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Implicit and Explicit Memory for Visual and Haptic Objects: Cross-Modal Priming Depends on Structural Descriptions

José Manuel Reales and Soledad Ballesteros
Universidad Nacional de Educación a Distancia

Previous research on cross-modal priming has used verbal stimuli presented to vision and audition. This study examined whether priming is modality specific and whether there are dissociations between several implicit and explicit memory measures when familiar objects are presented to vision and touch. The experiments showed significant priming between and within modalities. Experiment 1 showed similar presemantic priming between and within modalities. Experiment 2 found robust cross-modal priming using 2 different implicit memory tests: picture-fragment completion and object decision. However, priming was greater when pictures were presented at study and test than when visual or haptic objects were given at study and pictures were shown at test. Conversely, the study of objects haptically or visually enhanced free recall. Experiment 3 found that within- and cross-modal priming were both unaffected by study-test delay. The findings suggest that similar structural descriptions mediate object priming in vision and touch.

The goal of this study was to explore whether the perceptual representations of visual and haptic real objects that mediate priming are modality specific and how this represented information is accessed under implicit and explicit conditions. Graf and Schacter (1985) used the terms *implicit* and *explicit* to refer to two different ways of accessing prior acquired information, as well as the forms in which memory is expressed. Explicit memory for objects is related to conscious recollection of previous experience with the objects. In contrast, implicit memory is unveiled when previous experiences with the objects do not require conscious or intentional recollection of previously perceived information (Schacter, 1987).

Implicit memory is usually assessed by showing repetition priming effects, which mean better performance in accuracy or response time for stimuli that have been previously encountered in comparison with performance with new stimuli. During the last few years, the area of implicit and explicit memory has produced an enormous amount of research (for reviews, see Richardson-Klavehn & Bjork, 1988; Roediger & McDermott, 1993; Schacter, 1987).

Studies on implicit and explicit memory have focused mainly on verbal materials (words, nonwords, pair-associated words) presented either visually or auditorily (e.g., Church & Schacter, 1994; Schacter & Church, 1992). The tests more frequently used were word-fragment completion (e.g., Tulving, Schacter, & Stark, 1982), word-stem completion (e.g., Roediger & Blaxton, 1987; Schacter & Graf, 1989), word identification (e.g., Graf & Ryan, 1990; Jacoby & Dallas, 1981), and word–nonword decisions (e.g., Kirsner, Milech, & Standen, 1983). More recently, however, a number of studies have focused on nonverbal visual materials. These implicit tests have included possible–impossible judgments of unfamiliar objects (e.g., Carrasco & Seamon, 1996; Schacter, Cooper, & Delaney, 1990a), object naming (e.g., Biederman & Cooper, 1991a, 1991b, 1992; Srinivas, 1993), the drawing of 2-D straight-line patterns (Musen & Treisman, 1990), or symmetrical–asymmetrical judgments of visual patterns (Ballesteros & Cooper, 1992; Ballesteros, Cooper, & Reales, 1999). Compared with the large number of visual studies, haptic studies are almost lacking. Below, we review a number of issues on the topic of the implicit and explicit representations of visual and haptic objects, such as whether priming is perceptually and modality specific, the characteristics of visual and haptic exploration, and the dissociation between implicit and explicit tasks for haptic stimuli.

Is Priming Perceptually and Modality Specific?

Visual studies have mostly supported the idea that priming is perceptually specific. For example, priming is greatest when studied and tested pictures are identical, but when the

José Manuel Reales and Soledad Ballesteros, Departamento de Psicología Básica II, Universidad Nacional de Educación a Distancia, Madrid, Spain.

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Correspondence concerning this article should be addressed to Soledad Ballesteros, Departamento de Psicología Básica II, Universidad Nacional de Educación a Distancia, Ciudad Universitaria, 28040 Madrid, Spain. Electronic mail may be sent to mballesteros@psi.uned.es.

object exemplars change from study to test (e.g., upright piano vs. grand piano), priming diminishes (e.g., Biederman & Cooper, 1991b; Cave, Bost, & Cobb, 1996; Srinivas, 1993). Likewise, the change in the typestyle of words from study to test reduces priming (e.g., Graf & Ryan, 1990; Roediger & Blaxton, 1987). On the contrary, these manipulations have little effect on explicit memory measures. Moreover, word–picture studies have found larger priming when observers studied words and then were tested with words than with pictures (e.g., Durso & Johnson, 1979; Kirsner, Milech, & Stumpfel, 1986; Lachman & Lachman, 1980; Park & Gabrieli, 1995; Rajaran & Roediger, 1993; Warren & Morton, 1982; Weldon & Roediger, 1987). Furthermore, some studies have found diminished priming when visual fragments change from study to test (Snodgrass & Feenan, 1990; Srinivas, 1993), but other studies have found equal priming with same and complementary picture fragments (e.g., Biederman & Cooper, 1991b; Snodgrass, Hirshman, & Fan, 1996).

Repetition priming, however, is not sensitive to all the perceptual characteristics of objects. For example, changes in the size or the right–left orientation of objects from study to test do not reduce priming but impair recognition (e.g., Biederman & Cooper, 1991a, 1992; Cooper, Schacter, Ballesteros, & Moore, 1992). In addition, when object dimensions such as color, surface pattern, contrast polarity, or illumination changed, recognition was impaired but priming was not (Cave et al., 1996; Cave & Squire, 1992; Srinivas, 1996). However, changes on other dimensions such as rotation in the picture plane of unfamiliar objects (Cooper, Schacter, & Moore, 1991) and 2-D patterns (Ballesteros et al., 1999) as well as changes relatively large in orientation in depth of familiar objects and nonobjects reduce both priming and recognition (Biederman & Gerhardstein, 1993; Srinivas, 1995).

Repetition priming as a measure of implicit memory is assumed to be largely modality specific (e.g., Schacter, Chiu, & Ochsner, 1993). Researchers have usually investigated the effects of modality shifts presenting verbal stimuli at study to one modality (e.g., audition) while at test the same stimuli plus a number of new stimuli are presented to a different modality (e.g., vision). The pattern of results that emerged from these one-way cross-modal studies has shown that priming is usually reduced and sometimes eliminated after modality change (e.g., Graf, Shimamura, & Squire, 1985; Jacoby & Dallas, 1981; Kirsner & Smith, 1974; Rajaram & Roediger, 1993; Roediger & Blaxton, 1987; Srinivas & Roediger, 1990). Similar results have been reported when the modality changed from vision to audition (e.g., Bassili, Smith, & McLeod, 1989; McClelland & Pring, 1991). On the tactual modality, Hamann (1996) reported weaker cross-modal priming in a Braille word-stem completion test from auditory study. The findings showing that modality shifts rarely eliminate repetition priming do suggest that priming is not totally modality specific and entirely based on low-level perceptual features (e.g., Kirsner, Dunn, & Standen, 1989; Roediger & Blaxton, 1987). We reasoned that the reduced cross-modal priming observed in previous studies might be due to the lack of overlap between the perceived information (e.g., sounds and visual letters). This hypothesis encouraged us to explore the nature of the mental representations supporting repetition priming when objects are presented to vision and touch, which are both well suited to deal with real 3-D objects (see next section). It might well be the case that repetition priming is a perceptually based phenomenon but still sensitive to higher level abstract characteristics of objects such as its shape and the interrelations among its constituent parts.

Next, we review some results suggesting that there is some evidence that representations extracted by vision and by touch were similar. These representations might then be used in cross-modal repetition priming.

Haptic Versus Visual Exploration

The haptic system is a complex perceptual system that encodes input information from cutaneous as well as from kinesthesic receptors (Loomis & Lederman, 1986). Important similarities as well as differences have been noted in object processing and recognition by vision and by touch. Solid substances and real objects are perceptible by both modalities; the eyes embrace a large object while the hands explore at once only a limited-size object. Nevertheless, the eyes fixate in succession just as the fingers explore in succession (Gibson, 1962). Haptic perception depends on complementary information from tactual acuity, active movement, and spatial cues; furthermore, stimulus size and familiarity are not as important in vision as they are in touch (Millar, 1994). Researchers on touch have documented the substantial role of active and systematic movements during haptic exploration (e.g., Gibson, 1962; Klatzky & Lederman, 1987; Locher & Simmons, 1978; Zinchenko & Lomov, 1960).

In a recent study, Ballesteros, Manga, and Reales (1997) showed that touch, like vision, is more accurate at detecting symmetric than asymmetric 3-D unfamiliar objects. Careful analysis of videotaped hand movements showed that the movements more often performed were *enclosure* and *contour following,* which are related to the detection of structural properties of shape (Klatzky & Lederman, 1987). *Enclosure* is a very efficient and fast movement that allows the simultaneous processing and parallel extraction of structural shape information. Two-hands active exploration of 3-D objects enhances object identification by allowing the perceiver to make contact with all the parts of the object simultaneously. This mode of exploration made haptic processing somehow similar to visual processing and contrasts clearly with the sequential exploration mode required by impoverished 2-D raised displays (Ballesteros, Manga, & Reales, 1997). Another series of experiments with 2-D raised stimuli provided additional support for the similarity of processing from the two modalities showing that bilateral symmetry is an encoding property for vision as well as for touch even though the task did not require explicitly the detection of symmetry (Ballesteros, Millar, & Reales, 1998). Symmetry facilitated processing in touch under a two-handed exploration condition in which body-axis reference cues for spatial organization were provided. It is still an open question whether the mental representations that support implicit memory for objects in the world are the same (common abstract, structural representations) regardless of being accessed visually or haptically.

