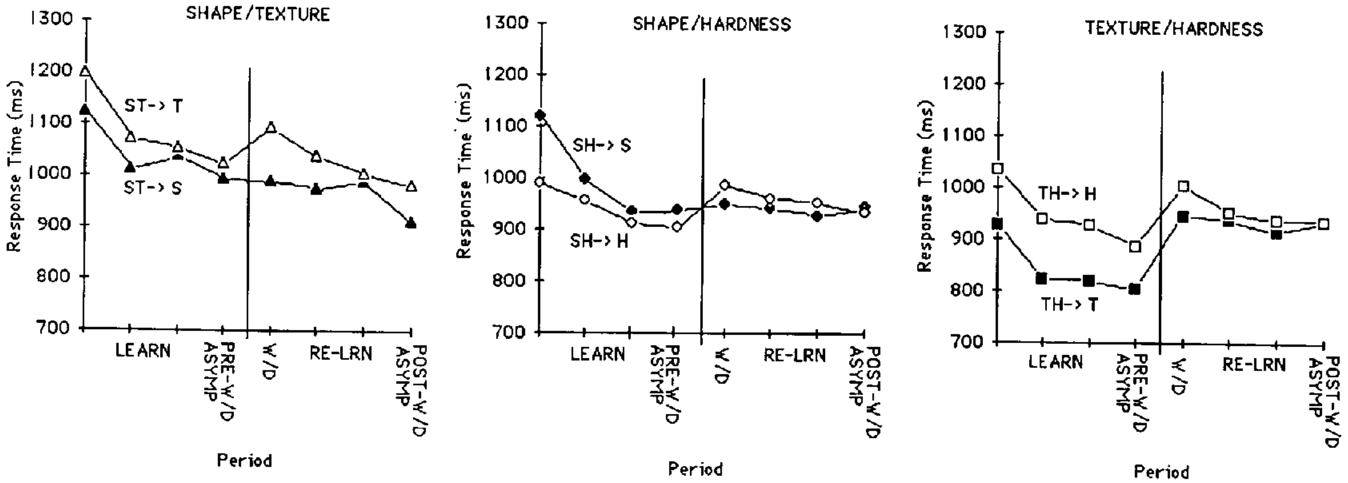

Figure 3. Mean response time (in milliseconds) in Experiment 2, by group and period (Learn = learning; Pre-W/D Asymp = prewithdrawal asymptote; W/D = withdrawal; Re-Lrn = relearning; Post-W/D Asymp = postwithdrawal asymptote). (*T*, *H*, and *S* abbreviate texture, hardness, and shape, and groups having initially redundant dimensions in common are shown together.)

dicted, this difference was significant for both the T/H groups (132 ms for T/H→T and 103 ms for T/H→H), and these values did not differ significantly. However, the difference was significant for only one member of the S/H and S/T pairs (71 ms for S/T→T and 84 ms for S/H→H). Thus the shift was symmetric for the T/H groups and asymmetric for the others.

We also tested for differences between the prewithdrawal and postwithdrawal asymptotes, although as noted above, these would be undermined by any learning throughout the experiment. There were only two significant asymptote effects, and one was actually negative (−106 ms for S/T→S). This reflects continued learning and no apparent withdrawal effect for that group. The expected asymptote effect for the T/H groups was significant only for the T/H→T group (124 ms). Recall that the T/H→H group had not as clearly reached asymptote prior to withdrawal, however, which would allow for greater learning and would reduce the magnitude of the asymptotic difference.

One may question why we did not obtain greater dimension-withdrawal effects in the shape/substance groups from which substance was withdrawn. Some increment would be expected, given that subjects were shifted from two redundant dimensions to one. It may be that learning acted sufficiently against such a shift as to mitigate the withdrawal effect. Recall that at the time of withdrawal, subjects were barely to a point where response times were not consistently decreasing, and Experiment 1 does suggest further learning beyond that point. Indeed, learning appears to be very substantial in the shape/texture groups beyond the withdrawal point. In any case, this rapid adjustment to withdrawal points to the flexibility of coding under shape/substance pairings.

