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Transfer between vision and haptics: Memory for 2-D patterns and 3-D objects

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Explicit memory tests such as recognition typically access semantic, modality-independent representations, while perceptual implicit memory tests typically access presemantic, modality-specific representations. By demonstrating comparable cross- and within-modal priming using vision and haptics with verbal materials (Easton, Srinivas, & Greene, 1997), we recently questioned whether the representations underlying perceptual implicit tests were modality specific. Unlike vision and audition, with vision and haptics verbal information can be presented in geometric terms to both modalities. The present experiments extend this line of research by assessing implicit and explicit memory within and between vision and haptics in the nonverbal domain, using both 2-D patterns and 3-D objects. Implicit test results revealed robust cross-modal priming for both 2-D patterns and 3-D objects, indicating that vision and haptics shared abstract representations of object shape and structure. Explicit test results for 3-D objects revealed modality specificity, indicating that the recognition system keeps track of the modality through which an object is experienced.

It is clear from recent research that there is an important distinction between *explicit* and *implicit* memory. Explicit memory is measured with recall or recognition tests typically assumed to access semantic, modality-independent representations, while perceptual implicit memory is measured with identification tests typically assumed to access presemantic, modality-specific representations (Schacter, 1994; Squire, 1992; Tulving & Schacter, 1990). The modality specificity of the representations underlying perceptual implicit memory has been inferred from priming studies where changes in modality between a study session and subsequent identification test result in substantially reduced facilitation (see Roediger & McDermott, 1993, for a review). In contrast, explicit memory tests are typically unaffected by changes in study–test modality (e.g., Rajaram & Roediger, 1993).

Recently, we questioned whether perceptual implicit memory tests necessarily tapped modality-specific representations, and demonstrated comparable cross- and within-modal priming for vision and haptics using verbal materials (Easton, Srinivas, & Greene, 1997). Our explanation of this finding is that visual and haptic verbal information can be presented to both modalities in the same geometric form, whereas verbal information is quite different for vision and audition, that is, geometric versus phonological. This raises the possibility that reduced cross-modal priming for visual and auditory words is not attributable to modality modularity, but rather to different forms of perceptual information presented to the modalities.

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An objection to this interpretation could be that cross-modal transfer between vision and haptics for verbal materials is mediated by shared *lexical* representations. To address this possibility, cross-modal transfer between vision and haptics in the *nonverbal* domain was assessed by using novel 2-D patterns in Experiment 1 of the present study. Because haptic perception of 2-D patterns can be a difficult task that may elicit the use of visual imagery (Lederman, Klatzky, Chataway, & Summers, 1990), and because it is known that images generated at study can prime words and pictures on later perceptual tests (e.g., McDermott & Roediger, 1994), cross-modal transfer between vision and haptics for common 3-D objects was assessed in Experiment 2. In fact, haptics appears to be far better suited for perception of 3-D structure (Klatzky, Loomis, Lederman, Wake, & Fujita, 1993), and haptic identification of 3-D objects probably does not involve the use of visual imagery (Lederman et al., 1990). While haptic identification can also be based on such material properties of objects as surface roughness, compliance, or thermal conductivity, which are not readily available to vision, their contribution has been found to be small compared to an object's global shape and structure (Klatzky et al., 1993).

With nonverbal materials, especially novel 2-D line patterns, it is unlikely that shared lexical representations could mediate cross-modal transfer. Thus, the specific question addressed in this study is as follows: If comparable information is presented to the modalities (i.e., 2-D or 3-D geometric structure), are visual and haptic representations sufficiently abstract to permit exchange across the modalities or are the representations largely specific to modality? If the latter is the case, we would expect to find transfer to be greater when study and test modality are maintained than when they are changed. On the other hand, if the representations are sufficiently abstract (geometric), we would expect to find little or no effects on priming of changing modality between study and test.

EXPERIMENT 1

Novel, three-line patterns were designed, with alphanumeric similarities being avoided, which could be presented to vision or haptics (raised lines), on the basis of an earlier finding that novel line patterns result in reliable priming effects in the visual system when a drawing task is used to index identification (Musen & Treisman, 1990). In addition to assessing within- and cross-modal priming, explicit recognition memory was also assessed to determine whether a dissociation between memory tests would occur, thus ruling out explicit memory contamination of implicit effects.

Method

Subjects. One hundred and eight Boston College undergraduates participated as subjects in this experiment in partial fulfillment of a course requirement.

