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IMPLICIT MEMORY: A Selective Review

*Daniel L. Schacter, C.-Y. Peter Chiu, and
Kevin N. Ochsner*

Department of Psychology, Harvard University, Cambridge,
Massachusetts 02138

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INTRODUCTION

The investigation of human memory has undergone a major transformation during the past decade, characterized by Richardson-Klavehn & Bjork (1988) as a "revolution in the way that we measure and interpret the influence of past events on current experience and behavior . . ." (pp. 476-77). It is not clear whether this transformation should be viewed as a paradigm shift, as Kuhn (1962) suggested, or, more modestly, as the emergence of a new subarea of research. What does seem clear, however, is that the "revolution" has already yielded, and will continue to yield, an outpouring of new data and ideas concerning the nature of memory.

The scientific substance of this revolution turns on a distinction between two different ways in which memory for prior experiences can be expressed, most frequently referred to as explicit and implicit memory, respectively (Graf & Schacter 1985; Schacter 1987). Explicit memory entails intentional or conscious recollection of previous experiences. In a typical explicit memory experiment, subjects are initially shown a series of words, pictures, or some other set of to-be-remembered materials. Later, they are given a recall or recognition test, in which they must think back to the study episode in order to produce or select a correct response. The vast majority of studies on human memory have, until recently, conformed to this paradigm; theoretical ideas about memory have, with few exceptions, addressed explicit remembering. Implicit memory, by contrast, entails a facilitation or change in test performance that is attributable to infor-

mation or skills acquired during a prior study episode, even though subjects are not required to, and may even be unable to, recollect the study episode. Implicit memory is assessed by examining the impact of study episodes on subsequent performance of tasks that do not require recollection of those episodes, such as completing a fragment of a word, choosing which of two stimuli they prefer, or reading inverted text.

Given the established tradition of research on explicit memory in cognitive psychology and neuropsychology, it took a series of striking findings to shift attention to implicit memory. By the end of the 1970s, evidence already existed that patients with organic amnesic syndromes could show substantial and, occasionally, normal levels of performance on various tests that would now be characterized as implicit memory tasks, such as motor skill learning (Milner et al 1968) and completion of fragmented words and pictures (Warrington & Weiskrantz 1974)—despite the apparent absence of any recollection for having previously performed the tasks. During the early and mid-1980s, many studies were published that confirmed, extended, and clarified these observations of spared implicit memory in amnesic patients (e.g. Cohen & Squire 1980; Graf et al 1984; Moscovitch 1982; Schacter 1985). At about the same time, several studies with normal, nonamnesic subjects revealed surprising dissociations between implicit and explicit memory: Experimental variables affected the two forms of memory in different, and even opposite, ways (Graf et al 1982; Jacoby & Dallas 1981; Tulving et al 1982), and statistical independence between implicit and explicit task performance was observed (Jacoby & Witherspoon 1982; Tulving et al 1982). These findings led to various theoretical proposals concerning the mechanisms involved in implicit memory and stimulated a virtual avalanche of research that explored numerous aspects of the phenomenon.

We should emphasize that the term “implicit memory” is a descriptive label that refers to one way in which the influence of past experiences can be expressed in subsequent task performance—unintentionally and without conscious recollection of a learning episode. Other, less-frequently used descriptive labels with similar meanings include memory without awareness (Jacoby & Witherspoon 1982), indirect memory (Johnson & Hasher 1987), and nondeclarative memory (Squire 1987). Several different manifestations of implicit memory have been investigated in the experimental literature. Perhaps the most extensively studied implicit memory phenomenon is that of repetition, or direct priming, in which exposure to a word or object on a study list facilitates its subsequent identification when degraded perceptual cues are provided (Tulving & Schacter 1990). Various types of perceptual, motor, and cognitive skill learning can also be considered expressions of implicit memory, in that they can occur

without reference to, or recollection of, prior learning episodes. At an operational level, the main differences between priming and skill learning are that the former phenomenon is typically observed after a single study trial or small number of study trials and reflects memory for specific items, whereas the latter is typically observed after numerous study trials and need not involve memory for particular items.

In addition to priming and skill learning, other manifestations of implicit memory have also been studied, including the biasing effects of previous experience on various types of perceptual, cognitive, affective, and even social judgments (e.g. Bargh 1989; Jacoby et al 1989; Kunst-Wilson & Zajonc 1980; Mandler et al 1987); classical conditioning in amnesic populations (e.g. Daum et al 1989; Weiskrantz & Warrington 1979); and learning of grammatical and other kinds of rules (Kinsbourne & Wood 1975; Knowlton et al 1992; Reber 1967). We focus here on priming, because it has been the most thoroughly investigated implicit memory phenomenon and the primary concern of most theoretical views of implicit memory. However, we consider briefly literature on skill learning, as well as the relation between priming and skill learning. The review also focuses on research from the past five years, because several reviews deal thoroughly with earlier research (cf. Richardson-Klavehn & Bjork 1988; Roediger 1990; Schacter 1987).