As in Experiment 1, the exploratory hand-movement data were used to augment and interpret the response times. Hand movements were analyzed for 8 subjects in each group, sampling (a) the last 18 trials prior to withdrawal, (b) the interval of exposure to the new set of objects (i.e., free exploration of nine objects), (c) the nonspeeded test trials (one for each of the nine objects), and (d) the first 18 trials after withdrawal. Figure 4 shows the proportion of the objects in each of these intervals that were explored with at least one occurrence of the targeted exploratory procedures. The figure indicates that prior to the shift, subjects were generally using exploratory procedures relevant to both dimensions, in some mixture.

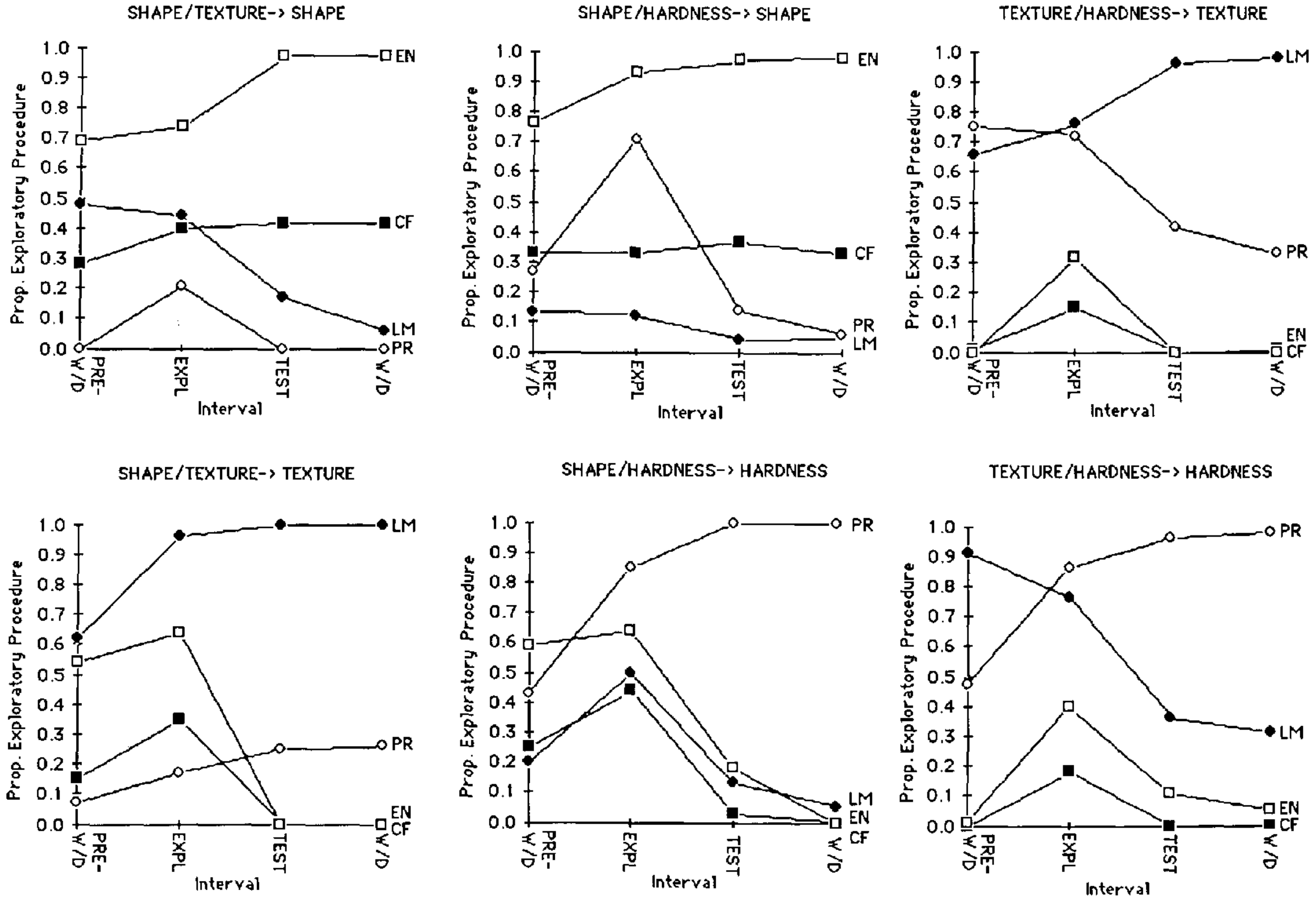

Figure 4. Proportion (prop.) of objects in Experiment 2 explored with each exploratory procedure (PR = pressure; LM = lateral motion; CF = contour following; EN = enclosure), by group and interval of exploration (Pre-W/D = prewithdrawal; Expl = exploration; Test = test trials; W/D = withdrawal.)

(The rather anomalous use of pressure in the S/T→T group reflects some subjects' pressing objects as they moved laterally across them.) When the new set of objects was introduced, procedures were more varied but generally kept their relative ordering. The shift to a single relevant procedure dominating exploration was quite marked by the time the test trials occurred, although there was some perseveration of previously appropriate procedures.

The patterns observed in Figure 4 were supported by an ANOVA on group (6), procedure (4), and interval (4). This showed all possible interaction effects—for the three-way, $F(45, 378) = 8.16$; Procedure × Interval, $F(9, 378) = 2.62$; Group × Procedure, $F(15, 126) = 43.79$; Group × Interval, $F(15, 126) = 2.27$—and main effects of interval and procedure, $Fs(3, 126) = 73.32$ and 40.63. Within each group, a significant Interval × Procedure interaction confirmed the shift in exploratory patterns.

As before, we addressed whether individual subjects were purposively sampling both redundant dimensions or whether they selected a preferred one. Again, a preponderance of subjects sampled both redundant dimensions (on at least 10% of trials—and generally more) before withdrawal, although the shape/hardness groups showed a substantial number of subjects focusing on just one. Perseveration of exploration