Apparatus and Materials. The stimuli in this experiment were the 30 novel three-line shapes presented in Appendix A. The shapes consisted of three lines that were horizontal, vertical, or diagonal (45° or 135° slope) to maximize discriminability under conditions of haptic identification. Additionally, pairwise connections were characterized in three ways: endpoints, endpoints-to-midlines, and intersections. The shapes were rectangular to make maximal use of the area on the surface of an Optacon II (see below).

The haptic presentation of these stimuli was achieved in two ways: (1) the stimuli were presented as configurations of vibrating pins on a computer-interfaced Optacon II (a print reading device for the visually impaired consisting of 20 rows and 5 columns of pins), and (2) raised-line drawings of the images were presented on 7.6 × 7.6 cm plastic cards (raised lines were prepared with a serrated wheel). The images on the Optacon II were 1.92 cm long and .94 cm wide; the images on the plastic cards were 6.1 cm long and 2.0 cm wide. The visual images were .46 cm long and .15 cm wide and were viewed at a distance of approximately .76 m.

Design. A 3 (study condition: visual, haptic, or nonstudied) × 2 (modality at test condition: visual or haptic) × 2 (type of test: perceptual identification or explicit recognition) mixed design was used. Study condition was manipulated within subjects, whereas modality at test and type of test were manipulated between subjects. The subjects were assigned randomly: 36 to the visual perceptual identification test, 36 to the haptic perceptual identification test, 18 to the visual explicit recognition test, and 18 to the haptic explicit recognition test. For each test in each modality, the 30 stimuli were divided into three groups and each group was rotated through visual, haptic, and nonstudied conditions to achieve counterbalancing. This resulted in the creation of three study lists. Half of all participants studied the shapes visually first, and half studied them haptically first.

Procedure. At study, all subjects were presented with 20 shapes (10 in the haptic condition and 10 in the visual condition). In the visual study condition, subjects were presented with a black-and-white line drawing of the shape on a computer screen for 2 sec. In the haptic study condition, subjects felt the shape as a set of vibrating pins for 10 sec on the Optacon II. In both study conditions, subjects were instructed to give an accurate description of the presented shapes to ensure correct encoding of the shape. This description had to specify the orientation of each line, the positions of the lines relative to each other, and their intersections. If the descriptions were inaccurate, the subjects were informed of their error without specifying the correct shape. For example, if the subject described a capitalized I as having a vertical line with a horizontal line at the top endpoint and a diagonal line at the bottom endpoint of the vertical, he/she would be informed that there was no diagonal line in the shape. Because a pilot study had indicated that subjects could correctly encode the haptically presented shapes on the Optacon II only 80% of the time, they were also provided with a second presentation of the shape as a raised-line drawing during haptic study and then asked to give a revised (if necessary) description of the shape. The raised-line drawings were presented on cards that were shielded from view while subjects felt the shapes. Pilot data had indicated that this procedure enabled correct recognition of the haptically presented shape 95% of the time and ensured complete coding of pattern structure (see Musen & Treisman, 1990).

Between study and test, the subjects participated in a 5-min distractor task, where they selected and rank-ordered the 20 most familiar buildings at Boston College. At test, the subjects were presented with 20 studied and 10 nonstudied shapes in five different random orders to control for order effects. Subjects in the perceptual identification tests were informed that they would be given brief presentations of shapes, and that they had to draw the shapes correctly after each presentation. In the visual test condition, the shapes were presented on the computer for 1/30th second. In the haptic test condition, the shapes were presented for 6 sec on the Optacon II. Stimulus-duration parameters were selected on the basis of a pilot study ($n = 30$), and durations that allowed for the correct identification of 20%–50% of nonstudied shapes in both test conditions were adopted for use, thus avoiding ceiling and floor effects.

The drawings were scored on the basis of the correctness of line orientation, categorical line position, and intersections based on the scoring system of Musen and Treisman (1990). Relative line length, size, and so forth, were not scored. Shapes were judged to be either completely correct or incorrect without knowledge of which study condition they appeared in. Pilot testing revealed nearly perfect reliability among the accuracy scoring of three judges.

In the explicit recognition conditions, the study and test procedures were identical to those in the perceptual identification conditions, except that at test the subjects were asked to reply "Yes" if the shape had appeared at study and "No" if not.

Results and Discussion

The following conventions were adopted in reporting the results of all experiments in this paper. The results of the visual and haptic perceptual identification and explicit recognition tests were analyzed separately because of base-rate and procedural differences between the two types of tests. All experimental effects were computed by including counterbalancing as a between-subjects factor (Pollatsek & Well, 1995). All planned pairwise comparisons were performed using the omnibus mean squared error term. All analyses reported as significant in this paper were reliable at the .05 level unless stated otherwise, and the results are reported on the basis of subject variability (item variability was computed, but item analysis did not differ from the subjects analysis). Standard error bars about means in the figures were calculated on the basis of the within-subjects MS_e (Loftus & Masson, 1994).