Implicit and Explicit Memory for Haptic Objects

Most research on implicit and explicit memory has focused on stimuli presented either visually or auditorily (for reviews, see Roediger & McDermott, 1993; Schacter, 1987). The few studies that have investigated implicit memory for touch have shown significant implicit memory for objects presented to touch. As the aim of the present study was to explore cross-modal priming between vision and touch, we review briefly the literature on implicit memory for haptic objects. Wippich and Warner (1989) reported an early experiment in which implicit memory for haptic objects and nonobjects was calculated by subtracting the time needed to answer questions related to a haptic dimension between the first and the second presentation of each object. Lately, our research has been directed at finding out whether significant priming effects could be observed for haptic objects when different tasks were used at study and test (Ballesteros, 1993; Ballesteros, Manga, & Reales, 1994). In an experiment, observers at study explored haptically a series of familiar objects and verbally judged their weight (e.g., heavy or light), their temperature (e.g., warm or cold), their size (e.g., large or small), their shape (e.g., round or sharp), and their texture (e.g., soft or rough). Then, incidentally, half of the observers were asked to name the objects (implicit memory) and the other half participated in an "old–new" recognition test (explicit memory). Half of the participants in each memory test used gloves whereas the other half performed the task without gloves. The substantial repetition priming even in conditions in which the mode of exploration changed by having participants use gloves during the implicit memory task suggests that haptic priming is not hyperspecific and that real objects can be recognized by structural cues (Ballesteros et al., 1994; see also Klatzky, Loomis, Lederman, Wake, & Fujita, 1993). It is important to note that the most diagnostic property for haptic objects is the structural property of shape, followed by size (Lederman & Klatzky, 1990). These object properties may be accessed when observers use gloves as well as when they explore without gloves, allowing the activation of identical structural descriptions. Conversely, explicit recognition was impaired in the gloves condition, suggesting that the mental representations that support explicit memory include all kinds of distinctive, low-level, sensory-based information about objects (such as their texture, their temperature, their softness, their hardness, and so on). These results show a dissociation between the implicit and explicit tests (Ballesteros, Reales, & Manga, in press; see also Wippich, 1990).

On the other hand, we failed to observe priming using both a symmetry detection task and a drawing task when blindfolded observers explored five to six raised-line, small (2 × 2 cm) novel shapes under structural and semantic encoding conditions (for a full description of the shapes, see Ballesteros, Manga, et al., 1997). We attributed the lack of priming for these small novel shapes to the difficulty at encoding spatial information under reduced kinesthesic feedback as well as to the lack of spatial reference under blindfolded conditions (Ballesteros, Manga, et al., 1997, 1998; Millar, 1994). Several researchers in the field of touch have noticed that blindfolded sighted observers performed quite poorly not only with unfamiliar shapes but also with raised line drawings of familiar objects (e.g., Ikeda & Uchikawa, 1978; Klatzky et al., 1993; Lederman, Klatzky, Chataway, & Summers, 1990; Loomis, Klatzky, & Lederman, 1991; Magee & Kennedy, 1980). However, small raised shapes and dot stimuli can be identified with a great amount of practice (Heller, 1989; Millar, 1978, 1994). In the present study, we used 3-D real objects and two-hands exploration to avoid familiarity problems and the lack of spatial reference frames in haptic exploration.

Experiments

Is there visual–haptic cross-modal priming? The present experiments investigated whether priming is maintained when at study observers are presented with objects in one modality (e.g., touch) and then, incidentally, implicit memory is evaluated in the other modality (e.g., vision). Changes in a perceptual variable introduced from study to test usually reduce performance on implicit memory tests but have little or no effect on explicit memory tests (Roediger & McDermott, 1993; but see Jacoby & Dallas, 1981).

Studies specially designed to test the modality effect with real-world objects presented to vision and touch are necessary to understand how humans code information about objects in the real world. In the present experiments, we presented real objects through vision and touch, and not simply words or novel shapes, for several reasons. First, there is considerable overlap between the information underlying visual and haptic object perception. Second, real objects are successfully recognized by structural cues alone. Third, vision and touch are very efficient in dealing with 3-D objects. Fourth, unlike novel shapes, real objects are ecologically valid. The reduction or total absence of priming effects obtained in previous cross-modal implicit memory studies (e.g., Graf et al., 1985; Jacoby & Dallas, 1981; Kirsner & Smith, 1974; Rajaram & Roediger, 1993) might be due to the lack of overlap between the type of stimulus information extracted from the modalities under investigation.

The two main theoretical views of implicit memory predict that modality shifts should have adverse effects on priming but little effect on explicit memory. According to the transfer-appropriate processing account, data-driven tests such as picture naming, picture identification, and picture completion are enhanced when perceptual processes that occurred during the study episode match those processes engaged at test (Blaxton, 1989; Roediger, 1990; Roediger & Blaxton, 1987; Roediger & Weldon, 1987). On the other hand, the memory-systems view sustains that object priming is mediated by the structural descriptions of objects that represent the stimulus structure. These descriptions are assumed to be presemantic and modality specific (Tulving & Schacter, 1990). These two theories, however, rely on results from visual and auditory studies. So, research on other modalities, such as touch, is necessary before strong conclusions about modality specificity can be reached.

We reasoned that as the structure of an object remains unchanged whether it is presented to vision or to active touch (Ballesteros & Reales, 1995), a single, abstract mental representation (a similar structural description) would be created after the object is perceived once. A *structural description* refers to a mental representation of an object that is volumetric and specifies its global form and structure (see Riddoch & Humphreys, 1987). Were this true, we expected to obtain substantial cross-modal priming as well as the usual within-modal priming when modalities changed between the study and test phases. Cross-modal priming (visual–haptic studies), however, should disappear when changes across modalities interfere with the structural descriptions of the objects.

The first experiment in this series evaluated the effect of modality on repetition priming presenting exactly the same stimulation to vision and touch. In addition, it explored whether the mental representations that support within-modal as well as cross-modal priming are presemantic. Experiments 2a and 2b were designed to examine whether cross-modal priming was mediated by name codes and investigated dissociations between implicit and explicit memory tasks. Finally, Experiment 3 considered the role of delay on cross-modal and within-modal implicit and explicit memory to reveal the nature of underlying representations and processes responsible for cross-modal priming.

Experiment 1

In this experiment, we combined study modality and test modality factorially to investigate cross-modal and within-modal priming. If object priming were mediated by abstract, structural, modality-independent representations, cross-modal priming should be similar to within-modal priming. In addition, this experiment served as a replication of the haptic priming effects previously observed (Ballesteros, 1993; Ballesteros et al., 1994). The use of 3-D real objects provides the opportunity to look for priming under more realistic, ecological conditions. The haptic identification of real objects is both fast and very accurate (Klatzky, Lederman, & Metzger, 1985), but studies using raised displays as well as those representing arbitrary configurations have shown worse performance (e.g., Lederman, Klatzky, & Barber, 1985; Magee & Kennedy, 1980). This difference might be due to the lack of familiarity with the stimuli and of potential cues that could be processed by the haptic perceptual system. In common life, humans interact continuously with real objects.

A manipulation that has received much attention because it can dissociate implicit and explicit memory tests is *levels of processing*. The experimental manipulation of this variable has shown different effects on implicit and explicit memory tests. Semantic (deep) encoding at study normally produces an advantage over physical (shallow) encoding on explicit memory tests. On the contrary, the effect of semantic encoding is usually nonsignificant and levels of processing has little or no effect on perceptual implicit memory tests (e.g., Jacoby & Dallas, 1981; Schacter et al., 1990a). Although some investigators have argued that cross-modal priming is due to the engagement of a semantic or lexical system (e.g., Keane, Gabrieli, Fennema, Growdon, & Corkin, 1991), Richardson-Klavehn and Gardiner (1996, 1998) maintained that deficits in lexical processing during shallow encoding tasks suggest the implication of lexical as well as perceptual processes in priming. We were interested in exploring whether the levels-of-processing variable affects visual and haptic cross-modal memory for real objects as the impact of this variable has not yet been studied. Consistent with the structural hypothesis, the absence of levels-of-processing effects would suggest that the mental representations that support object priming are presemantic. However, an effect of levels of processing would weaken this interpretation. We anticipate significant cross-modal and within-modal object priming because, as discussed earlier, shape is the most diagnostic dimension for haptic as well as for visual identification of familiar objects (e.g., Klatzky et al., 1993; Lederman & Klatzky, 1990). Such an outcome would favor the hypothesis that mental structural representations are abstracted similarly by both modalities.

Method

Participants

Forty-eight Universidad Nacional de Educación a Distancia undergraduates participated in partial fulfillment of a course requirement. All the participants had normal or corrected vision and were naive as to the purpose of the experiment.

Materials and Equipment

The target stimuli were 60 familiar objects. Ten more objects were used for practice trials. Examples of the objects used in Experiments 1, 2, and 3 are displayed in Figure 1. The objects were selected from several basic-level categories, such as vegetables, household objects, personal care objects, and tools, with the following restrictions. First, the size of the object should be adequate to allow enclosing within the hands to facilitate haptic exploration. Second, objects should not make special noises. Third, objects should not emit strong odors. Fourth, objects should be common and easy to identify. Fifth, objects should not give rise to negative emotional feelings.

The apparatus was a 3-D real visual–haptic object tachistoscope constructed following the technical specifications provided by Fikes, Klatzky, Pellegrino, Hebert, and Murdock (1990). It was made in black methacrylate and had a liquid crystal (13.7 × 13.7 cm) located at the eye level on the vertical methacrylate panel in front of which the observer was seated. The window allows for real object visual presentation. For haptic trials, the apparatus was provided with a piezoelectric board that acted as the object presentation platform. The piezoelectric board at which the objects were displayed had a piezosensor located underneath at the center of the platform, directly below the position at which the stimulus was presented. For trial presentation and data collection, the apparatus was interfaced with an IBM-System/2 computer. To stop the internal clock of the computer, we attached a Lafayette vocal key to the collar of the participant.

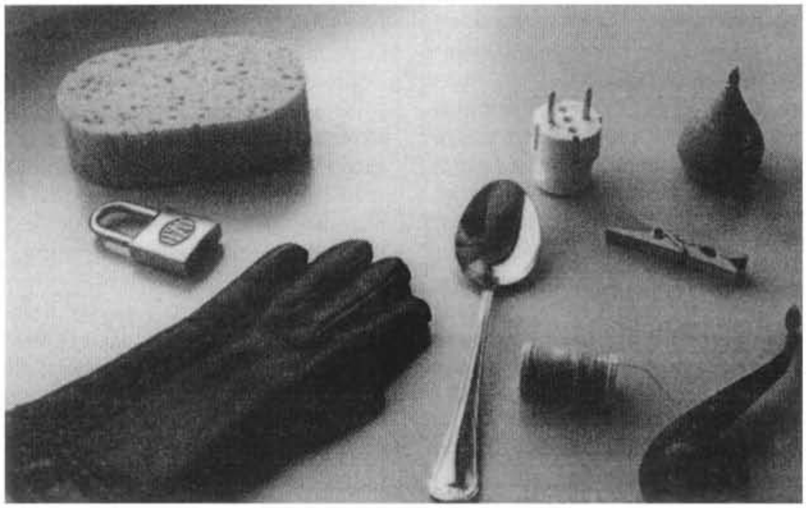

Figure 1. Examples of objects used in Experiment 1.