for the withdrawn dimension was minimal in all but the texture/hardness groups, where all but 3 subjects persisted in exploring for the now constant dimension. Overall, the data suggested that the increase in response time subsequent to withdrawal is not due to inadequate sampling of the relevant dimension. Rather, subjects seem to have an inability to dispense with either dimensional processing that was previously functional or with motor habits formed during learning that are nonoptimal for the now single relevant dimension.

In summary, Experiment 2 further indicates that the extent of haptic integration differs, depending on the dimensions. Specifically, the integration of the two substance dimensions, under haptic exploration, appears to be greater than the integration of either with planar shape. Processing of two dimensions frequently occurred for all redundant combinations, at least as evidenced by purposive exploratory patterns that were pertinent to both. However, only the texture/hardness combination showed a symmetric pattern such that withdrawal of either impaired performance, and exploration for the withdrawn dimension persisted.

Experiment 3

In Experiment 3 we pursued another indication of integrative processing by using a variant of the withdrawal paradigm. We asked whether joint exploration for redundant dimensions would be spontaneously induced, under instructions to attend to one. Previously, subjects had not been informed about relevant dimensions, but had been informed about the switch in stimuli at the point of withdrawal. In this study the reverse held. Subjects were given a series of trials with stimuli that could be classified by either of two redundant dimensions, but they were told in advance that one particular dimension defined the stimulus classes. After more than 100 trials, the second dimension, about which subjects had not been informed, was switched from redundant variation to a constant value. No mention was made to the subjects about a shift in stimulus sets. If the second dimension is entering into classificatory processing, response time should be increased by withdrawal. Because the trials continue without pause at the point of withdrawal, effects may be even larger than in Experiment 2, where subjects were informed about and practiced with the new stimulus set.

Method

There were 12 subjects in each of six groups, defined as in Experiment 2.