The principal message of the review is straightforward: Research on implicit memory has provided strong evidence for the hypothesis that memory is not a unitary entity, but is instead composed of separate, yet interacting, systems and subsystems. Some of the functional characteristics of these systems and subsystems have been delineated, and empirically based ideas about their neural basis are beginning to emerge.

PRIMING: DATA AND THEORY

We first review experimental findings concerning the nature of priming and then consider theoretical interpretation of the data. The empirical review is divided into three main sections, which correspond to three types of priming that have been most often studied: visual word priming, visual object priming, and auditory word priming. The great majority of studies have investigated visual word priming. Within each section, we first consider research on normal subjects and then turn our attention to studies of various memory-impaired populations.

Visual Word Priming

Four main experimental paradigms have been used to investigate visual word priming: stem completion, in which subjects are given the three letters

with multiple possible completions and asked to provide the first word that comes to mind [e.g. for__ (forest)]; fragment completion, in which word fragments with one or two possible completions are provided with similar instructions [e.g. a-a-i-n (assassin)]; word or perceptual identification, in which target items are exposed for brief durations (e.g. 35 ms), and subjects attempt to identify them; and lexical decision, in which subjects are shown letter strings that constitute real words or nonwords (e.g. flig) and are asked to make a word/nonword decision as quickly as possible. *On the first three tasks, priming is indicated when subjects complete or identify more studied than nonstudied items; on the fourth task, priming is indicated when subjects make lexical decisions about studied items more quickly than about nonstudied items.*

STUDIES OF NORMAL SUBJECTS A key finding from research in the early 1980s was that manipulating level or depth of encoding of target items during a study task had little effect on priming, despite large effects on explicit memory. That is, semantic study tasks that focus subjects' attention on meaningful properties of a word (e.g. judging the semantic category to which a word belongs) produced much higher levels of explicit memory than did nonsemantic study tasks that focus attention on a word's physical features (e.g. judging whether it has more vowels or consonants). However, the two types of study tasks yielded comparable levels of priming (Graf et al 1982; Graf & Mandler 1984; Jacoby & Dallas 1981). More recent studies have replicated and extended this phenomenon on a variety of tasks (cf. Bowers & Schacter 1990; Graf & Ryan 1990; Hashtroudi et al 1988; Roediger et al 1992; Schacter & McGlynn 1989). This finding is important because (a) it suggests that different processes are involved in priming and explicit memory and provides theoretical clues concerning the nature of those processes, and (b) it indicates that priming effects on implicit memory tasks in normal subjects should not be attributed to the "surreptitious" use of explicit memory strategies. With respect to the latter point, when college students participate in implicit memory experiments, there is always the possibility that they (in contrast to amnesic patients) may "catch on" concerning the relation between the implicit task and the prior study list, and make use of their explicit memory abilities to enhance task performance—that is, they may turn a nominally implicit task into a functionally explicit one. However, this kind of "contamination" from explicit memory is ruled out when an experimental manipulation, such as depth of study processing, has different effects on priming and explicit memory under conditions in which the same nominal cues are provided on the two tests, and only test instructions are varied: If subjects are engaging in explicit retrieval on an implicit test, then they should show higher levels

of performance following semantic than nonsemantic encoding tasks (see Schacter et al 1989, for further discussion; Jacoby 1991, for another approach to the issue). Indeed, Bowers & Schacter (1990) found that subjects who were entirely unaware of the relation between the completion task and the prior study list (as assessed by a post-test questionnaire) showed robust priming effects of equivalent magnitude following semantic and nonsemantic encoding tasks. These findings indicate that it is possible to obtain dissociations between implicit and explicit memory in normal subjects that are similar to those observed in amnesic patients.

Effects of encoding processes on implicit memory have also been examined in conjunction with a phenomenon known as the generation effect—the observation that explicit memory for words that were generated at the time of study (e.g. political killer—assa-n) is typically more accurate than for words that were simply read during the study task (political killer—assassin; e.g. Slamecka & Graf 1978). A striking reversal of this generation effect on the word identification task was reported initially by Winnick & Daniel (1970) and then by Jacoby (1983): Priming effects were greater in the read than in the generate condition; in fact, significant priming was not observed in the generate condition. Although this finding was seized upon as theoretically crucial by some (Jacoby 1983; Roediger et al 1989), it is now clear that conditions exist in which priming can be higher for generate than for read items (Masson & Macleod 1992; Toth & Hunt 1990). Gardiner and colleagues have reported a series of studies in which fragment completion priming benefited from target generation during a study task (Gardiner 1988; Gardiner et al 1989), even with subjects who are “test unaware,” as described earlier (Gardiner 1989). Importantly, however, such generation effects tend to be observed only when subjects are given the identical fragment at study and test (e.g. subjects generate assassin from political killer—a-a-in during the study task, and are given a-a-in at test). Generation benefits are reduced or absent when subjects are given different fragments at study and test (e.g. political killer—ss—ss—followed by a-a-in), thereby suggesting that priming can be highly specific to the perceptual form of target items.