Design

A 2 (study modality: vision vs. touch) × 2 (test modality: vision vs. touch) × 3 (study conditions: semantic study vs. physical study vs. nonstudied objects) mixed factorial design was used. The first two variables were manipulated between subjects, whereas type of study was manipulated within subjects. Twelve participants were randomly assigned to each of the four experimental conditions. In addition, the 60 experimental stimuli were divided randomly into two sets of 30 stimuli each. These two sets were further subdivided into two additional subsets of 15 stimuli. Stimuli in both sets appeared equally often as studied and nonstudied items. Each subset of 15 stimuli appeared equally often as semantically or physically encoded.

Procedure

Participants were tested individually in a quiet room. They were informed that they were participating in an experiment on object perception. The experiment always started with a study phase in which participants were presented with a series of objects either visually or haptically. Those in the haptic encoding condition were allowed 10 s to feel each object with their hands. Fifteen objects were encoded semantically and the other 15 were encoded physically in a counterbalanced order. The computer program generated a random presentation order for each participant. Observers who studied the objects visually were asked to look at the object through the liquid crystal window of the apparatus for 10 s also. According to the encoding condition, observers had to generate a meaningful sentence including the object's name (semantic encoding) or to rate the object's volume on a 5-point scale (physical encoding). Studied objects were presented exactly at the same orientation at study and at test. A 5-min distractor task was performed between study and test consisting of underlining all the words in a page that included the letter *e*.

At test, participants were asked to name each object as quickly and accurately as possible. Half of the participants who studied the objects visually were tested visually (the within-modal group); the other half were tested haptically (the cross-modal group). Similarly, half of the participants who studied the objects haptically were tested in the same modality (the within-modal group), and the other half were tested visually (the cross-modal group). Participants in the visual test modality were presented with each object through the liquid crystal window of the tachistoscope whereas those in the tactual test condition explored each object located at the piezoelectric board. In this phase of the experiment, 30 new objects were added to the set of objects previously encoded under semantic and physical conditions.

In the haptic test modality, the experimenter placed a randomly selected object at the center of the presentation board. A tone from the computer alerted the participant that the object was in place. Latencies were recorded from the time the hands first made contact with the object to the naming response. In the visual test, response times were recorded from the time the liquid crystal window allowed the participant to see the object until the naming response. On each trial, the participant placed two forefingers on a placeholder. When the fingers were raised from the holder, the liquid crystal window allowed visual inspection of the object. There was no fixation point. A vocal key attached to the participant's collar was used to stop the internal clock of the computer. Before the visual or haptic test, participants performed five practice trials.

Eight subjects participated in a pilot study in which after the study phase (visual or haptic) an old–new recognition task followed. Because this pilot study showed ceiling effects, a recognition task was not included in the present experiment.

Results

Latencies corresponding to correct responses were the main dependent variable, but accuracy was also recorded to check for speed–accuracy trade-offs. No such effect was found. The main percentage of errors for the studied items was lower than for the nonstudied items (3.18% and 4.68%, respectively). Figure 2 displays the results on latency from the implicit memory task as a function of study modality (vision or touch), test modality (vision or touch), and study condition (physical study, semantic study, or nonstudied).

Three main findings from the latency data are worth noting. First, there is an important facilitatory priming effect for studied compared with nonstudied objects (0.27 s). Second, cross-modal (0.25 s) and within-modal (0.29 s)

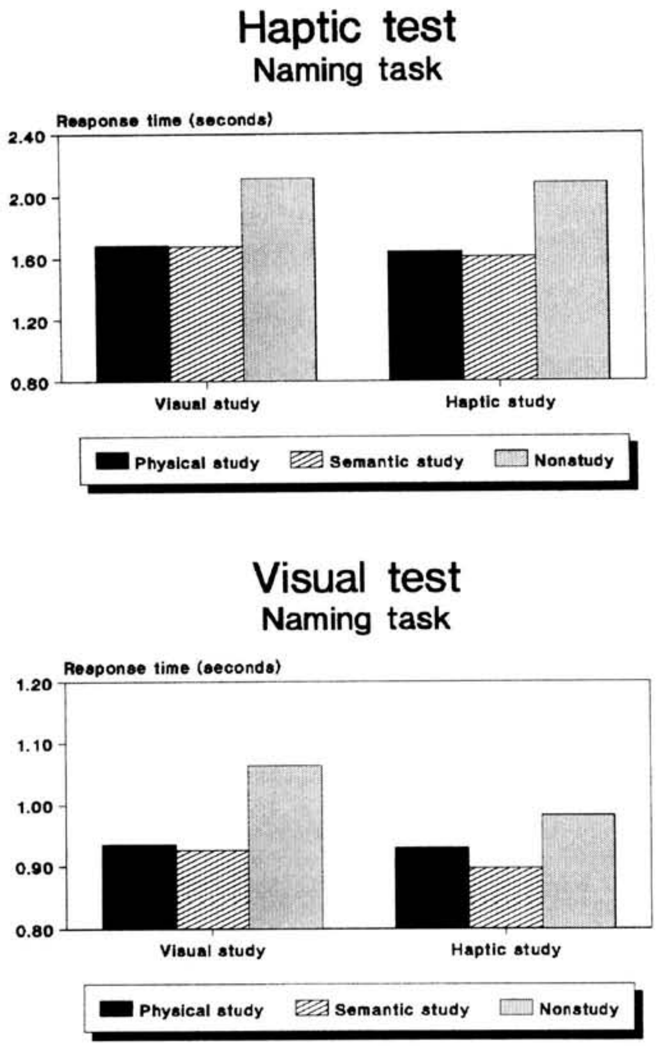

Figure 2. Response time (in seconds) in the haptic (top) and visual (bottom) object naming test as a function of level of study (physical study, semantic study, and nonstudied) and study modality (visual encoding or haptic encoding).

facilitation were of comparable magnitude. Third, facilitation was not affected by the levels-of-processing variable; the facilitation observed under physical encoding (0.26 s) was comparable with the facilitation corresponding to semantic encoding (0.28 s).

Two three-factor mixed analyses of variance (ANOVAs) were conducted with study modality and test modality as the between-subjects variables and study conditions (semantic, physical, and nonstudied objects) as the within-subjects variable. As for all the experiments, ANOVAs were conducted for both subject (F_s) and item (F_i) variability. Only latencies corresponding to correct responses were included in the analyses. The significance level for this and the following experiments was set at .05. These analyses confirmed the previous description. Visually as well as haptically studied objects were named faster (at the haptic and visual naming tests) than nonstudied objects. The main effect of study condition was significant, $F_s(2, 88) = 47.87$, $MSE = 0.025$; $F_i(2, 112) = 41.02$, $MSE = 0.015$. Studied objects were named reliably faster than nonstudied objects (1.29 s vs. 1.56 s, respectively). Post hoc Newman–Keuls tests showed that the semantic and physical study conditions did not differ significantly. However, these two study conditions differed significantly from the nonstudied condition. The main effect of study modality was not significant ($F < 1$), but the main effect of test modality was reliable; visual judgments were faster than haptic judgments (0.96 s vs. 1.80 s, respectively), $F_s(1, 44) = 150.67$, $MSE = 0.17$; $F_i(1, 56) = 271.38$, $MSE = 0.060$. The Study Condition × Test Modality interaction was significant, $F_s(2, 88) = 19.04$, $MSE = 0.025$; $F_i(2, 112) = 26.66$, $MSE = 0.013$; interaction comparisons (Keppel, 1982) showed that latency differences for studied objects compared with nonstudied objects were larger when the test modality was touch than when it was vision, $F_s(1, 44) = 27.09$, $MSE = 0.035$. No other interaction was significant. The absence of a statistically significant three-way interaction suggests a complete cross-modal transfer between vision and touch.

An additional ANOVA conducted on accuracy showed the advantage of the study conditions (error rates 3.38%, 2.99%, and 4.68% for physically studied, semantically studied, and nonstudied, respectively), $F_s(2, 88) = 13.89$, $MSE = 1.13$. Post hoc Newman–Keuls tests showed a significant difference between studied and nonstudied stimuli. As in the latency analysis, no reliable difference was found between physical or semantic study. No other effects nor any interactions were significant.

Discussion

The finding of complete cross-modal transfer between modalities suggests that earlier reports of an advantage for within- compared with cross-modal priming were probably due to the choice of modalities (see Easton, Srinivas, et al., 1997, for a similar argument). The finding is consistent with our hypothesis. It suggests that when objects are processed by two modalities specialized in processing structural dimensions, as vision and touch, priming obtained on the naming task is not mediated by modality-specific representations. Results support the hypothesis that priming is preserved when a cross-modal change occurs from vision to touch and vice versa.

The within-modal findings replicate previous research with visual line drawings depicting real objects (e.g., Biederman & Cooper, 1991a; Snodgrass & Feenan, 1990; Srinivas, 1993) and with haptic objects (Ballesteros et al., 1994). However, this is the first visual priming study in which observers were presented with real objects.[1]

[1] We learned about the study by Easton, Greene, and Srinivas (1997, Experiment 2) after having conducted the first two experiments and having submitted this article (in March 1997). In fact, we have presented parts of this article at several conferences (see author note). Easton et al., using also 3-D objects, reported the lack of difference between cross- and within-modal priming, but the priming effects were in the direction of perceptual

Cross-modal positive (auditory to visual) priming effects obtained with implicit perceptual tests have usually been interpreted as evidence of conceptual participation in such tests. Weldon (1991) proposed that implicit perceptual tests are not pure tests and that a number of variables such as perceptual processing, lexical access, and conceptual processing can all affect priming in implicit tests to different degrees. The absence of levels-of-processing effects suggests that the representations that support object priming are presemantic and agree with recent studies showing that the levels-of-processing variable does not affect implicit memory tests. These studies have used verbal stimuli (e.g., Hamann, 1990; Hirshman, Snodgrass, Mindles, & Feenan, 1990; Parkin, Reid, & Russo, 1990; Perruchet & Baveaux, 1989), unfamiliar line drawings representing 3-D objects (Schacter et al., 1990a), and familiar and unfamiliar objects presented haptically (Ballesteros et al., 1994).

Other researchers have reported significant effects of levels of processing in a perceptual word-fragment completion test (e.g., Challis & Brodbeck, 1992; but see Brown & Mitchell, 1994, for an opposite conclusion). However, Toth, Reingold, and Jacoby (1994) attributed many demonstrations of conceptual effects on perceptual indirect tests (as a measure of implicit memory) to consciously controlled uses of memory. Cross-modal priming has been attributed to the participation of conceptual processes in implicit memory (e.g., Hirshman et al., 1990; Keane et al., 1991).