The procedure was identical to that of Experiment 2, with two important changes. (a) Subjects were told that the objects could be classified by a simple rule, for example, "All *A*s are oval, all *B*s are hourglass shaped, and all *C*s are three-lobed." They were not told about other dimensions of variation, and they were given only one sample object from each set before beginning the speeded trials, so that they would not learn about the redundancy. (b) The withdrawal did not constitute an interruption; rather, the experimenter simply introduced the new set of objects at Trial 118. The number of trials subsequent to withdrawal was 45.

At the end of the experiment, subjects were asked whether they noticed any way to classify the objects other than by the assigned dimension and whether they noticed that the objects changed during the trials.

Results and Discussion

Errors, fumbles, and aberrant response times were eliminated as in Experiment 2. The mean error rate was 1.6%, and this did not vary with group.

The data were initially divided into 18 nine-trial blocks and then into 7 periods, defined similarly to Experiment 2. (See abscissa for Figure 5.) The prewithdrawal asymptote period was defined as Blocks 12 and 13 (the last two before withdrawal), on the same basis as for Experiment 2. The remainder of the prewithdrawal trials were divided into 3 learning periods of 33 trials each. The withdrawal period was defined as Block 14 (there is no difference in results if Block 15 is also included). The postwithdrawal asymptote period included Blocks 17 and 18, and the remaining two blocks (15 and 16) were classified as relearning. Figure 5 shows the response-time data for these 7 periods.

An ANOVA over the prewithdrawal four periods, with three groups (T/H, S/H, S/T) as a second factor, produced main effects of period, $F(3, 207) = 116.12$, and group, $F(2, 69) = 7.89$, replicating the previously observed advantage for classifying by texture and hardness.

The main interest was in the withdrawal manipulation. There was a very substantial increase in response time immediately after withdrawal of the redundant dimension, for both the T/H groups. The groups for which the dimension of shape was redundant with a substance dimension, texture, or hardness, showed much less or no effect. These observations were confirmed with an ANOVA on the variables group (6, defined by the redundant and withdrawn dimensions) and period (4—from prewithdrawal asymptote to postwithdrawal asymptote). There were effects of period, $F(3, 198) = 20.34$