This latter issue—the extent to which priming effects reflect the acquisition of specific perceptual information about target words—has received a great deal of experimental attention. It has been established beyond dispute that visual word priming is largely modality specific: Auditory presentation of target materials reduces and sometimes eliminates priming on stem completion (Graf et al 1985b), fragment completion (Donnelly 1988; Roediger & Blaxton 1987), word identification (Hashtroudi et al 1988; Jacoby & Dallas 1981), and lexical decision (Scarborough et al 1979) tasks. A similar pattern of reduced or absent priming is observed when

subjects study pictorial equivalents of words (e.g. Weldon & Roediger 1987). And, there is little or no cross-language priming when bilingual subjects study a word in one language and are tested with same-meaning but different-form words from another language (Durgunoglu & Roediger 1987; Gerard & Scarborough 1989; Kisner et al 1984; Smith 1991, Experiment 2; but see Experiment 1).

Although the conclusion that visual word priming is largely modality specific seems inescapable, there is a good deal more uncertainty and controversy concerning the extent to which priming is specific to the precise surface form of a target word. Gardiner's (1988, 1989) work on generation effects in fragment completion shows such specificity, and Hayman & Tulving (1989) have provided related evidence for "hyperspecific" priming of fragment completion. Several studies have indicated that priming effects are reduced when the case of words is changed between study and test (e.g. uppercase to lowercase; Roediger & Blaxton 1987a; Scarborough et al 1977) or when words are studied and tested in different typographies (Jacoby & Hayman 1987). However, other experiments have failed to find evidence of such format-specific priming (e.g. Carr et al 1989; Clarke & Morton 1983; Tardif & Craik 1989; for review and discussion, see Carr & Brown 1990; Jacoby et al 1992; Kirsner et al 1989; Roediger & Blaxton 1987a; Schacter 1990; Whittlesea 1990).

Several recent studies have taken steps toward resolving the apparent inconsistencies by delineating conditions under which format-specific priming is and is not observed. In a study by Graf & Ryan (1990), for example, subjects performed different encoding tasks on target words that were presented in two Applesoft typefonts: one task focused the subjects' attention on the physical characteristics of the words (they rated the readability of the word); the other task focused on semantic attributes (they rated the pleasantness of the word). Priming was tested with a word identification task, and typefont was either held constant or changed between study and test. Graf & Ryan found less priming in the different typefont than same typefont condition following the readability task, but found no effect of changing typefont following the pleasantness task (see also Carr & Brown 1990). Marsolek et al (1992) examined the contributions of the left and right hemispheres to format-specific priming effects. Subjects studied a list of target words under full-field viewing conditions. They were then given a completion test in which half of the stems were briefly exposed in the left visual field and half were briefly exposed in the right. Case of words was either same or different at study and test. Marsolek et al found that changing case between study and test reduced priming when stems were exposed in the left visual field, but had no effect on the magnitude of priming when stems were exposed in the right, thereby suggesting a right

hemisphere locus for the perceptually specific component of priming. It is thus conceivable that in the Graf & Ryan (1990) study, the readability encoding task preferentially engaged the right hemisphere and, hence, yielded format specific effects. More generally, these studies indicate that visual word priming is neither entirely specific nor entirely abstract; both kinds of priming can be observed in different conditions, and the differential contributions of the two hemispheres may play a role in determining which kind of priming is observed.