The present findings support the idea that repetition priming is a perceptual instead of a conceptual phenomenon. One potential problem, however, with our findings—levels of processing and the lack of modality effect—is that they are based on the acceptance of the null hypothesis. However, our interpretation is grounded on positive priming effects in all experimental conditions rather than relying on the acceptance of a negative effect (see Cooper et al., 1992). Nonetheless, before making inferences about the nature of the mental representations underlying implicit memory for objects processed by vision and by touch, we investigate converging evidence from other tasks.

Experiments 2A and 2B

Experiments 2A and 2B were designed as an attempt to gather converging evidence of cross-modal priming and to examine whether cross-modal priming is mediated by name codes. Furthermore, we sought to find evidence for possible dissociations between implicit and explicit memory tests across and within modalities. Because a pilot study (see Experiment 1) showed that recognition was at ceiling, in these experiments a free-recall test was used to assess explicit memory and to rule out explicit memory contamination of implicit tests. We also attempted to provide converging evidence for cross-modal priming using two widely used tasks to assess implicit memory: picture-fragment completion in Experiment 2A (e.g., Biederman & Cooper, 1991b; Gollin, 1960; Snodgrass & Feenan, 1990; Snodgrass & Vanderwart, 1980; Srinivas, 1993; Warrington & Weiskrantz, 1974) and object decision in Experiment 2B (e.g., Kroll & Potter, 1984; Srinivas, 1995).

We wanted to establish whether the priming obtained in Experiment 1 was specific to the naming task. In these experiments, we were interested in comparing objects with pictures of objects because most visual experiments have used pictures instead of real objects.

Experiment 2A

Experiment 2A explored the effect of three study conditions (study pictures, study objects by touch, or study objects by vision) on a speeded picture-fragment completion test and its possible dissociations from explicit free recall.

Method

Participants. Thirty-six new observers from the same sample pool participated in the experiment. Twelve observers were randomly assigned to each of the three study conditions.

Materials and equipment. The 64 target stimuli were selected from Snodgrass and Vanderwart's (1980) norms with the restriction that the size of the objects was adequate to be presented at the piezoelectric board for haptic exploration. Also, negative or aversive stimuli were discarded. Figure 3 shows an example of the eight levels of completion.

Fifty-eight of the 64 target pictures corresponded to the real objects used in Experiment 1; the other 6 real objects did not have their corresponding picture in the Snodgrass and Vanderwart (1980) norms and were replaced by other stimuli. For preparation of the fragmented stimuli, the algorithm provided by Snodgrass, Smith, Feenan, and Corkin (1987) was used. The stimuli were digitized using a scanner (HP Scanjet IIc) and were prepared to be presented in graphic mode (resolution 640×480 pixels). The digitized files were saved in graphic BMP format. The image generated was projected on the computer monitor. A 16×16 grid was simulated and was superimposed to the projected image. All the 16×16 pixel blocks that contained some black pixels were identified. This information was stored in an array and then was randomly permuted. The deleted block rate of the image followed from the exponential function: $P = 0.7 \times e^{8.0 \times \text{level}}$. Each picture was stored as fragmented images at eight different levels of completion. Level 1 corresponded to the most fragmented image, whereas Level 8 was the complete picture. The proportion of deleted pixel blocks was 0.91, 0.88, 0.83, 0.76, 0.65, 0.51, 0.30, and 0.00 from Level 1 to Level 8, respectively.

The equipment used to run the study phase was the same as in Experiment 1. For the picture-fragment completion and object-decision tests, a Dell 486 and SVGA screen were used. A vocal key was connected to the computer to measure response time. The key was constructed after the indications of Dalrymple-Alford (1992) and Hawley and Izatt (1992).

Design. The main experimental design consisted of a 3 (study conditions: intact pictures of objects vs. real haptic objects vs. real visual objects) $\times$ 2 (item types: studied vs. nonstudied stimuli) mixed factorial. The first variable was manipulated between subjects; the other was within subjects. Moreover, the 64 target objects were randomly divided into two sets of 32 objects each. The two sets were rotated through all experimental conditions, producing a counterbalanced design in which each stimulus set appeared

specificity. They found a marginally significant Study $\times$ Test interaction ($p < .08$), which means that although cross-modal priming was robust, within-modal priming was slightly larger.

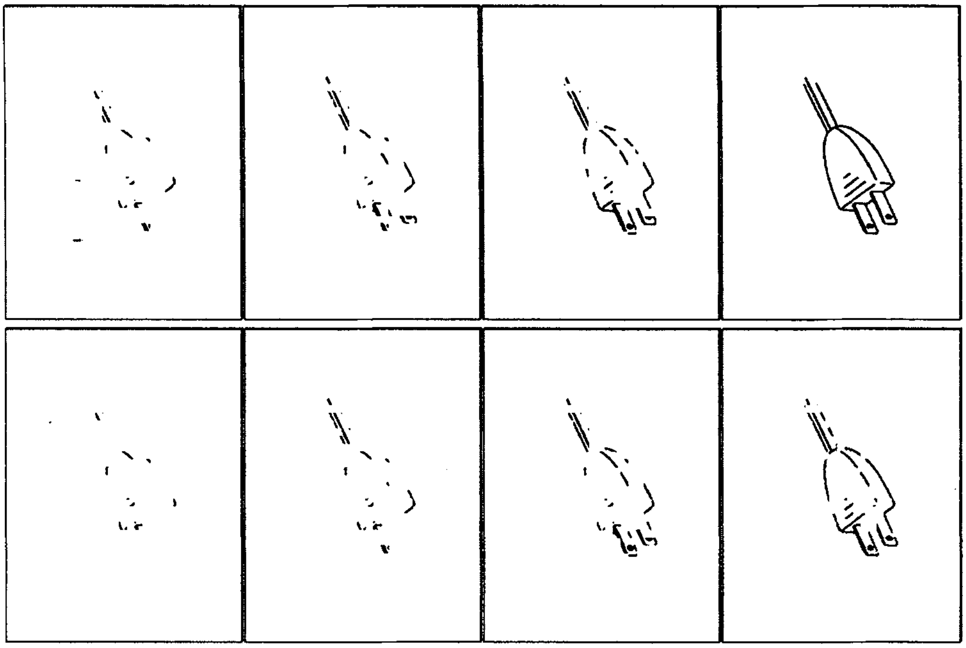

Figure 3. An example of the eight levels of completion used in the object completion test (picture-fragment completion) starting from the lower left side (the most incomplete, Level 1) to the upper right side (the most completed level, Level 8).

equally often as studied and nonstudied stimuli in each cell of the design.

Procedure. Participants were informed that they were participating in a (haptic or visual) perceptual investigation. At study, they were asked to name as quickly as possible pictures of the objects, real objects presented visually, or real objects presented haptically. After completing the study phase, all of the participants performed the same distractor task as in Experiment 1.

At test, all of the participants were asked to identify progressively less fragmented pictures as soon as possible, by pressing the space key of the keyboard when they identified the object. A prompt on the screen asked them to type the object's name on the keyboard. After 1.5 s without pressing the stop key, the next more complete version of the picture appeared on the screen automatically. If the name was incorrect, the computer beeped and the object at the next fragmentation level was automatically displayed. The procedure was repeated until the correct response was provided. On each trial, the level of fragmentation at which the stimulus was correctly identified was automatically recorded by the computer. After a 2-s pause, a new randomly selected stimulus was presented. Ten practice trials preceded the experimental trials. The orientation of the pictures was the one provided by Snodgrass and Vanderwart's (1980) norms. The experimenter monitored the participants and recorded falsely triggered responses (less than 2% of the trials).

After the implicit task, participants were allowed 2 min to write down the name of the objects studied during the first phase of the experiment. After completing the explicit task, participants were questioned on their awareness of the relationship between both tests. They were also asked about the specific moment at which they realized that some stimuli were repeated (before or during the test phase of the experiment). Finally, they were asked whether they had followed any strategy to remember the stimuli to improve performance in picture-fragment completion.

Results

We report first the results from the implicit test. The explicit memory test results are reported in the corresponding section of Experiment 2B.

Figure 4 (top) summarizes performance in picture-fragment completion, expressed as correct completion levels, as a function of the study conditions (pictures, haptic objects, visual objects) and the studied versus nonstudied item status. Following Snodgrass et al.'s (1987) assessment procedure, a trial was rated as 1 when the picture was identified at the most fragmented level (Level 1), as 2 when the item was identified at Level 2, and so on. When the object was identified at Level 8 (the completed stimuli), the trial was recorded as Level 8. When the picture was not identified even at Level 8, it was recorded as Level 9 (the mean number of errors was very low, 2%, and was not analyzed).

Several features of the results deserve attention. First, studied stimuli in all studied conditions were identified at a lower fragmented level than nonstudied stimuli. Second, the level of facilitation was similar whether the familiar objects were studied haptically or visually. Third, priming was higher when participants were presented with pictures at study than with real objects, either visually or haptically.