Visual perceptual identification test. The results of the visual and haptic perceptual identification tests are provided in Figure 1, top left. As can be seen, priming scores (studied minus nonstudied accuracy) indicated little or no differences between the visual (8.8% facilitation) and haptic (7.3% facilitation) study conditions, but performance in these two conditions was better than performance in the nonstudied condition (40.8% correct identification). Repeated measures analysis of variance (ANOVA) confirmed these observations. Analysis of the main effect of study indicated a significant difference among study conditions [$F(2,66) = 4.95$, $MS_e = 155.4$]:

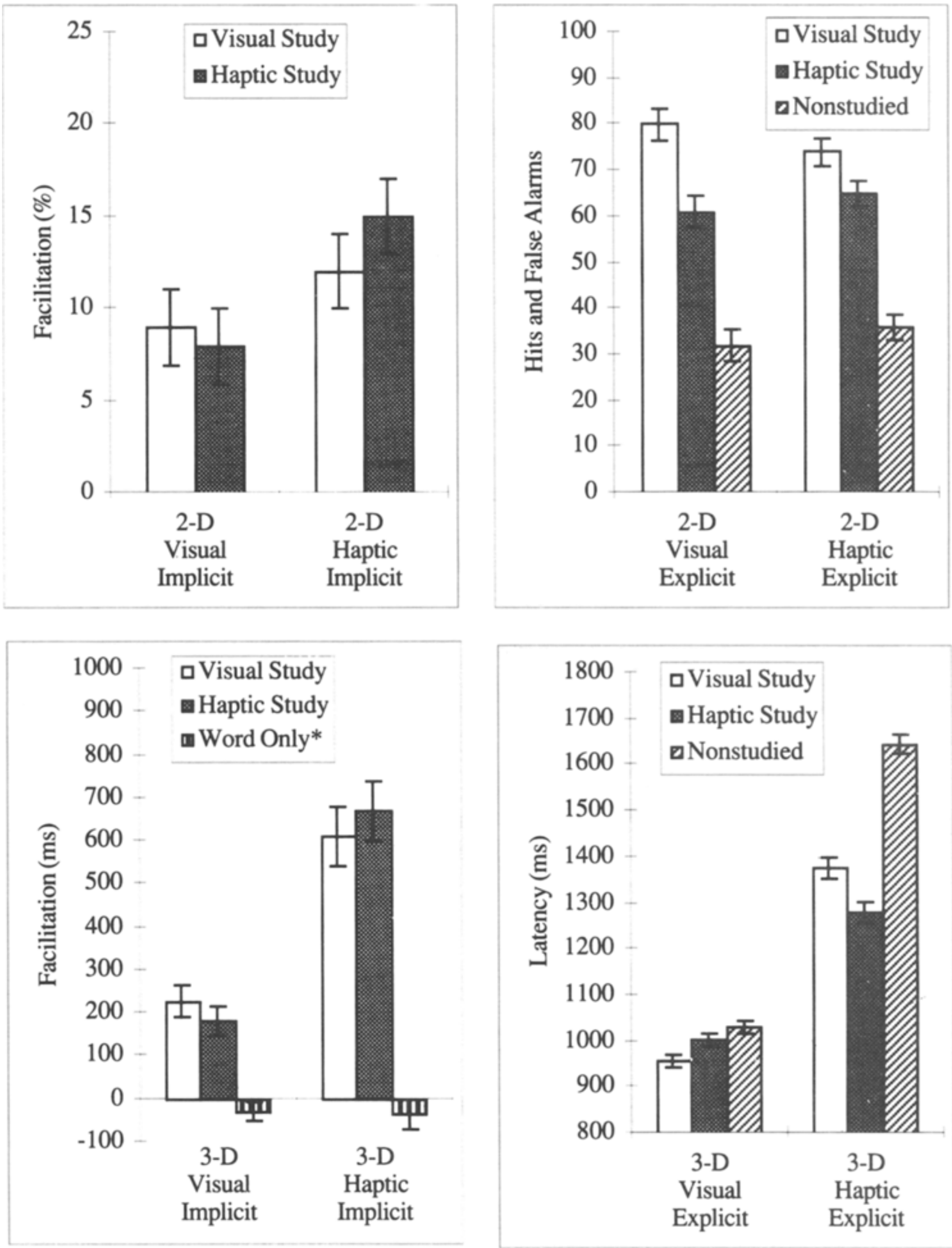

Figure 1. The effects of within- and cross-modal study on visual and haptic implicit and explicit tests for 2-D patterns and 3-D objects. For implicit tests, priming scores were computed by subtracting non-studied base rates from study scores. For the 3-D implicit test, priming scores were compared (between subjects) to the word-naming-only control experiment.