Another feature of visual word priming that appears to depend on particular experimental conditions is the time course of the phenomenon. For example, early evidence indicated that stem completion priming is a relatively transient phenomenon that disappears after a two-hour retention interval (Graf & Mandler 1984), whereas priming on the perceptual identification task persisted across a 24-hour delay (Jacoby & Dallas 1981). Priming on the fragment completion task lasted for seven days in one study (Tulving et al 1982) and over a year in another (Sloman et al 1988). However, because of initial failures to observe long-lasting fragment completion priming in amnesic patients (Squire et al 1987; see below), some investigators concluded that priming is a short-lived effect that dissipates within hours (Graf et al 1984; Squire 1987; Squire et al 1987). This conclusion appears to be incorrect, because, as discussed below, long-lasting priming has now been observed in amnesic patients. Also, recent evidence indicates that the apparent rapid decay of stem completion priming is not a fundamental feature of such priming, but rather a particular feature of the materials used by Graf & Mandler (1984) and Squire et al (1987). Roediger et al (1992) found that when word fragments and stems are constructed from the same set of target materials and tested under identical experimental conditions, long-lasting priming that persisted across one week was observed on both fragment and stem completion tasks. The longevity of visual word priming may be related to another observed feature of the phenomenon: Priming on fragment and stem completion tasks is not affected by manipulations of proactive and retroactive interference under conditions in which explicit memory is impaired by interference (Graf & Schacter 1987; Sloman et al 1988). However, conditions do exist under which some priming effects are sensitive to interference manipulations (Booker 1991; Mayes et al 1987), although the nature of the interference effects are poorly understood.

In the studies reviewed thus far, target materials have consisted of familiar words that have preexisting representations in memory. An important question concerns whether priming can also be observed for novel items that do not have preexisting memory representations. Some evidence favoring the latter possibility has been provided by studies in which sub-

jects who were initially exposed to nonword letter strings, subsequently exhibited significant priming effects on tests of lexical decision (Bentin & Moscovitch 1988; Kersteen-Tucker 1991; Scarborough et al 1977) and perceptual identification (Feustal et al 1983; Rueckl 1990; Salaso et al 1985; Whittlsea & Cantwell 1987). However, nonword priming on the lexical decision task is exceedingly transient. For example, Bentin & Moscovitch (1988) only found nonword priming when the test trial immediately followed the initial exposure of the target; when even a single item intervened, priming effects disappeared. By contrast, longer-lasting effects have been observed with the perceptual identification test (e.g. Salasoo et al 1985), thus suggesting a possible role for task differences.

A second approach to examining priming of novel verbal information has been to test implicit memory for newly acquired associations between unrelated word pairs. For example, in a paradigm developed by Graf & Schacter (1985), subjects initially study normatively unrelated word pairs (e.g. ship-castle) and are then given a stem completion task in which the target stem is paired with its study list cue (ship-cas___; same context condition) or with some other unrelated word (officer-cas___; different context condition). Priming of new associations, as indicated by higher completion performance in the same context condition than in the different context condition, has been documented on this task. The observed priming—in contrast to explicit memory—exhibits modality specificity (Schacter & Graf 1989), insensitivity to proactive and retroactive interference (Graf & Schacter 1987), and little effect of elaborative and organizational encoding manipulations (Graf & Schacter 1989; Micco & Masson 1991; Schacter & Graf 1986a). In contrast to priming of familiar words, however, priming of new associations appears to involve some minimal degree of semantic study processing (Graf & Schacter 1985; Schacter & Graf 1986a; but see Miccio & Masson 1991) and is not observed readily in test-unaware subjects (Bowers & Schacter 1990; see also Howard et al 1991).

Little is known about the neural basis of priming in normal subjects, although the evidence suggesting a role for the right hemisphere in perceptual specificity effects provides some initial clues. Further evidence comes from a recent neuroimaging study that used positron emission tomography (PET) to investigate stem completion priming. Squire et al (1992) found that priming was associated with a reduction of blood flow to right extrastriate cortex. They also found some evidence for hippocampal activation during priming, but suggested that this effect was attributable to test awareness and subjects' use of explicit retrieval processes under the specific conditions of this experiment. Explicit memory performance (cued recall), however, was associated with marked activation in the right hippocampus.

In all the studies reviewed thus far, priming has been assessed with so-called data-driven implicit memory tasks, in which performance is primarily guided by physical properties of test cues (cf. Jacoby 1983; Roediger & Blaxton 1987b). But, it is also possible to assess priming with conceptually driven implicit tasks, in which semantic-level processing is required, such as producing a category instance in response to a category name. Indeed, priming has been observed on such tasks (Hamann 1990) and has been dissociated from perceptual priming effects on data-driven tests (e.g. Blaxton 1989; Srinivas & Roediger 1990).