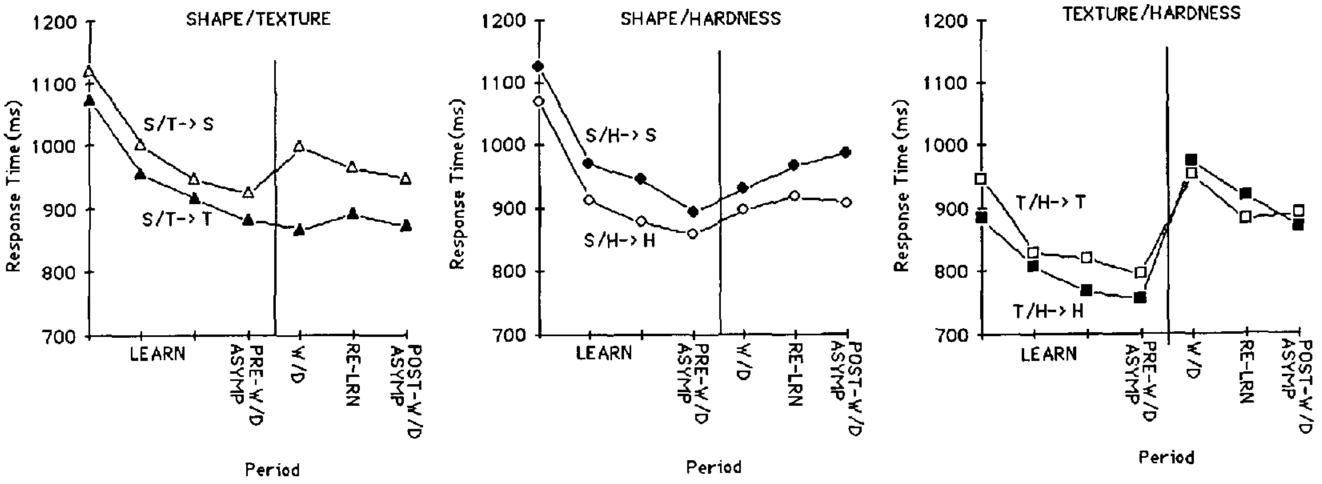

Figure 5. Mean response time (in milliseconds) in Experiment 3, by group (*T*, *H*, and *S* abbreviate texture, hardness, and shape) and period. (Learn = learning; Pre-W/D Asymp = prewithdrawal asymptote; W/D = withdrawal; Re-Lrn = relearning; Post-W/D Asymp = postwithdrawal asymptote). (Groups having initially redundant dimensions in common are shown together.)

and an interaction, *F*(15, 198) = 3.71, reflecting different withdrawal effects for the different groups.

Subsequent tests again probed for effects of the withdrawal, defined as a difference between the prewithdrawal asymptote and the withdrawal period. This difference was significant for both the T/H groups (159 ms for T/H→T and 219 ms for T/H→H) and (one-tailed only) for S/T→S (74 ms). Again, there was also a test for differences between the prewithdrawal and postwithdrawal asymptotes, although these would be undermined by any learning throughout the experiment. Four of six groups showed significant asymptotic differences, reflecting a redundancy gain that overrode learning: Groups T/H→T (98 ms), T/H→H (114 ms), S/H→S (94 ms), and (one-tailed only) S/H→H (48 ms). For the T/H combinations, asymptote differences were failures to recover completely from the sharp effect of withdrawal, whereas the S/H groups showed a more gradual rise in response time.

Answers to the postexperimental questions indicated, first, that relevant substance information is consciously noticed more than shape. None of the subjects told to focus on a substance dimension noticed that shape was redundant. On the other hand, close to half the subjects told to focus on shape noticed the redundant substance dimension. Second, answers to the questions indicated an asymmetry in conscious notice of hardness versus texture. Within the paired substance groups, only ¼ of those focusing on texture noticed redundant hardness, whereas ¾ of those focusing on hardness noticed redundant texture.

Finally, the subjects' reports indicate a difference among noticing initial redundancies, noticing their withdrawal, and the magnitude of the withdrawal effect. Not all subjects who noticed the redundancy reported noticing when one redundant dimension was eliminated. Moreover, substantial withdrawal effects on response time were observed when relatively few subjects reported noticing the redundant dimensions, as in the T/H→T group.

As before, the exploratory procedures were used to address issues about purposive sampling of redundant dimensions. Figure 6 shows the exploratory procedure proportions for 8 subjects in each group, sampling the 18 trials in the prewithdrawal asymptote period and the first 18 after the point of withdrawal. In general, prior to withdrawal subjects primarily used the procedure relevant to the instructed dimension, but execution of the procedure relevant to the redundant dimension is also evident. Redundant exploration was greatest for the texture/hardness groups and was minimal for the shape/substance pairings where substance was focal. The same trends were evident in the individual subject data. This pattern is similar to the questionnaire data in indicating that redundant shape is excluded from processing more readily than is substance.

There was only limited change in exploration due to withdrawal. The change was most substantial in the S/H→S and T/H→H groups; exploration for the secondary dimension decreased but was not eliminated. These patterns were confirmed in an overall ANOVA with factors period, procedure, and group. There was an effect of procedure, *F*(3, 126) = 59.78; group, *F*(5, 42) = 3.19; Procedure × Group, *F*(15, 126) = 64.90; Procedure × Period, *F*(3, 126) = 3.12; and three-way interaction, *F*(15, 126) = 2.95. Individual analyses by group all showed effects of procedure, but the Procedure × Period interaction was significant only for the S/H→S and T/H→H groups. Thus this study shows more uniform persistence in exploring for previously valid information than Experiment 2, where subjects were informed about the withdrawn dimension.