Planned comparisons revealed that priming had occurred [$F(1,66) = 9.68$] and that the visual and haptic study conditions did not differ significantly from each other ($F < 1$). The visual study condition differed from the nonstudied condition [$F(1,66) = 8.59$], as did the haptic study condition [$F(1,66) = 6.04$].

Haptic perceptual identification test. Analysis of the haptic identification test data (priming scores) indicated little or no differences between the visual (11.1% facilitation) and haptic (13.6% facilitation) study conditions, but performance on these two conditions was better than performance in the nonstudied condition (23.6% correct identification). Repeated measures ANOVA confirmed these observations. Analysis of the main effect of study indicated a significant difference among study conditions [$F(2,66) = 12.72$, $MS_e = 148.7$]. Planned comparisons revealed that priming occurred [$F(1,66) = 24.67$] and that the visual and haptic study conditions did not differ significantly from each other ($F < 1$). The visual study condition differed from the nonstudied condition

[$F(1,66) = 14.94$], as did the haptic study condition [$F(1,66) = 22.43$].

These results for the perceptual identification tests indicate that for novel 2-D shapes, a shift in modality between study and test did not result in a decrement in priming. Unlike the similar findings we have obtained with verbal materials (Easton et al., 1997), it is more difficult with these stimuli to argue that cross-modal transfer is mediated by shared lexical representations. However, because, at study, we had subjects provide verbal descriptions of shape geometry to ensure complete encoding (especially for haptics), it is possible that an abstract form of lexical mediation (i.e., other than naming) could account for cross-modal transfer. While this argument does not explain why so much more cross-modal facilitation is found with vision and haptics than with vision and audition, we directly addressed the issue of lexical mediation in Experiment 2 by assessing word naming on subsequent 3-D object identification.

Given the robust cross-modal transfer obtained in Experiment 1, one would expect substantial correlations over stimulus item accuracies among the four visual (v) and haptic (h) study–test conditions (i.e., v–v, h–v, v–h, h–h). Table 1 presents the intercorrelation matrix among the study–test conditions in Experiment 1. As can be seen, all the correlations are substantial (>.5) and significant, indicating that successful item identification in one modality is a strong predictor of item identification in the other modality.

It could be argued that the lack of modality specificity found above was due to a lack of experimental sensitivity. We believe this conclusion to be unlikely for several reasons. First, significant priming was found in all four study–test conditions, thus revealing experimental sensitivity (note also that our ANOVAs factored out counterbalancing effects, thus reducing MS_e and increasing sensitivity). Furthermore, a power analysis (see Keppel, 1991) revealed that the effect of study modality at the visual or haptic test was so small (i.e., *estimated omega squared* equaled .003 and .01, respectively) that, with power set for a very modest .50, over 700 subjects would be needed to achieve statistical significance (.05) for the visual test and nearly 200 subjects for the haptic test. Even so, it might still be argued that because within-modal priming is relatively small in this study (i.e., 8%–9%), any reduced facilitation accompanying modality change could be detected only with the use of hundreds of subjects. However, using exactly the same novel 2-D shapes, we have recently demonstrated ($n = 30$) that a change in the pattern's left-right orientation between study and test significantly reduces priming, for both vision and haptics (Srinivas, Greene, & Easton, in press). This priming specificity stands in contrast to the effect of modality change and attests to the sensitivity of the paradigm.

Finally, from a modality-specific representation perspective, one would predict a significant interaction between study and test conditions in the present priming experiment. In fact, there appears to be a hint of an interaction among the means of Figure 1 (top left panel), with a numerical advantage for visual study in the visual test condition (1.3%) and, conversely, an advantage for haptic study (2.5%) in the haptic test condition. We tested this interaction in a 2 × 2 mixed ANOVA, but the effect failed to reach significance ($F < 1$; priming scores were computed for each subject by subtracting the base rate in the nonstudied condition from scores in the two studied conditions). In the light of these data, we hypothesize that the representations that mediate priming for 2-D patterns generalize across the visual and haptic modalities. We now turn to the explicit recognition data.