Two-factor mixed ANOVAs using completion level as the dependent variable with study modality as the between-subjects variable and item type as the repeated measure showed a reliable effect of item type; studied stimuli in all the study conditions were identified at a lower fragmented

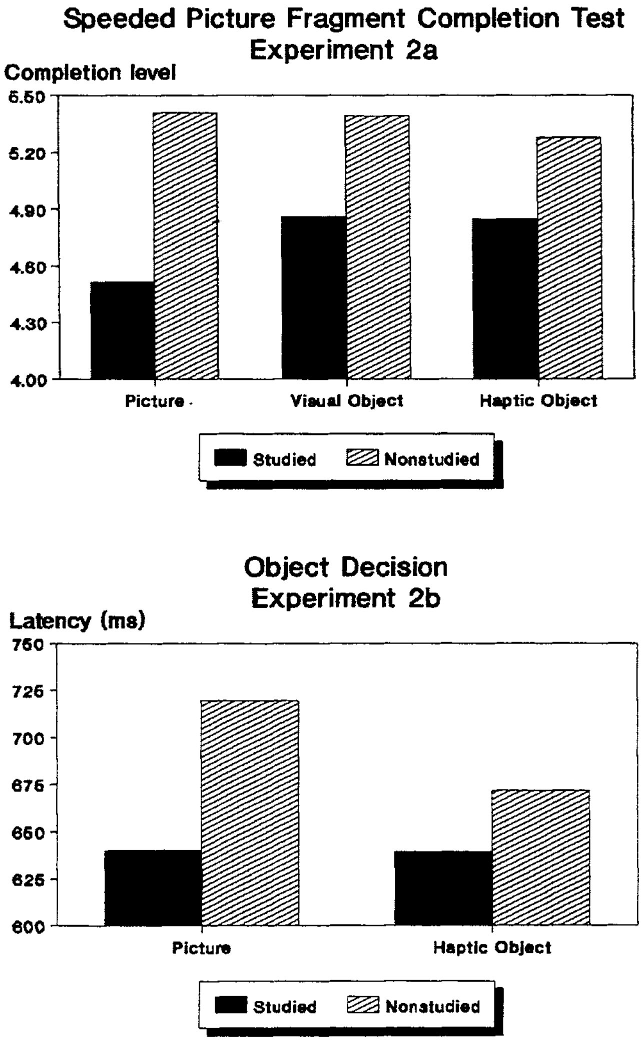

Figure 4. Top: Performance on the picture-fragment completion test in Experiment 2a, expressed as correct completion level as a function of type of encoded material (pictures, visual objects, and haptic objects). Bottom: Latencies (in ms) in the object–nonobject decision task in Experiment 2b, expressed as a function of type of encoded material (pictures or haptic objects) for studied and nonstudied stimuli.

level than nonstudied stimuli, showing a highly significant priming effect, $F_s(1, 33) = 116.41$, $MSE = 0.060$; $F_i(1, 63) = 66.95$, $MSE = 0.56$. The main effect of study conditions was not significant ($F < 1$), but the Study Condition $\times$ Item Type (studied vs. nonstudied) interaction was significant, $F_s(2, 30) = 5.91$, $MSE = 0.060$; $F_i(2, 126) = 7.90$, $MSE = 0.260$. Interaction comparisons (Keppel, 1982) showed that study pictures produced larger priming than study objects, $F_s(1, 33) = 6.58$, $MSE = 0.060$, but study visual and haptic objects produced equivalent levels of priming ($F < 1$). Priming (assessed by the difference between the study and nonstudied items) was greater when participants were presented with (intact) pictures of objects at study (0.896) than when they saw (0.531) or felt (0.432) real objects that did not differ. Processing pictures of objects at study may form picture-specific representations that can be matched with pictures at test producing larger priming.

Responses to the questionnaire showed that all of the participants noticed that the stimuli were repeated between the study and the test phase; only 8% of the participants indicated they suspected that the fragment-picture completion task was used as a memory task. Finally, 64% of the participants indicated that they had tried to use conscious strategies to perform well on the implicit test.

Experiment 2B

Experiment 2B was designed to gather further convergent evidence of cross-modal priming using a test that does not require a naming response. It could be the case that the cross-modal priming of Experiment 2A is present because the implicit memory task requires participants to name the stimuli. In contrast, to explore the conceptual nature of priming, we used an object decision task (see Kroll & Potter, 1984). Object decision judgments can be performed without access to the lexicon. In this case, the nature of priming would be perceptual although not necessarily low level.

As priming was more pronounced for pictures of objects than for 3-D visual objects, we continue with pictures in this experiment instead of using visual objects. At the same time, to keep exploring cross-modal priming, we also used haptic objects. Note that both visual and haptic object study conditions produced equivalent levels of priming. Thus, we decided not to use visual objects.

Method

Participants. Twenty-four new participants from the same sample pool participated in this experiment.

Materials and apparatus. The same familiar target stimuli as in Experiment 2A were used. However, as performance in the object-decision task is quicker than in the picture-fragment completion task, 32 additional nonstudied stimuli were added in the picture-fragment completion task to equate the time elapsed between the study phase and the explicit test. The nonobjects were a subset formed by 64 stimuli from Kroll and Potter (1984). Examples of the objects and nonobjects are displayed in Figure 5. The same equipment as in previous experiments was used.

Design. A 2 (study conditions: pictures vs. real objects explored haptically) $\times$ 2 (item types: studied vs. nonstudied items) mixed factorial design was used. In addition, the target stimuli were randomly divided into two subsets that were rotated across all experimental conditions. This manipulation produced a totally counterbalanced design.

Procedure. As in previous experiments, participants were tested individually in a quiet room under incidental memory conditions. Twelve participants were randomly assigned to each encoding condition (visual pictures or real haptic objects). No information was provided at any time that other tasks would follow the study phase.

During the study phase, participants were presented with a series of pictures or haptic objects. Participants in the visual study condition were told that a series of pictures depicting real objects would be presented on the computer screen and were asked to identify them as quickly and accurately as possible. After completing the study phase, participants performed the same distractor task

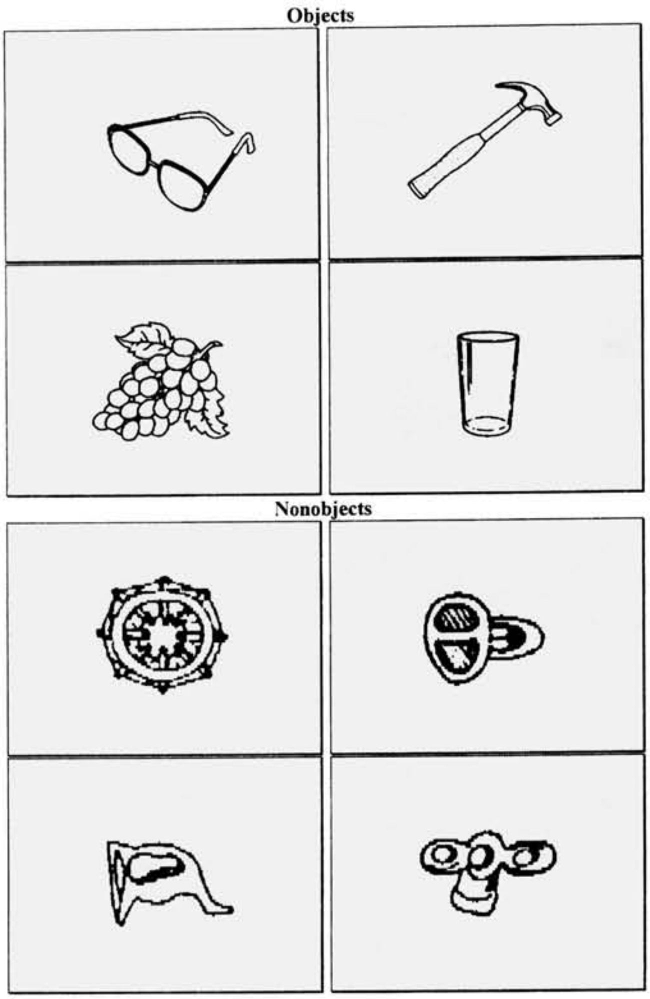

Figure 5. Examples of objects (top) and nonobjects (bottom) used in Experiment 2B.

as in previous experiments, followed by the implicit and then the explicit tests.

Implicit memory was assessed by the object-decision task (see Kroll & Potter, 1984; Srinivas, 1995). Participants were asked to respond yes if the picture corresponded to an object and no if the picture corresponded to a nonobject. Latencies were the main dependent variable and were recorded automatically by the vocal key. The experimenter introduced the oral responses through the keyboard and whether the trial was correct or incorrect. Nonobject trials were of no interest and were not entered in the analysis. The intertrial interval was approximately 3 s. The orientation of the pictures was the one provided by the Snodgrass and Vanderwart (1980) and Kroll and Potter (1984) norms.

On the free-recall test, participants were asked to write down for 2 min the name of the objects presented at the beginning of the experiment. Finally, participants were required to complete the same questionnaire as in Experiment 2A.

Results

Object-decision results are reported first, followed by the free-recall data corresponding to Experiments 2a and 2b. The mean latencies for the nonstudied stimuli were computed collapsing the 32 experimental nonstudied stimuli plus the 32 additional nonstudied stimuli (see *Materials and apparatus*).

Object–decision test. The main dependent variable was latency. Accuracy was very high; the mean percentage of errors was low (2.17%). The results corresponding to the object decision test are shown in Figure 4 (bottom) as a function of study condition (pictures vs. haptic objects) and item type (studied vs. nonstudied stimuli). Note that as in previous experiments, priming was significant in both study modalities. The overall reaction time for studied objects was lower than for nonstudied objects (639 vs. 695 ms, respectively), indicating substantial priming. Cross-exemplar priming (haptic objects to pictures) was smaller than within-modal priming (pictures to pictures; 33 and 79 ms, respectively).

Two-factor mixed ANOVAs with study modality as the between-subjects variable and item type as the within-subjects variable performed on latencies corresponding to correct responses confirm the results described above. The main effect of item type (studied vs. nonstudied items) was highly significant, $F_s(1, 22) = 36.75$, $MSE = 0.102$; $F_i(1, 63) = 21.90$, $MSE = 0.590$. Study condition was not significant ($F < 1$), but the Study Modality × Item Type interaction was significant. Cross-exemplar priming was significantly lower than within-modal priming; that is, naming real objects explored by touch at study produced lower priming than naming pictures, $F_s(1, 22) = 6.25$, $MSE = 0.102$; $F_i(1, 63) = 5.03$, $MSE = 0.660$. This pattern of results suggests that the physical features of the stimuli are important in repetition priming and are an example of specificity in priming.

Free-recall test. Figure 6 displays the combined results of the free-recall tests corresponding to Experiments 2a and 2b, expressed in terms of the percentage of stimuli correctly recalled minus intrusions, as a function of study condition. Intrusions were retrieved stimuli that were not presented during the study phase.

The ANOVA performed on the free-recall data corresponding to Experiment 2A showed a significant effect of study conditions, $F(2, 33) = 8.94$, $MSE = 77.630$. A post hoc Newman–Keuls test showed that studying pictures produced worse free recall (32% correct) than studying real objects, either visually or haptically (46% correct and 45% correct, respectively). The ANOVA conducted on the data from Experiment 2b showed the same pattern of results, $F(1, 22) = 9.83$, $MSE = 99.460$. Explicit memory was higher when participants studied real objects haptically (45% correct) than when they studied pictures of objects (30% correct).

As in Experiment 2A, the results from the questionnaire showed that all of the participants noticed that some stimuli were repeated. Furthermore, only 8% of the participants suspected that the object-decision task would be used as a memory test; nevertheless, only 16% of the participants informed that they had used conscious retrieval strategies to try to improve their performance in the implicit memory test.