General Discussion

The present three studies have examined a variety of manipulations and data related to haptic integration. At this

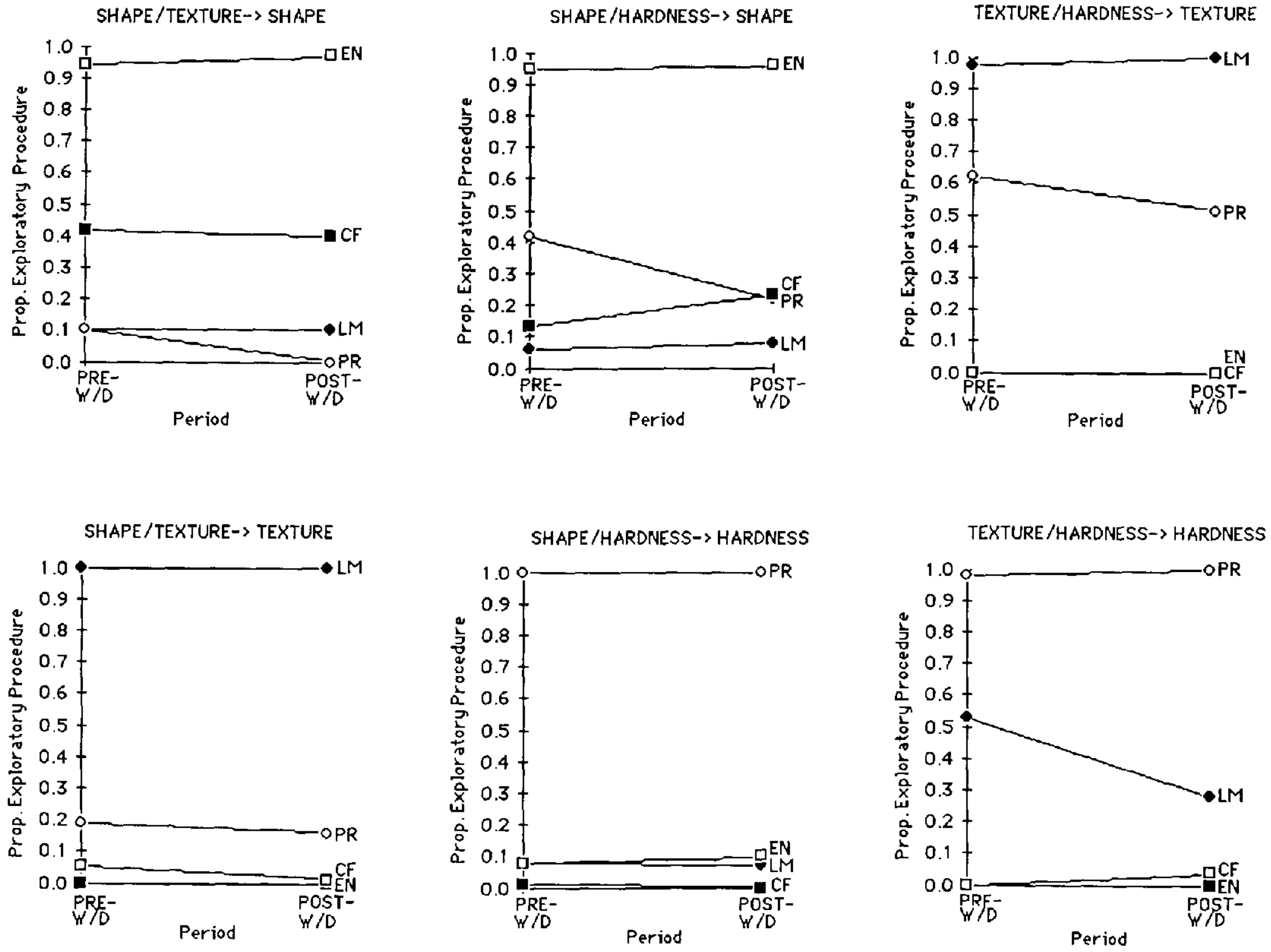

Figure 6. Proportion (prop.) of trials in Experiment 3, where each exploratory procedure (PR = pressure; LM = lateral motion; CF = contour following; EN = enclosure) was observed, before and after withdrawal (pre-W/D and post-W/D), by group.

point, we will summarize our findings. Experiment 1 showed that haptic dimensions could be integrated in classification. Specifically, classification by single dimensions was slower than by two, but a third redundant dimension did not speed performance (even when it replaced an orthogonal one). Exploration data indicated that most subjects sampled both of two redundant dimensions but that when texture, hardness, and shape were correlated, exploration for the first two dominated. There was also a tendency for the texture/hardness combination to be fastest of the two-dimensional groupings, and this became significant in the next two studies.