Visual explicit recognition test. The results of the visual and haptic explicit recognition tests are provided in Figure 1, top right. As shown, the results indicated that test performance was better following visual study (80.0% correct recognition) than following haptic study (60.5% correct recognition), and that both exceeded the rate of false alarms (32.3%). Repeated measures ANOVA revealed that the visual and haptic study conditions differed significantly from each other [$F(1,15) = 15.75$, $MS_e = 216.1$].

Haptic explicit recognition test. Analysis of the haptic recognition data indicated that test performance was better following visual study (74.4% correct recognition) than following haptic study (65.0% correct recognition), and that both exceeded the rate of false alarms (35.6%). Repeated measures ANOVA revealed significant differ-

Table 1
Correlations Over Stimulus Item Accuracies in Experiment 1 and Over Stimulus Item Latencies in Experiment 2

Study–Test	Haptic–Visual	Visual–Visual	Haptic–Haptic	Visual–Haptic
		Experiment 1 ($n = 30$)		
Haptic–Visual	–	.644†	.531†	.642†
Visual–Visual		–	.640†	.530*
Haptic–Haptic			–	.687†
Visual–Haptic				–
		Experiment 2 ($n = 30$)		
Haptic–Visual	–	.803†	.598†	.447†
Visual–Visual		–	.572†	.426†
Haptic–Haptic			–	.393*
Visual–Haptic				–

*$p < .01$. †$p < .001$.

ences between visual and haptic study conditions [$F(1,15) = 5.29$, $MS_e = 151.7$].

For explicit recognition of novel shapes, the results indicate a significant advantage for visually studied items, whether recognition was tested visually or haptically. This result is contrary to previous findings of the insensitivity of explicit memory to changes in modality. Note, however, that this conclusion is based primarily on the manipulation of modality (audition and vision) for verbal materials. If one considers, instead, the literature on cross-modal matching between vision and haptics for novel shapes, a visual study advantage is almost always obtained (see Jones, 1981, for a review). Thus, on delayed matching-to-sample tasks with delays up to 30 sec between standard and comparison objects, visual study produces better performance than haptic study regardless of test modality. Jones hypothesized that the visual study advantage was a function of relative efficiency in the extraction of object information for visually perceived standard objects, which then guides exploration of the comparison object. We return to consider these explicit recognition findings for 2-D patterns in General Discussion.

Finally, the results of the explicit memory version of Experiment 1 indicate a dissociation between implicit (perceptual identification) and explicit (recognition) memory. The implicit memory tests showed no effects of changing modality between study and test for nonverbal shapes, whereas the explicit memory tests showed an advantage for visually studied shapes. These data suggest that it is unlikely that the priming data are contaminated by explicit memory or that they reflect semantic or conceptually based transfer across modalities.

EXPERIMENT 2

Haptic identification of 2-D patterns is a difficult task which may elicit the use of mental imagery (Lederman et al., 1990), and this could have mediated cross-modal transfer in Experiment 1. On the other hand, it has been demonstrated that active exploration of an object provides near immediate access to 3-D structure (Chan, Carello, & Turvey, 1990; Gibson, 1962; Klatzky, Lederman, & Metzger, 1985; Klatzky et al., 1993). It is also important to note that with the 2-D patterns used in Experiment 1, the *only* information relevant for visual or haptic pattern identification was geometric structure. In contrast, for 3-D objects, material properties are available to haptics but not readily available to vision, although their contribution is small compared with an object's global shape and structure (Klatzky et al., 1993). In addition to assessing 3-D objects, Experiment 2 also directly addressed the issue of lexical mediation of cross-modal transfer by including a control group of subjects who were required to read object names at study and later identify objects by vision or haptics at test (Greene, 1997).

An explicit memory test was also assessed in Experiment 2 to determine whether a dissociation between the memory tests would occur, thus allowing us to rule out explicit memory contamination.

Method

Subjects. Eighty-four Boston College undergraduates participated as subjects in this experiment in partial fulfillment of a course requirement.

Apparatus and Materials. The stimuli in this experiment were a set of 30 common objects found in ordinary household and office/school settings (see Appendix B). Additionally, the objects were selected to be readily identifiable both haptically and visually and small enough to be enclosed by the hands. Pilot testing had confirmed that each object was correctly identified visually and haptically at least 95% of the time.