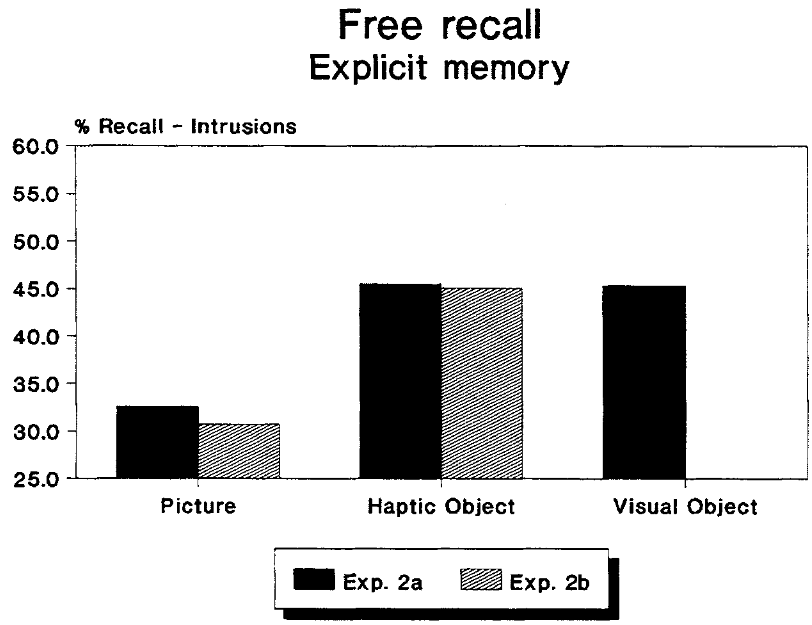

Figure 6. Free-recall results expressed as percentage of objects correctly recalled minus intrusions from Experiment (Exp.) 2a and Experiment 2b, as a function of study condition (picture, haptic object, and visual object).

Discussion

The central finding of Experiment 2 was the significant priming effects obtained in all the study conditions. The results from the two implicit memory tasks (picture-fragment completion and object decision) showed robust priming effects in cross-exemplars conditions as well as in within-modal conditions. The data indicated, however, greater priming when the stimuli were presented in the same exemplar in both phases of the experiment (as pictures) compared with conditions in which the exemplar of the items changed (from real objects presented haptically or visually to pictures of objects) from study to test. The decrement in priming observed might be due to several reasons, such as a change in the modality, a change in the exemplar of the object (see the introduction section), or, alternatively, a change in the angle at which the stimuli were shown at study and test. Further research is needed to disentangle these three possible interpretations.

It is important to note also that in both experiments there was a double dissociation between explicit and implicit memory tasks. Explicit memory performance was significantly enhanced after studying real haptic or visual objects as compared with studying line drawings, whereas the opposite pattern was true for implicit memory. Given that the implicit and explicit memory representations for real objects can be functionally dissociated, it seems unlikely that the implicit memory results are contaminated by explicit memory.

Regarding picture-fragment completion performance, the specific priming (the difference between same-modality same-exemplar and different-modality different-exemplar priming) is form specific and perceptual. However, it is important to note that priming was still significant even when the specific physical features of the stimuli changed, suggesting that there is another, more abstract component of priming that is not form specific. This component makes priming significant when a change in the specific perceptual features of the stimuli takes place from study to test. Although the baseline latencies for nonstudied stimuli across the two encoding conditions of Experiment 2B were uneven, notice that significant priming effects were obtained not only in the picture-fragment completion test but also in the object-decision test, in which it is unlikely that the lexicon needs to be accessed. Nevertheless, the difference in baselines made it more difficult to interpret adequately the less robust cross-exemplar priming than the within-modal priming. This result deserves further investigation.

A finding that deserves further discussion is that priming (0.90 m Experiment 2A) was lower than the priming (1.96 m) reported by Snodgrass et al. (1987). We attributed the discrepancy to two main differences in experimental designs. First, Snodgrass et al. used the same task at encoding and test whereas we used different tasks in both phases of the experiment. Second, and more important, Snodgrass et al. allowed participants to decide when the next completion level should be presented at the screen, whereas participants in our experiment were presented automatically with the next level of completion after 1.5 s without response. As Snodgrass et al. pointed out, the perceptual learning effect could depend on the use of explicit retrieval strategies or on the memory for names of the stimuli presented at study. The lower priming effect obtained in our experiment under time pressure suggests the possibility that our procedure might have been more successful in eliminating, or at least reducing, participants' explicit retrieval strategies while performing the implicit task. In any case, the stimulus presentation with fixed intervals seems to interfere with the explicit retrieval or the guessing rate. Furthermore, as priming was also found in object decision, the possibility of contamination from explicit memory is even lower. It seems improbable that participants in our experiment had used an explicit strategy when performing this speeded task.

In clear contrast to the results in the implicit memory tasks, Experiments 2A and 2B showed that explicit memory tests produced a different pattern of results than the implicit measures. Real objects, encoded either visually or haptically, yielded higher levels of episodic memory than line drawings. The results suggest that explicit memory is mediated by representations that specify the distinctive physical attributes of objects that are potentially useful in recalling particular objects studied either visually or haptically. Characteristics such as texture, temperature, or hardness that made the object distinctive are contained as part of the episodic representation. These results are consistent with the hypothesis that explicit memory for visually encoded objects includes information about shape as well as specific information that makes the object distinctive from other objects (e.g., Biederman & Cooper, 1992; Cooper et al., 1992). The present results extended previous visual findings to the haptic domain.

The double dissociations obtained in these experiments made also implausible the intentional recollection hypothesis.[2] This hypothesis has frequently been invoked to account for cross-modal priming (see McDermott & Roediger, 1994). If participants used explicit retrieval strategies to improve performance on the implicit memory tests, the results would have shown better performance after studying real objects, either haptically or visually, than after studying line drawings, as found in the free-recall test. In addition, the task order was always the implicit test followed by the explicit test.

Finally, the only difference between the answers to the questionnaires was in the question of whether participants had tried to retrieve information from the first phase of the experiment to improve performance on the implicit task. Three main arguments on the discrepancy between the responses to the questionnaires and the experimental results should be enumerated. First, even though the percentage of participants who responded affirmatively to this question was larger for those who performed the picture-fragment completion compared with those engaged in object decision (64% vs. 16%, respectively), the priming effects were qualitatively similar in both experiments. Second, although a larger percentage of participants said they tried to retrieve information in fragment completion than in object decision, the results from the explicit tasks showed exactly the same pattern in Experiments 2A and 2B. Third, if the "aware" participants tried to retrieve information consciously to improve performance on fragment completion, the actual performance on the implicit and the explicit tests would have shown the same pattern instead of the double dissociation actually found. In fact, the pattern of results was just the opposite. The discrepancy between the experimental data and the responses to the questionnaire suggests that both types of data depended on different processes. The data from the questionnaires might depend on participants' attributions, whereas the experimental data seem to be determined by mental representations and processes. This suggestion makes sense because fragment completion is a much slower task than object decision. Thus, participants performing the picture-fragment completion test may be biased to attribute performance to conscious processes. Richardson-Klavehn and Gardiner (1996, 1998) distinguished memory state of awareness (conscious vs. unconscious) from retrieval volition (voluntary vs. involuntary). The questionnaire data might reflect involuntary retrieval that is accompanied by conscious awareness.

Experiment 3

The main theoretical claim made in this article is that cross-modal object priming is mediated by structural, abstract object representations that are long-lasting. In the visual domain, Schacter et al. (1990a) found that the magnitude of priming for structurally possible objects was robust at a 1-hr delay and comparable with that observed after a delay of several minutes. Moreover, Ballesteros, Reales, Carrasco, and García (1997, 1999) also obtained robust priming effects in a visual study with familiar objects in which the delay between study and test was systematically manipulated up to a month. Experiment 3 was designed to see whether cross-modal priming between touch and vision is long-lasting. To determine whether the cross-modal priming effects observed in Experiment 1 persist across a longer delay, we assessed cross-modal and within-modal priming after a 0.5-hr retention interval. After the study phase (either visual or haptic), participants performed a speeded object naming test under immediate and 0.5-hr delayed conditions followed by the explicit memory test.

In this experiment, we used the procedures in Experiment 1 in which complete, cross-modal transfer was found between vision and touch. If the magnitude of cross-modal priming is similar to the magnitude of within-modal priming at 0.5-hr delay, the hypothesis that cross-modal priming is due to the structural object descriptions would be supported.

[2] In an additional experiment, 12 participants named real objects explored by touch at study followed by visual speeded word-fragment completion (using the same procedure as in picture-fragment completion) and free-recall tests. The results showed no priming at all. Explicit recall showed the same level of recall as in Experiments 2A and 2B. However, responses to a questionnaire showed that nearly all of the participants noticed that the implicit test contained some words denoting objects previously explored by touch. Although participants also believed that their performance was better for these words, priming data do not support this attribution. The findings do not support either the lexical or the explicit contamination hypothesis.

Method

Participants

Thirty-two new observers from the same pool as in the previous experiments participated in this experiment.

Material, Equipment, and Design

The target stimuli were 64 familiar objects. Four more objects were added to those used in Experiment 1. Ten more objects were used as practice trials. The apparatus was the same as in Experiment 1.

A 2 (study modality: vision vs. touch) × 2 (delay conditions: immediate vs. delayed) × 2 (item types: studied vs. nonstudied) mixed factorial design was used. The first variable was the between-subjects whereas the last two were the within-subjects variables. Sixteen participants were randomly assigned to each of the two study modalities. In addition, the 64 target objects were divided randomly in two sets of 32 stimuli each, which appeared equally often as studied and nonstudied. These two sets were further subdivided in two subsets of 16 stimuli each, which appeared equally often in the nondelayed and delayed conditions.

Procedure

Observers participated in the same study phase as in Experiment 1. Participants were presented with 32 objects either visually or haptically, according to the experimental condition. Those in the haptic study condition were allowed 5 s to explore each object with both hands. The same exploration time was allowed to those participants in the visual encoding condition. Observers were asked to use the whole 5 s to be able to judge as accurately as possible the object's volume on a 5-point scale. We decided to use only the physical (shallow) encoding task because Experiment 1 showed similar significant priming effects under shallow and deep encoding in both cross-modal and within-modal conditions.