Experiments 2 and 3 dealt with the effects of a withdrawal of previously redundant information. In Experiment 2, subjects were not directed as to which dimensions to attend to, either before or after withdrawal. For groups with redundant substance and shape dimensions, there was evidence of asymmetric weighting of redundant dimensions prior to withdrawal. Moreover, flexibility of processing was evidenced in both postwithdrawal exploration (which appropriately eliminated procedures relevant to the withdrawn dimension) and response time (which showed minimal effects of withdrawal and rapid relearning). In contrast, when the substance dimensions of texture and hardness were combined, weighting appeared to be more symmetric, exploration for the previously redundant dimension persisted after the point of withdrawal, and response times showed greater and more long-lasting impairment due to withdrawal.

In Experiment 3, subjects were initially informed that one of two redundant dimensions was relevant, and the other dimension was subsequently withdrawn. As in Experiment 2, withdrawal of either dimension from a texture/hardness pairing resulted in a large increase in response time. However, unlike Experiment 2, effects of withdrawal were much less for other combinations. This difference is readily understood, in that in Experiment 2, subjects could freely choose dimensions to process and might focus on a subsequently withdrawn one. Even under the instructed focus of Experiment 3, there was a strong tendency both to explore for redundant dimensions in the texture/hardness case and to persist in such exploration after the incidental dimension was no longer relevant. These trends were not so apparent, however, for redundant combinations of shape and substance.

On the whole, these data make two primary points: (a) Integration of dimensions does appear to occur in haptics, although there are clear limitations on its occurrence. An effect of redundancy can be seen on both exploratory behavior and on classification time. (b) Dimensional integration of two substance dimensions, texture and hardness, is greater than the integration of planar contour and substance information.

These data provide a multitude of indications for substantial integration of texture and hardness. Some of these indications pertain to exploratory patterns. There is evidence of a strong link between exploration for texture and hardness, under conditions where they vary redundantly. Both are overtly sampled even under instructions motivating attention to just one and even after the redundancy is withdrawn. In addition, when texture, hardness, and shape are all redundant, exploration gravitates toward the first two. Other indications of texture/hardness integration pertain to response time. These include a tendency for responses to be fastest with this redundant combination, although single-dimension response times are essentially equated. Adding the third dimension of planar contour does not facilitate responses further. Finally, elimination of either dimension when texture and hardness are redundant results in substantial and long-lasting increases in classification time.

On the other hand, there are also clear indications of the integration of shape and substance at some point of processing. These include redundancy gains and redundant exploration. There are also some effects of withdrawing a redundant dimension when another is focal. However, these effects appear to be considerably more labile and directed by instruction than those relating to texture/hardness integration.

As indicated in the introduction, there are a variety of potential explanations for the tendency of texture and hardness to be integrated, more than for either to be integrated with planar contour. An important consideration is the compatibility of the corresponding exploratory procedures. The occurrence of a motor pattern that incorporated both lateral motion and normal force was common in these studies under conditions of redundant texture and hardness; this finding supported the notion of motoric compatibility. Compatibility with respect to position on the object is also important; the region that must be explored for contour is not necessarily the best place to explore for hardness or texture. Indeed, subjects were observed to explore almost exclusively in the center of the planar surfaces when texture, hardness, or both were relevant to classification, but shape was not.