Objects were placed in a 2.5-ft^3 stimulus chamber. Monocular viewing occurred through a tachistoscopic shutter inset in the top surface of the chamber, the inside of which was illuminated by a 25-W light bulb. Haptic exploration was performed by reaching under a curtain that constituted the front surface of the chamber. The object was placed on a force-sensitive platform (piezoelectric transducer; see Fikes, Klatzky, Pellegrino, Hebert, & Murdock, 1990). When the object was touched, very slight force on the platform triggered a clock that was then stopped via a voice-operated relay when the subject named the object. The subjects were allowed free haptic exploration, which sometimes resulted in the object's being lifted. For viewing, the opening of the tachistoscopic shutter initiated the clock, with object naming again stopping the clock.

Design. The design was identical to that used in Experiment 1. Twenty-four participants were assigned randomly to the visual perceptual identification test, 24 to the haptic perceptual identification test, 18 to the visual explicit recognition test, and 18 to the haptic explicit recognition test. The counterbalancing procedures were the same as those used in Experiment 1.

Procedure. At study, all participants were presented with 20 objects (10 in the haptic and 10 in the visual study condition) which they were instructed to name as quickly and as accurately as possible. In the visual study condition, each object was placed in the stimulus chamber and the shutter opened for 2 sec, which pilot testing had revealed to be sufficient to correctly name the object. In the haptic study condition, objects were placed in the stimulus chamber, participants reached in, touched the object with both hands, and named the object.

Between study and test, the subjects participated in a 5-min distractor task, in which they named 30 world cities. At test, the subjects were presented with 20 studied and 10 nonstudied objects. All objects at test were presented in precisely the same manner as at study. Subjects in the perceptual identification tests were to identify each object as quickly and as accurately as possible, and those in the recognition tests were to reply "Yes" if the shape had appeared at study and "No" if not. Latency and accuracy were recorded.

Control group. An additional group of 24 subjects was required at study to read the names of 20 objects, each name printed on an index card. At test, half the subjects were required to identify all 30 objects visually, and half were required to do so haptically.

Results and Discussion

Visual perceptual identification test. The results of the visual and haptic perceptual identification tests are provided in Figure 1, bottom left. As can be seen, the priming score (i.e., nonstudied latency minus studied latency) results indicated little or no difference between the visual (220-msec facilitation) and the haptic (180-msec facilitation) study conditions, but the performance on these two conditions was better than performance in the nonstudied condition (latency = 1,217 msec). Repeated measures ANOVA confirmed these observations. Analysis of the main effect of study indicated a significant difference among study conditions [$F(2,42) = 16.05$, $MS_e = 21{,}650.2$]. Planned comparisons revealed that priming occurred [$F(1,42) = 30.82$] and that the visual and haptic study conditions did not differ significantly from each other [$F(1,42) = 1.27, p < .21$; for the item analysis [$F(1,54) = 1.73, p < .19$]. The visual study condition differed from the nonstudied condition [$F(1,42) =$ 28.85], as did the haptic study condition [$F(1,42) = 18.02$].

Haptic perceptual identification test. Analysis of the haptic identification priming scores indicated little or no difference between the visual (610-msec facilitation) and haptic (671-msec facilitation) study conditions, but performance on these two conditions was better than performance in the nonstudied condition (latency = 1,981 msec). Repeated measures ANOVA confirmed these observations. Analysis of the main effect of study indicated a significant difference among study conditions [$F(2,42) = 28.24$, $MS_e = 117,305.7$]. Planned comparisons revealed that priming occurred [$F(1,42) = 56.11$] and that the visual and haptic study conditions did not differ significantly from each other ($F < 1$). The visual study condition differed from the nonstudied condition [$F(1,42) = 38.22$], as did the haptic study condition [$F(1,42) = 46.14$].

Word naming control condition. The results of the implicit identification tests indicate comparable within- and cross-modal priming. While it is unlikely that the robust cross-modal transfer for 3-D objects was mediated by visual imagery, transfer may have been mediated by lexical representations, especially as subjects were required to name the objects at study. Even though it is known that reading names of objects does not prime subsequent identification of pictures of objects (e.g., Srinivas, 1993), we felt it prudent to test for this possibility using actual 3-D objects (Greene, 1997). Results for the visual and haptic tests (Figure 1, bottom left) revealed no advantage for studied over nonstudied objects (visual test, 1,211 vs. 1,182 msec, $F < 1$; haptic test, 2,105 vs. 2,069 msec, $F < 1$), thus ruling out verbal mediation of cross-modal transfer.