STUDIES OF MEMORY IMPAIRED POPULATIONS By the mid-1980s, it was well established that amnesic patients show intact priming of familiar words and word pairs on data-driven implicit tests, such as stem completion, perceptual identification, and lexical decision (cf. Cermak et al 1985; Graf et al 1984; Moscovitch 1982; Warrington & Weiskrantz 1974), as well as on implicit tests that involve some conceptual processing, such as category instance production and free association (Gardner et al 1973; Graf et al 1985; Schacter 1985; Shimamura & Squire 1984). Numerous authors have considered these findings as evidence that the limbic regions that are typically damaged in amnesia, including the hippocampus and related structures, are not necessary for priming of familiar verbal information (for review, see Mayes 1988; Shimamura 1986; Squire 1987, 1992). However, as alluded to earlier, questions have been raised regarding the longevity of priming in amnesia, based principally on the finding that amnesic patients did not show priming on a fragment completion test when tested at a long delay (Squire et al 1987). However, Tulving et al (1991) have recently demonstrated normal and extremely long-lasting fragment completion priming in a profoundly amnesic head-injured patient (K. C.) who exhibits no explicit memory. Indeed, K. C. showed little or no reduction in priming across a 12-month retention interval. An earlier study by MacAndrews et al (1987) revealed robust priming in K. C. and another severely amnesic patient across a one-week delay on a conceptual priming task that involved solving sentence puzzles (for other findings of very long-lasting implicit memory effects in K. C. on more complex learning tasks, see Glisky & Schacter 1988). Although the issue is not yet resolved, conditions clearly exist in which priming of words and other kinds of verbal information can persist over long delays in densely amnesic patients.

During the past several years, a great deal of attention has been paid to the question of whether amnesic patients show normal priming for novel, as well as familiar, verbal materials; results to-date are mixed (for detailed review, see Bowers & Schacter 1992). Several studies have reported impaired priming of nonwords in Korsakoff patients on tests of perceptual

identification (Cermak et al 1985) and lexical decision (Smith & Oscar-Berman 1990). Diamond & Rozin (1984) had earlier found no priming of nonwords in a mixed group of memory-impaired patients. But, the Diamond-Rozin study entailed several methodological problems, and in the Cermak et al (1985) study, Korsakoff patients showed substantial nonword priming effects that were, nevertheless, smaller than those exhibited by control subjects. There are reasons to suspect, however, that control subjects' performance on the perceptual identification test was inflated by the use of explicit memory strategies (see Bowers & Schacter 1992; Haist et al 1991). Cermak et al (1988a) found near-normal priming of nonwords on a perceptual identification task in a densely amnesic encephalitic patient. Gabrieli & Keane (1988) observed what appeared to be intact nonword priming on a similar task in the well-known patient H. M. And, Haist et al (1991) found entirely normal nonword priming on a modified version of the perceptual identification task in a mixed group of amnesic patients. Similarly, Musen & Squire (1991) found that when reading and rereading lists of nonwords, amnesic patients showed normal decreases in reading time. Thus, although not all of the negative evidence can be explained, it now seems clear that amnesic patients can show intact priming of nonwords (for additional mixed outcomes, see Cermak et al 1991; Gordon 1988; Verfaillie et al 1991).

Several studies have also examined whether amnesic patients show priming for newly acquired associations, by using the Graf-Schacter (1985) cued stem completion paradigm described earlier. Graf and Schacter (1985; Schacter & Graf 1986b) observed priming of new associations in patients with relatively mild memory disorders, but not in patients with severe amnesia. Cermak and colleagues (1988b) found no evidence for associative effects in Korsakoff patients, but they (1988a) did observe priming of new associations in their encephalitic amnesic patient. Shimamura & Squire (1989) observed impaired priming of new associations in a mixed group of amnesic patients. Closer analysis of their data revealed an absence of such priming in the Korsakoff patients and a trend for associative effects in patients with amnesia attributable to anoxia and ischemia. Impaired priming of new associations in a mixed group of amnesic patients has also been reported by Mayes & Gooding (1989). Thus, although some positive trends exist, the bulk of the evidence from the Graf-Schacter paradigm suggests that newly formed associations between normatively unrelated words do not influence stem completion priming effects in densely amnesic patients (see also Moscovitch et al 1986; Tulving et al 1991).

Although research concerning priming and memory disorders has focused on amnesic patients, other populations and conditions have also been investigated. For example, several studies have reported that patients

with dementia of the Alzheimer's type (AD), who typically exhibit extensive pathology in cortical association areas, show impaired word priming on a standard stem completion task (Salmon et al 1988; Shimamura et al 1987). By contrast, patients with dementia attributable to Huntington's disease (HD), which is typically associated with pathology in basal ganglia, show intact stem completion priming (Shimamura et al 1987). There have also been reports of normal word priming in AD patients when tests of lexical decision (Ober & Shenaut 1988) and word identification (Keane et al 1991) are used, and several alternative hypotheses have been offered to account for the variable results (cf. Keane et al 1991; Martin 1992). Word priming has also been investigated in normal elderly subjects, who typically exhibit explicit memory deficits. Although entirely normal priming has been observed in elderly subjects (compared with young) on stem completion, fragment completion, perceptual identification, and lexical decision tests (cf. Light & Singh 1987; Mitchell et al 1990), reports of impaired priming on some of the same tasks have also been published (e.g. Chiarello & Hoyer 1988; Davis et al 1990). However, there are reasons to suspect that the latter findings may be attributable to the use of explicit memory strategies by test-aware young subjects (see Graf 1990; Schacter et al 1992, for discussion).