Motoric and regional compatibility probably account for the differences in awareness of secondary dimensions observed in Experiment 3. Exploration for substance in the object's center would preclude encoding shape, and indeed, substance-focus subjects were largely unaware of redundant shape variations. However, substance information would be available from edge exploration, and shape-focus subjects did tend to notice redundant substance. It is likely that texture can be extracted by light rubbing without encoding hardness, because substantial variation in pressure does not occur. But intentional pressure variation during the extraction of hardness might induce some lateral motion of the skin relative to the surface, thereby providing additional texture information. This would account for the asymmetry in conscious awareness that was obtained.

For the foregoing reasons, we do not view the present dimensional limitation on integration as being a general one, precluding the integration of every three-dimensional combination. Given greater compatibility, integration might well occur. For example, it may be possible to effectively combine information about thermal properties with texture and hardness.

These same issues also raise the question of whether shape and substance would be more fully integrated in objects having shape information redundantly available in large surface regions, as with planar objects having relatively large extent (i.e., thickness) on the contoured surface, or fully three dimensional objects such as spheres. (See Roland & Mortensen, 1987, for a model of the extraction of regular volumetric changes through local samples.) Further work is planned in order to determine generalization or constraints on the present findings.

In the case of thick planar objects, such as a drinking glass, regional incompatibilities might well generalize. Even with such objects, exploration for the planar envelope is likely to occur on an explicit edge (the rim of the glass) and thus to interfere with substance extraction. Edge exploration guarantees that the pathway followed is around a plane normal to the object's long axis, and deviation from such a path would distort its perceived shape. For example, it might become difficult to discriminate a glass from an oval vase, if the curved surface were followed along an elliptical cut.

It was not the goal of this article to localize integration effects at specific stages of processing. However, given the evidence reviewed above for the greater integration of texture and hardness than of other dimensional combinations, it is tempting to place such integration at relatively early stages of processing. That is, texture and hardness might be candidates for integral dimensions, in Garner's (1974) sense, or for perceptually dependent attributes, in the framework of Ashby and Townsend (1986). We are currently pursuing the possibility that shape and size will behave similarly. In contrast, the integration of shape with either substance dimension, in the present stimuli, might be attributed to later, decisional processing that can benefit from correlated but separable dimensions.

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Calls for Nominations for *JCCP, Educational, JPSP: Attitudes,* and *JPSP: Interpersonal*

The Publications and Communications Board has opened nominations for the editorships of the *Journal of Consulting and Clinical Psychology*, the *Journal of Educational Psychology*, and the Attitudes and Social Cognition section and the Interpersonal Relations and Group Processes section of the *Journal of Personality and Social Psychology* for the years 1991–1996. Alan Kazdin, Robert Calfee, Steven Sherman, and Harry Reis, respectively, are the incumbent editors. Candidates must be members of APA and should be available to start receiving manuscripts in early 1990 to prepare for issues published in 1991. Please note that the P&C Board encourages more participation by members of underrepresented groups in the publication process and would particularly welcome such nominees. To nominate candidates, prepare a statement of one page or less in support of each candidate.

- For *Consulting and Clinical*, submit nominations to Martha Storandt, Department of Psychology, Washington University, St. Louis, Missouri 63130. Other members of the search committee are Bernadette Gray-Little, Frederick Kanfer, and Hans Strupp.
- For *Educational*, submit nominations to Richard Mayer, Department of Psychology, University of California, Santa Barbara, California 93106. Other members of the search committee are Robert Glaser, Jill Larkin, Sigmund Tobias, and Noreen Webb.
- For *JPSP: Attitudes*, submit nominations to Don Foss, Department of Psychology, University of Texas, Austin, Texas 78712. Other members of the search committee are Marilyn Brewer, David Hamilton, Melvin Manis, and Richard Petty.
- For *JPSP: Interpersonal*, submit nominations to Frances Degen Horowitz, Department of Human Development and Family Life, University of Kansas, Lawrence, Kansas 66045. Other members of the search committee are Kay K. Deaux, Phoebe C. Ellsworth, and Robert M. Krauss.

First review of nominations will begin February 15, 1989.