The lack of differences between cross- and within-modal priming in Experiment 2 again raises the issue of experimental sensitivity. In fact, the obtained priming effects are in the direction of modality specificity (i.e., a 48-msec visual study advantage at visual test and a 61-msec haptic study advantage at haptic test). We tested the study–test interaction with a 2 × 2 mixed ANOVA, which, unlike Experiment 1, proved to be marginally significant [$F(1,46) = 3.2, p < .08$]. Thus, although cross-modal priming was very robust, within-modal priming may be slightly larger for identification of 3-D objects.

One possible explanation for this finding is that material properties of objects that are not available to vision may have slightly attenuated cross-modal priming. To explore this possibility further, correlations over stimulus-item accuracies among the four study–test conditions were again computed (see Table 1, Experiment 2). As can be seen, all the correlations were significantly greater than zero, which would be predicted by the hypothesis that vision and haptics shared 3-D structural representations. However, it is also of note that the highest correlation (.80) occurred when study–test combinations both entailed visual testing, while the lowest correlation (.39) occurred when the study–test combinations both entailed haptic testing. In fact, a Fisher z test revealed that these correlations differed significantly from one another ($z = 2.52, p < .02$). Our tentative interpretation of this pattern of correlations is that vision and haptics share 3-D structural representations, and this is strongly evidenced at visual testing, which would favor coding of structural features. At haptic testing, however, material properties of the objects not readily available to vision may also contribute to identification and slightly attenuate cross-modal transfer. This issue clearly needs further empirical scrutiny; what is important to note for now is that robust, if not complete, cross-modal priming did occur for identification of 3-D objects.

Visual explicit recognition test. The results of the visual and haptic explicit recognition tests are provided in Figure 1, bottom right. As can be seen, the results indicated that test performance was faster following visual study (latency = 958 msec) than following haptic study (latency = 1,002 msec) and that both were faster than the nonstudied condition (latency = 1,029 msec). A planned comparison confirmed that the visual and haptic study conditions differed significantly from each other [$F(1,15) = 4.7$, $MS_e = 3,766.3$].

Haptic explicit recognition test. Analysis of the haptic recognition data indicated that test performance was slower following visual study (latency = 1,376 msec) than following haptic study (latency = 1,280 msec) and that both are faster than for the nonstudied condition (latency = 1,645 msec). A planned comparison confirmed that the visual and haptic study conditions differed significantly from each other [$F(1,15) = 10.0, MS_e = 8,317.9$].

The results of the explicit recognition tests reveal a modality-specific effect; at visual test, visual study resulted in faster recognition, while at haptic test, haptic study resulted in faster recognition. Because we did not find modality specificity for explicit recognition in Experiment 1, and because modality specificity is not commonly associated with explicit recognition in the verbal domain (even for vision and haptics; Easton et al., 1997), we decided to replicate the explicit recognition effects. Rather than requiring subjects to name the objects at study, we asked them to judge whether the objects "were wider than they were tall." This replication ($n = 12$ for each test) constituted a depth-of-processing manipulation when compared with the explicit recognition results presented above. Once again, we found a significant visual study advantage at visual recognition test [1,089 vs. 1,155 msec; $F(1,9) = 6.4$, $MS_e = 4,076.1$] and a haptic study advantage at haptic recognition test [1,464 vs. 1,586 msec; $F(1,9) = 3.7, p < .1$]. In addition, mean recognition latency for study conditions increased significantly from 1,154 msec in Experiment 2 to 1,323 msec for the replication [$F(1,58) = 4.8, MS_e = 13,934$]; accuracy was also reduced significantly from 94.7% to 73.7% [$F(1,58) = 28.9$, $MS_e = 864.5$]. The decrement in recognition performance for the "shallower" study task in the replication experiment conforms to the typical depth-of-processing effects reported in the explicit recognition literature. As a result, we feel confident that the modality-specificity findings for explicit recognition of 3-D objects are reliable and stand in contrast to the lack of modality effects reported for explicit recognition of verbal material.

Finally, it is important to consider the explicit recognition results in the context of possible explicit memory contamination of the implicit memory results. While the marginally significant study–test interaction for implicit identification suggests slight modality-specific contributions, the planned contrasts comparing study conditions at tests did not even approach significance. For explicit recognition, however, the corresponding contrasts were reliable. Additionally, a dissociation between implicit and explicit measures of memory is strongly suggested by the naming control experiment conducted in conjunction with the implicit identification study. That is, the finding of no object-identification priming by named words is consistent with implicit but not explicit memory effects. Thus, we would argue that the slightly attenuated cross-modal priming effects obtained for implicit identification are not likely attributable to explicit memory contamination. In any event, very robust cross-modal transfer was obtained for implicit identification.