Several investigators have adopted a pharmacological approach to the investigation of priming by administering drugs that typically produce explicit memory deficits to normal subjects. Although few studies have been reported, available evidence indicates that stem completion priming is spared by the benzodiazepine diazepam (Danion et al 1989), but is virtually eliminated by lorazepam, another benzodiazepine (Brown et al 1989). The anticholinergic agent scopolomine appears to reduce, but not eliminate, priming on a word fragment completion task (Nissen et al 1987).

Visual Object Priming

Although priming research has relied heavily on verbal stimuli, many investigators have developed tasks that use objects, patterns, and other nonverbal materials for studies of normal subjects and memory-impaired populations. These tasks include picture naming, in which subjects name previously presented pictures as quickly as possible (e.g. Biederman & Cooper 1991; Durso & Johnson 1979); picture fragment completion, in which subjects are given fragmented versions of pictures and asked to identify them (e.g. Snodgrass & Feenan 1990; Warrington & Weiskrantz 1968); object decision, in which subjects are shown drawings of real and nonsense objects (Kroll & Potter 1984) or structurally possible and impossible objects (Schacter et al 1990a) and are asked to make object/nonobject decisions; and dot pattern identification, in which subjects are exposed to

degraded versions of dot patterns that they either copy (Musen & Treisman 1990) or complete (Gabrieli et al 1990). In all cases, priming is indicated by greater accuracy or reduced latency for studied items relative to nonstudied items (for detailed review, see Schacter et al 1990b).

STUDIES OF NORMAL SUBJECTS As with visual word priming, a major issue in the nonverbal domain concerns the specificity of visual object priming. For example, when exposed to a picture of a table, priming effects might subsequently be observed for only that particular picture or for other pictures of tables. In an early study of picture naming, Bartram (1974) found maximal priming effects when subjects named an identical photograph of an object on two occasions, somewhat less priming when the same object was presented in two different views, and still less (but significant) priming for two different objects with the same name (e.g. two different tables). Warren & Morton (1982) and Jacoby et al (1989) subsequently reported a similar pattern of results and also found that initial study of an object's name (i.e. the word table) produced no subsequent priming of picture naming, thereby indicating that priming effects for different objects with the same name cannot be attributed to activation of the name or to activation of semantic information about the object. Specificity effects have also been observed on the fragment completion task (Snodgrass & Feenan 1990). One interpretive difficulty with these studies, however, is that they either did not include explicit memory tests or did not produce dissociations that could rule out the possible contribution of explicit memory processes (see Schacter et al 1990b). Other studies, however, have dissociated priming from explicit memory; Mitchell & Brown (1988), for example, showed that priming of picture-naming latency persisted across a six-week retention interval, despite a decline in recognition memory.

Despite the possibility that explicit memory played a role in some of the foregoing studies, they suggest rather strongly that object-specific visual information is involved in priming. Several recent experiments have provided evidence bearing on the nature of that information. For example, study-to-test changes in the size and left-right reflection (i.e. mirror image) of target objects have no effect on priming in a picture-naming paradigm (Biederman & Cooper 1992a,b) or in an object decision paradigm (Cooper et al 1992). In the latter paradigm, subjects study drawings of novel objects, half of which are structurally possible (they could exist in three dimensions) and half of which are structurally impossible (they contain various surface and edge violations that would prohibit them from existing in three dimensions). Subjects are then given brief exposures to studied and nonstudied objects and are asked to make possible/impossible decisions about them.

Importantly, performance on explicit memory tests in the Biederman & Cooper (1992a,b) and Cooper et al (1992) studies was impaired by the study/test changes in size and reflection, thereby indicating that the priming effect cannot be attributed to explicit retrieval processes. The fact that priming in these paradigms is size and reflection invariant suggests that the visual representation that supports priming does not include information about object size and reflection. By contrast, priming on the object decision task is eliminated by study-to-test changes in the picture-plane orientation of an object, thus suggesting that information about an object's orientation with respect to a principal axis may be involved in priming (Cooper et al 1991; see also Jolicouer 1985; Jolicouer & Millikan 1989).