At test, all participants performed a speeded visual object-naming test. They were shown the target objects through the liquid crystal window of the apparatus. During this test, 32 stimuli (16 studied and 16 nonstudied) were presented after the study session (immediate items). Immediately thereafter, they performed a Stroop-like task that lasted 0.5 hr. Following a 5-min break, all of the participants performed the visual naming test with the other 16 studied and 16 nonstudied objects. The two sets of 32 stimuli were rotated through all experimental conditions, producing a counterbalanced design in which each stimulus set appeared equally often as studied and nonstudied stimuli in each cell of the design. Response naming time was recorded on each trial from the time the window allowed the observer to see the object until the onset of the oral response. Finally, as in Experiment 2, after completing the implicit task participants performed a free-recall test. They were allowed 2 min to write down the name of the objects studied during the first phase of the experiment.

Results

As in previous experiments, the results corresponding to the performance on implicit and explicit memory tasks were analyzed separately.

Object Naming

Figure 7 displays the results from the implicit memory task as a function of study modality (vision or touch), delay condition (immediate or delayed), and item type (studied or nonstudied). The main dependent variable was latency, but accuracy was also reported to check for speed–accuracy

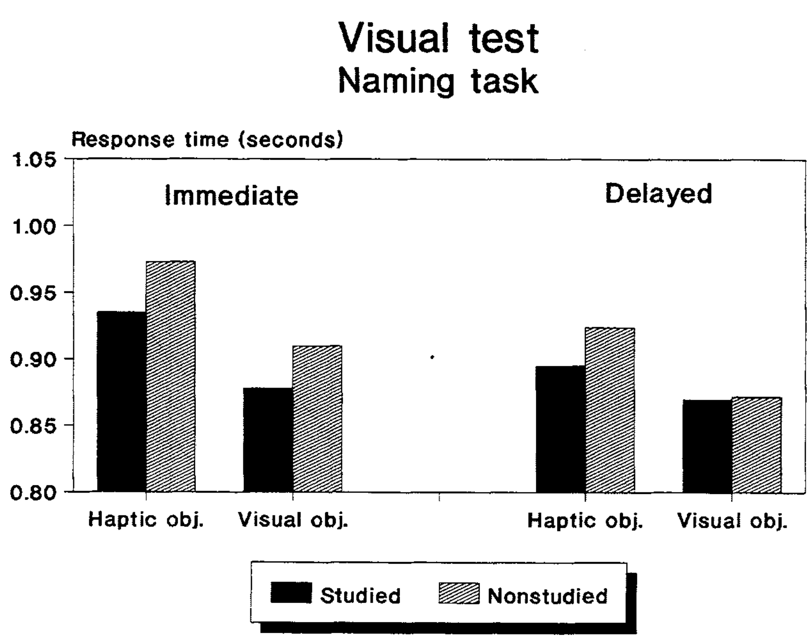

Figure 7. Response time (in seconds) in the visual object (obj.) naming test as a function of study modality (touch or vision) and delay conditions (immediate or delayed) and item type (studied or nonstudied) in Experiment 3.

trade-offs. The main percentage of errors was similar for the studied objects and for the nonstudied objects (5.25% vs. 4.98%). The difference was not significant, and there was no speed–accuracy trade-off between accuracy and latency.

The latency data showed that there is a facilitatory effect. Studied objects were named on average 25 ms faster than nonstudied objects. Furthermore, this facilitatory effect was present not only in the within-modal condition (17 ms) but also in the cross-modal condition (33 ms). Furthermore, the delay between study and test did not eliminate cross-modal priming. In fact, when participants studied objects haptically and were tested visually, the facilitation (29 ms) was larger than in the within-modal condition (2 ms).

Three-factor mixed ANOVAs were performed on latencies with study modality as the between-subjects variable and delay condition and item type as the within-subjects variables. Only latencies corresponding to correct responses entered the ANOVAs. The analyses confirmed the previous description. Studied objects either visually or haptically were named faster than nonstudied objects at the implicit visual test. The main effect of item type was significant, $F_s(1, 30) = 11.21$, $MSE = 0.179$; $F_i(1, 59) = 5.61$, $MSE = 0.838$. Studied objects were named reliably faster than nonstudied objects (0.89 s vs. 0.92 s). The main effect of study modality was not statistically significant ($F = 1.4$) but delay was, $F_s(1, 30) = 4.83$, $MSE = 0.744$; $F_i(1, 59) = 4.99$, $MSE = 1.284$. The delayed implicit memory test was performed on average 33 ms faster than the immediate implicit test. This effect may be due to a learning effect. More important, the Study Modality × Item Type interaction was not significant ($F < 1$), showing a complete cross-modal transfer between modalities. The Delay Condition × Item Type interaction was also not significant ($F < 1$), showing that delayed cross-modal facilitation was not smaller than immediate cross-modal facilitation and these did not differ from within-modal facilitation. No other effects nor any other interaction was significant.

An additional ANOVA conducted on accuracy did not show any significant effect of item type (error rates 5.38% and 4.98% for studied and nonstudied, respectively), study modality (5.50% and 4.60%, for touch and vision, respectively), or any interaction (all Fs < 1).

Free-Recall Test

Figure 8 displays the results from the explicit memory test, expressed as the percentage of stimuli correctly recalled minus intrusions, as a function of study modality and temporal interval between the two parts of the implicit naming test: the items presented immediately after study (corresponding to the immediate condition) and the items presented later (corresponding to the 0.5-hr delayed condition) and just before the free-recall task. Free recall was higher when participants studied objects haptically (28% correct) than when they studied objects visually (16% correct). Furthermore, free recall was higher for those items of the naming task that were presented in a short temporal interval with the explicit task (delayed condition) than for those items that were presented in a long temporal interval (immediate condition): 26% versus 17%, respectively.

These results were confirmed by a three mixed-factorial ANOVA with study modality as the between-subjects variable and delay and item type as the within-subjects variables. The main effect of study modality was significant,

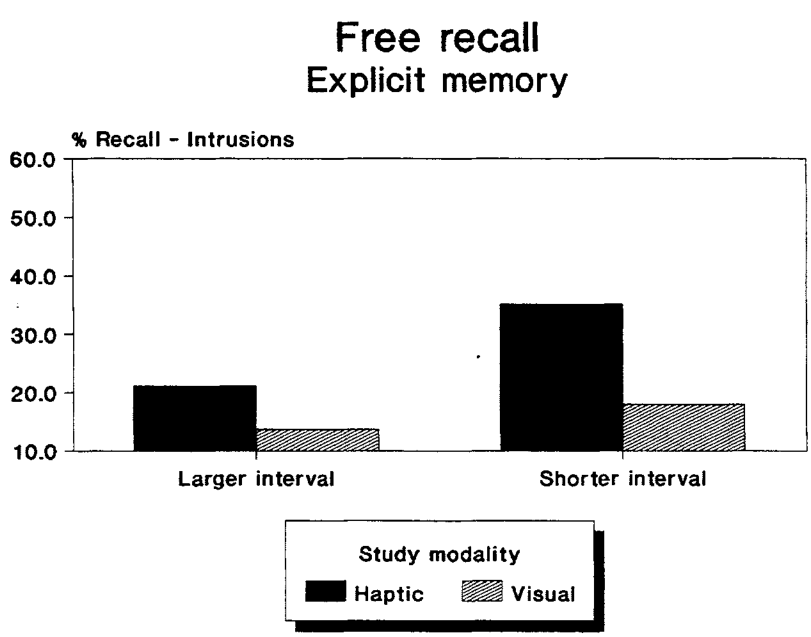

Figure 8. Free-recall results expressed as percentage of objects correctly recalled minus intrusions from Experiment 3, as a function of study modality (haptic or visual) and the temporal distance between implicit and explicit tests.

$F_s(1, 30) = 5.99$, $MSE = 0.404$. In addition, the main effect of temporal interval between the implicit test items and free recall was also significant, $F_s(1, 30) = 14.14$, $MSE = 0.953$. Those objects that were shown again just before the explicit test were recalled better than those that were shown earlier (just after study). Moreover, the interaction between study modality and temporal interval between the implicit and the explicit tests was also significant, $F_s(1, 30) = 4.26$, $MSE = 0.953$; the interaction indicates that participants recalled more haptically than visually studied objects but the advantage was more pronounced in the short than in the long delay.

Discussion

This experiment demonstrated a complete cross-modal transfer between touch and vision, thus replicating the main and new result obtained in Experiment 1. Studied objects were named faster than nonstudied objects independently of study modality; that is, the fact that the objects were presented at study at the same modality (vision) or at different modality (touch) had no effect on priming. Furthermore, the present experiment showed that both cross-modal priming and within-modal priming resist delay. The magnitude of priming in this condition is comparable with that observed after no delay. As far as we know, this finding has not been demonstrated before. We can say confidently that cross-modal touch to vision priming lasts at least for 0.5 hr. The main purpose of this experiment was to use delay to reveal the temporal nature of the underlying representations responsible for cross-modal facilitation between vision and touch. The complete transfer between these modalities found after delay is consistent with the hypothesis that abstract structural representations underlying cross-modal priming are long-lasting.

Another finding from Experiment 3 needs to be underlined. To our knowledge, this is the first time that using exclusively a physical (shallow) encoding task has shown complete cross-modal priming. In Experiment 1, we found the same level of priming when observers encoded the objects' volume, a physical dimension, than when they encoded the objects semantically. However, the levels-of-processing variable was manipulated within subjects. Thus, participants studied some of the objects physically and some semantically. The absence of an effect of levels of processing suggested that the representations that support the priming were presemantic. The significant cross-modal priming shown in Experiment 3 using only shallow encoding not only replicates these findings of Experiment 1 but also supports the presemantic nature of object repetition (within-modal and cross-modal) priming.

An aspect of the present results was unanticipated. We observed that after both visual and haptic study, delayed judgments were made faster than immediate judgments. We attribute these results to the within-subjects character of the delay variable that may be attributable to a learning effect. Participants may have learned from the immediate trials to make faster responses after a 0.5-hr delay ($M = 33$ ms).