GENERAL DISCUSSION

Explicit memory tests such as recognition are thought typically to access semantic, modality-independent representations, while perceptual implicit memory tests access presemantic, modality-dependent representations (Schacter, 1994; Squire, 1992; Tulving & Schacter, 1990). We have recently questioned the generalizability of this assumption by demonstrating robust cross-modal priming with the visual and haptic modalities using verbal materials (Easton et al., 1997). Because visual–haptic transfer with verbal materials could be mediated by lexical representations, we assessed cross-modal priming in the nonverbal domain using novel 2-D patterns and common 3-D objects. In each case, we found robust cross-modal priming which was nearly, if not completely, comparable in magnitude to within-modal priming. Experiment 2 directly ruled out lexical mediation as an explanation of the findings for 3-D objects. Additionally, while cross-modal priming for the 2-D patterns could have been mediated by mental imagery due to the difficulty of the task, it is unlikely that this was the case for 3-D objects due to their very rapid haptic identification (Lederman et al., 1990).

Whether or not cross-modal facilitation is complete, the robustness of the effects stands in sharp contrast to reduced cross-modal facilitation reported for visual and auditory verbal materials. The results lead us to believe that if comparable information can be presented to two modalities, as is the case for vision and haptics, perceptual representations can be formed which are sufficiently abstract to permit sharing or exchange across modalities. In fact, from a systems perspective, it could be argued that a visual–haptic system has evolved due to the inherent reciprocity between the modalities necessary for visual-motor coordination during object identification and manipulation (Goodale & Milner, 1992).

The generalizability of the claim that recognition memory taps modality-independent representations can also be considered in view of the present results. The explicit recognition results of Experiment 2 (and a replication) indicate that modality-specific representations are being accessed for recognition of common objects. That is, for 3-D objects, the explicit recognition system apparently keeps track of the modality through which an object was experienced. This finding is opposite to what has been found for recognition of verbal material, but does not seem unreasonable given the abstract nature of verbal symbols. One puzzling aspect of the explicit memory results, however, is the recognition data of Experiment 1, where a visual study advantage was found regardless of test modality. While it is true that the visual study advantage at haptic test was smaller than at visual test [Figure 1, top right: the study–test interaction was marginally significant, $F(1,34) = 2.22$, $p < .14$], it remains unclear why a haptic advantage was not obtained. One possibility is that for 2-D patterns, material properties of the objects favoring haptics were at a minimum, which made encoding the patterns more difficult at study (see Jones, 1981). Consistent with this hypothesis, the visual study advantages reported in the cross-modal matching literature have all entailed 2-D raised-line patterns, planar objects (i.e., cutouts), or novel 3-D objects made of the same material, all of which minimize the distinctive material properties.

In any case, the present experiments do demonstrate robust cross-modal transfer for visual-haptic implicit memory for nonverbal materials. These findings raise the possibility that the perceptual representations that underlie perceptual implicit memory test performance are not necessarily modality-specific, and that the representations that underlie explicit recognition memory are not necessarily modality independent.

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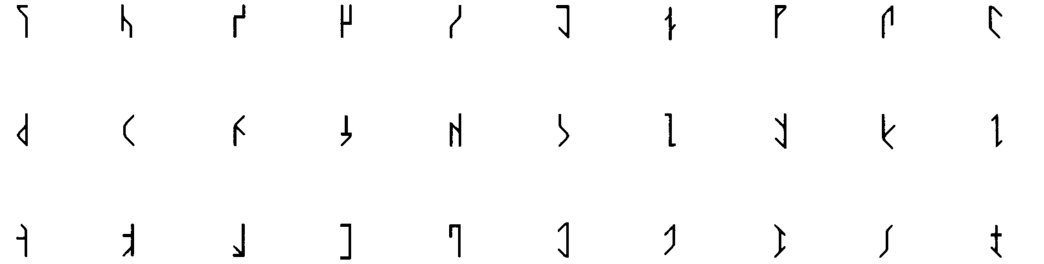
APPENDIX A
Thirty Novel Three-Line Stimuli Used in Experiment 1



APPENDIX B
Thirty Common Objects Used as Stimuli in Experiment 2

Screwdriver	Pliers	Wrench
Measuring cup	Cup	Fork
Comb	Toothbrush	Lighter
Eraser	Tape	Stapler
Cassette	Dart	Battery
Spoon	Can opener	Cork screw
Knife	Sunglasses	Key
Scissors	Staple remover	Calculator
Marker	Golf ball	Lock
Tape measure	Watch	Razor

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