The fact that priming is observed at all in the possible/impossible object decision paradigm highlights another important point: Priming of visual objects, like priming of verbal materials, can be observed for novel information that does not have any preexisting memory representation. Schacter et al (1990a) reported that whereas object decision priming is robust following tasks that require encoding of information about the global structure of target objects, it is not observed following tasks that require encoding of local object features or generating semantic elaborations about the objects. The latter finding is particularly important, because generating semantic elaborations about an object greatly enhances subsequent explicit memory performance (see Musen 1991, for similar findings concerning priming of novel dot patterns). Interestingly, significant priming on the object decision task is observed only for the possible objects. Impossible objects show little or no priming, perhaps because it is difficult to form an internal representation of their global three-dimensional structure (Schacter et al 1990a, 1991a; see also Kersteen-Tucker 1991, for a related finding concerning priming of novel polygons on a symmetry judgment task).

STUDIES OF MEMORY-IMPAIRED POPULATIONS Early studies indicated that amnesic patients show some, but not normal, priming on a picture-fragment completion task (Milner et al 1968; Warrington & Weiskrantz 1968); patients' priming deficit is likely attributable to the use of explicit memory by control subjects (cf. Milner et al 1968; Schacter et al 1990b). More recently, however, evidence for normal visual object priming in amnesic patients has been provided. Cave & Squire (1992), using the picture-naming paradigm developed by Mitchell & Brown (1988), found normal priming in a mixed group of amnesic patients and further demonstrated that the priming persists over a seven-day retention interval. Intact priming of novel objects has also been demonstrated in patients with memory disorders on the possible/impossible object decision task (Schacter et al

1991b) and in patient H. M. on a dot pattern completion task (Gabrieli et al 1990). Studies of normal elderly subjects have also yielded evidence of spared priming: Mitchell et al (1990) reported long-lasting priming effects by using their picture-naming paradigm, and Schacter et al (1992) reported intact priming in the object decision paradigm. By contrast, a recent study of dementia indicates impaired priming of picture fragment completion in AD patients, together with spared priming in HD patients (Heindel et al 1990; see also Martin 1992).

Auditory Word Priming

Only a few studies have investigated priming in the auditory domain. Two main implicit tasks have been used: perceptual identification, in which spoken words are masked in white noise, and subjects attempt to identify them; and auditory stem completion, in which initial syllables are spoken, and subjects provide the first word that comes to mind (for a different task, see Jacoby et al 1988).

Several features of auditory word priming have been delineated. First, the phenomenon is largely modality specific: Cross-modal priming is weak or absent on tests of auditory identification (Gipson 1986) and stem completion (Bassili et al 1989; McClelland & Pring 1991). Second, priming on both auditory identification and completion tasks does not require semantic study processing, as indicated by the finding that priming on both tasks is either less affected or unaffected by semantic versus nonsemantic encoding manipulations that enhance explicit memory (Schacter & Church 1992). Converging evidence on this point is provided by a recent case study in which a patient who exhibited difficulties understanding spoken words as a consequence of a left-hemisphere stroke, nevertheless showed normal priming of auditory identification performance (Schacter et al 1993). Third, evidence exists that priming on the auditory stem completion task is reduced by study-to-test changes in speaker's voice (Schacter & Church 1992), whereas priming on the identification-in-noise task is unaffected by voice change (Jackson & Morton 1984; Schacter & Church 1992).

Studies of auditory priming have not yet been reported in amnesic patients, demented patients, or normal elderly. However, studies of patients undergoing surgical anesthesia have provided some evidence for priming of information presented auditorily during anesthesia, on implicit tests given postoperatively, despite a complete absence of explicit memory (e.g. Ghoneim et al 1990; Kihlstrom et al 1990). Some investigators, however, have failed to find such effects (e.g. Eich et al 1985), and the differences among studies may be related to the particular anesthetics used (e.g. Cork et al 1992; for review, see Kihlstrom & Schacter 1990). Interestingly, a recent study of implicit memory for auditory information

presented during natural sleep failed to produce any evidence of priming (Wood et al 1992).

THEORETICAL ACCOUNTS OF PRIMING

Space does not permit us to provide a thorough review of the strengths and weaknesses of the various alternative theoretical accounts of priming (see Richardson-Klavehn & Bjork 1988; Schacter 1987, 1990). The main debate has involved a contrast between the multiple memory systems view, in which priming reflects the operations of a memory system (or systems) that is neurophysiologically and computationally distinct from the system that underlies explicit memory (e.g. Cohen 1984; Cohen & Eichenbaum 1992; Hayman & Tulving 1989; Keane et al 1991; Schacter 1990, 1992; Squire 1987, 1992; Tulving 1985; Tulving & Schacter 1990), and the processing view, in which priming can be understood with reference to the same principles that are used to understand explicit memory, without postulating multiple memory systems (e.g. Blaxton 1989; Jacoby 1983; Masson 1989; Roediger 1990). Various aspects of this debate have been summarized elsewhere by Roediger (1990) and Schacter (1990, 1992), who have also pointed out that the two views may serve complementary functions. We summarize one multiple memory account of priming that accommodates and integrates a good deal of the data considered here (for more detailed elaboration of this view, see Schacter 1990, 1992; Tulving & Schacter 1990; for related views, see Keane et al 1991; Squire 1992).