The results from the explicit memory test are consistent with the memory literature. It is well known that explicit memory benefits from repetitions and is impaired as a function of delay. Our data showed that the repetition of the stimuli in the implicit test just before the explicit test improves free recall. The explicit test also showed that when observers studied the real objects haptically, free recall was higher than when they studied the objects visually. Perhaps haptic exploration allows participants to encode physical attributes (such as texture, temperature, and hardness) that made the object distinctive. The higher free recall for haptically studied objects compared with visually studied objects obtained in Experiment 3 can be explained by the larger effort necessary to rate the object's volume through touch than through vision. Furthermore, haptically studied objects were recalled better than those items presented at the implicit test just before free recall (implicit delayed condition). The results differed from those obtained in Experiment 2 in which haptically and visually studied objects were equally recalled. This finding might be due to the experimental design. Although in both experiments free recall was performed after the implicit memory test, in this experiment some of the studied objects were presented visually immediately after study (immediate visual implicit test). Then, observers participated in a very demanding 0.5 hr of Stroop-like attentional task, after a 5-min break by the visual implicit delayed test that was performed just before free recall. It is possible that the Stroop-like task interfered more with visually than with haptically studied objects. Furthermore, the study tasks used in Experiments 2 and 3 were also different. In Experiment 2 at study participants named the objects presented either visually or haptically. On the other hand, in Experiment 3 they performed a shallow encoding task in which they were required to rate the object's volume instead of naming the object. This will explain the fact that free recall was higher in Experiment 2 than in Experiment 3. It is well known that semantic encoding produces better explicit memory.

General Discussion

This study yielded several main results. First, implicit memory for real objects evaluated by a speeded naming task showed an equivalent perceptual facilitation for haptically and for visually studied objects in both within-modal and cross-modal conditions (Experiments 1 and 2). Furthermore, a levels-of-processing manipulation did not have an effect on either within-modal or cross-modal priming (Experiment 1). When participants at study performed a physical or shallow encoding task, total transfer was found between modalities (Experiment 3). Second, picture-fragment completion and object-decision tests showed highly significant priming effects; however, facilitation was more pronounced when the perceptual features of the stimuli at study and test matched (within-modal same-format priming) than when these features changed from study to test (cross-modal different-format priming; Experiments 2A and 2B). That is, larger priming was found when participants were presented with line drawings at study and test than when they were presented with visual or haptic real objects, which did not differ. It is interesting to note that free-recall tests produced exactly the opposite results. Namely, haptic and visual objects produced better explicit free recall than line drawings (Experiments 2A and 2B). Third, the double dissociations obtained between implicit and explicit memory tasks suggested that implicit memory measures were not contaminated by explicit memory (Experiments 2A and 2B). Fourth, the delay between study and test did not affect differentially cross-modal and within-modal priming as the same priming was observed irrespective of delay. Cross-modal and within-modal priming were long-lasting. Fifth, a delay filled with a very demanding attentional Stroop-like task produced higher free recall for objects studied haptically than visually (Experiment 3).

Theoretical Explanations of the Dissociations Between Implicit and Explicit Cross-Modal and Within-Modal Memory Tests

Repetition priming effects are considered modality specific (for reviews, see Roediger & McDermott, 1993; Schacter et al., 1993). However, the studies reported so far have selected the visual and auditory modalities and verbal materials as stimuli. The only exception we are aware of is a study by Easton, Srinivas, and Greene (1997) in which equivalent cross-modal and within-modal priming for words presented to touch and vision were found. In the haptic condition, words were presented as a raised line drawing on a card. Easton et al. attributed the modality null effect to the geometric coding of verbal information by vision and touch.

Experiment 1 showed that speeded object naming by vision or by touch was facilitated evenly when objects were studied either by vision or by touch. To our knowledge, this finding is the first demonstration of complete cross-modal transfer between two sensory modalities specially tuned to deal with 3-D objects (see Footnote 1). Furthermore, the finding that a levels-of-processing manipulation did not influence priming is consistent with a large number of findings in the visual domain for novel objects (Schacter et al., 1990a, 1990b, Experiment 2) and verbal materials (e.g., Craik, Moscovitch, & McDowd, 1994; Roediger, Weldon, Stadler, & Riegler, 1992; Srinivas & Roediger, 1990, Experiment 3). Moreover, priming effects on three-line raised patterns identified by touch were also not affected by elaborative (deep) processing at study (Srinivas, Greene, & Easton, in press).

Experiment 2 showed that the three encoding conditions (encoding line drawings, haptic objects, or visual objects) produced significant priming. Moreover, studying the same line drawings that were used at test produced more priming than studying visual or haptic objects, which did not differ. The finding that line drawings produce more specific priming than visual or haptic objects suggests that the mental representations provided by pictures are not as full structural descriptions as those provided by real objects presented to either vision or touch. A second possibility is the generation of two types of perceptual representations: (a) volumetric, high-level structural descriptions that are shared by both modalities (vision and touch), and (b) perceptual, low-level, modality-specific descriptions. On this account, the larger priming effects obtained in within-modal conditions might be the result of the better match of the picture descriptions. A third possibility is that the highly significant but lower priming obtained in Experiment 2 is due to the exemplar change plus the modality change. Further research would clarify the plausibility of these alternatives.

From a multiple memory-systems framework (e.g., Cooper et al., 1992; Schacter, 1994; Schacter et al., 1990a, 1990b), priming occurs at the structural description level, whereas explicit memory is based on the episodic representations that are sensitive to perceptual, contextual, spatial, temporal, semantic, and structural shape-based information about objects. In vision, the memory-systems approach has interpreted certain insensitivities in priming as caused by the structural descriptions that are highly sensitive to the shape and structure of the stimuli but not to other physical dimensions such as size or parity. On the other hand, explicit memory is sensitive to these attributes (see Biederman & Cooper, 1992, for familiar objects; Cooper et al., 1992, for unfamiliar objects).

Structural Descriptions Hypothesis

The complete cross-modal transfer between vision and touch (Experiments 1 and 3) coupled with the finding that their supporting representations are long-lasting (Experiment 3) can be interpreted as suggesting that cross-modal implicit memory for real objects is mediated by object representations that are presemantic, structural, long-lasting, and somehow abstract. The hypothesis that a comparable structural description of a real object is activated after visual or haptic encoding is proposed to account for the complete transfer between the studied modalities. As pointed out in the introduction, vision and haptics are both modalities finely tuned to process an object's shape and structure and to detect small differences in shape. So, once activated, these structural representations might be responsible for the complete cross-modal transfer effects. Priming involving object identification at a basic level seems to be sensitive to high-level perceptual characteristics important to establish object identity (see Cave et al., 1996). These characteristics might well be shape and structure.

Our findings suggest that repetition priming is not totally modality specific but is sensitive to high-level structural features that define object shape. These features are essential for basic-level object identification. Real objects allow the construction of structural descriptions that, once built, can be accessed either by vision or by touch. On the other hand, line drawings created representations specific to the modality (vision in this case) that produced a better match when the same type of perceptual information was presented at test. The hypothesis is congruent with the idea that not only implicit memory for visually presented objects but also cross-modal vision and touch are based on perceptual mechanisms related to the extraction of object shape (e.g., Biederman & Cooper, 1991a; Biederman & Gerhardstein, 1993; Cave et al., 1996; Cave & Squire, 1992; Srinivas, 1993, 1996).

On the other hand, the results from the current explicit memory tests as well as other findings discussed earlier indicate that the mental representations that support explicit memory are sensitive to all the perceptual, contextual, spatial, temporal, semantic, and structural shape-based information about objects. Explicit memory is, therefore, sensitive to lower level perceptual information characteristics of visual objects such as size, right–left reflection, color, contrast polarity, and illumination (e.g., Cooper et al., 1992; see also Cave et al., 1996; Srinivas, 1996). Our explicit memory results suggest that when objects are explored by active touch, the episodic memory system may also be sensitive to other features of objects. These features may be shape, size, temperature, hardness, and texture.

Some researchers have questioned whether all the priming effects obtained in implicit memory tasks are due to perceptual processes. The existence of cross-modal (visual–auditory) priming has been attributed to the participation of conceptual, semantic, and strategic processes (the explicit contamination hypothesis) on visual implicit memory tests (e.g., Hirshman et al., 1990; Keane et al., 1991). However, other researchers have provided support for the hypothesis that these effects on auditory stem-completion tests are due to phonological processes (e.g., McClelland & Pring, 1991). Note, however, that the explicit or voluntary contamination hypothesis conflicts with the finding that patients with amnesia show intact cross-modality priming (see Graf et al., 1985). Furthermore, the contamination hypothesis conflicts also with results in the verbal domain showing that cross-modal priming in normal adults presents no advantage of deep over shallow processing when the shallow encoding task requires lexical access (e.g., Craik et al., 1994; Richardson-Klavehn & Gardiner, 1996). Richardson-Klavehn and Gardiner (1998) assessed priming with an incidental word-fragment completion test and found no advantage of semantic over phonemic study. Furthermore, a priming deficit was found following graphemic study.

Results from a new experiment (see Footnote 2) do not support the lexical hypothesis. At study, participants in our experiment named a series of familiar objects presented haptically followed by incidental speeded word-fragment completion and free-recall tests. Even though participants at study directed their attention to the stimuli as lexical units, priming was not found when they were presented with the corresponding fragmented words. The finding ruled out the lexical hypothesis. It is unlikely that the open or covert object naming at study would be responsible for the cross-modal priming observed. On the contrary, the results suggest that a basic determinant for cross-modal priming in vision and touch is the activation of invariant object structural descriptions between study and test. So, when objects were presented at study and implicit memory is assessed with words denoting these objects, facilitation was not found at all. The reason might be that in this situation there is no correspondence between the objects' structural descriptions and their words.

As suggested by Schacter (1994), the presence of cross-modal visual–auditory priming does not necessarily mean the involvement of conceptual processes in priming. The following results of the present study argue against the idea that the facilitation shown in the implicit tests is not perceptual. First, a levels-of-processing manipulation in the naming task was not significant (Experiment 1). Second, the double dissociation obtained between the two implicit tests and free recall made it highly improbable that priming was due to semantic factors (Experiment 2). Third, the fact that shallow encoding produced significant cross-modal and within-modal priming effects contradicted the nonperceptual nature of repetition priming (Experiment 3). Our results agreed with those from a number of studies that have manipulated the delay between study and test (Craik et al., 1994; Jacoby & Dallas, 1981; Roediger & Blaxton, 1987). These studies as well as the results from our Experiment 3 have not found a Modality × Delay interaction.

In summary, the present experiments investigated real-world objects and data-driven visual and haptic implicit memory tests performed in within-modal as well as in cross-modal conditions. Results showed that modality shifts from study to test sometimes reduced but did not eliminate priming. Cross-modal priming was significant in all three experiments; however, studying pictures produced higher priming than studying haptic or visual objects when pictures were used at test. That is, encoding real objects haptically or visually produced significant, although lower, priming than encoding pictures. Our results revealed that although vision and haptics are both well suited to process information about an object's shape and structure, as well as to deal with real objects, each modality contributes specialized information about these objects. At the same time, the two modalities also afford converging, common, more abstract representations that participate in both implicit and explicit memory tasks.

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