An adequate theory must account for at least three well-established experimental facts about perceptual priming that we have discussed in this review: 1. It can occur independently of semantic-level processing, as indicated by the weak or absent effects of semantic versus nonsemantic encoding manipulations. 2. It shows a large degree of modality specificity and, under certain circumstances, depends on highly specific perceptual information about a particular word or object. 3. It is preserved in amnesic patients. The latter finding provides particularly strong evidence that priming does not depend on the memory system that supports explicit retrieval of episodes and is tied closely to the hippocampus and other limbic structures (cf. Cohen & Eichenbaum 1992; Schacter 1987; Squire 1987, 1992). Accordingly, Schacter (1990, 1992) and Tulving & Schacter (1990) have suggested that priming effects on such data-driven implicit tests as perceptual identification, stem and fragment completion, and lexical and object decision, largely reflect experience-induced changes in a cortically based, presemantic perceptual representation system (PRS), which is in turn composed of several domain-specific subsystems. The various PRS subsystems are all dedicated to representing modality-specific information

about the form and structure, but not the meaning and other associative properties, of words and objects. Independent evidence for the existence of PRS has been provided by neuropsychological studies showing that patients with impaired access to semantic knowledge of words or objects can, nevertheless, show relatively intact access to perceptual/structural knowledge of those same items (cf. Kohn & Friedman 1986; Ridloch & Humphreys 1987; Schwartz et al 1980; Warrington 1982); and PET imaging studies showing different areas of activation for perceptual and semantic processing (Peterson et al 1989).

Three PRS subsystems have been discussed with respect to priming: a visual word form system, which represents orthographic information about words and likely has a locus in extrastriate cortex (cf. Peterson et al 1989; Schacter 1990; Schacter et al 1990c); a structural description system, which computes relations among parts of objects and may be based in inferior temporal regions (cf. Plaut & Farah 1990; Schacter et al 1991b); and an auditory word form system, which handles phonological/acoustic information and is based in regions of perisylvian cortex (cf. Ellis & Young 1988; Schacter & Church 1992). The three subsystems are implicated in visual word priming, visual object priming, and auditory word priming, respectively.

This formulation does not account for all priming phenomena, and various puzzles remain. For example, it may be necessary to subdivide visual and auditory word form systems further, into abstract and form-specific subsystems that are associated with the left and right hemispheres, respectively (cf. Marsolek et al 1992; Schacter & Church 1992). Similarly, according to the PRS framework, conceptual priming occurs outside of PRS, possibly in a semantic memory system. But, the exact nature of the semantic system and its relation to episodic memory remain poorly understood. And, disagreements exist concerning the extent to which some implicit tests, such as visual stem completion, are based on perceptual versus conceptual priming (cf. Keane et al 1991; Schacter 1990). Nevertheless, the PRS view provides a reasonably coherent account of the major phenomena of priming.

SKILL LEARNING AND IMPLICIT MEMORY

As noted at the outset, although priming is the most extensively studied implicit memory effect, it is by no means the only one. Another important type of implicit memory is embodied in the phenomenon of skill learning. Since the classic studies of Milner et al (1968) on patient H. M., we have known that amnesics can acquire new perceptual/motor skills, despite

absence of explicit memory for having acquired them. Subsequent work has shown that such learning can proceed normally in amnesic patients and that it extends to the acquisition of cognitive skills (e.g. Cohen & Squire 1980; Saint-Cyr et al 1988; Squire & Frambach 1990). Indeed, evidence from studies on learning of complex computer skills and knowledge indicates that severely amnesic patients can learn a great deal more than was previously thought (Glisky et al 1986; Glisky & Schacter 1988, 1989).

An important recent development concerns the double dissociation of motor skill learning and priming in patients with various forms of dementia. Specifically, investigators have shown that whereas AD patients can acquire new motor skills normally despite impaired stem completion priming, HD patients exhibit impaired motor skill learning together with intact priming (e.g. Eslinger & Damasio 1986; Heindel et al 1989; see Heindel et al 1991, for a related phenomenon). In view of evidence for abnormal corticostriatal circuits in HD patients, these findings suggest in part that motor skill learning is mediated by a corticostriatal system that is distinct from the cortical systems that subservise priming (Heindel et al 1989, 1991). There is also evidence that the cerebellum plays a significant role in learning of simple and complex sensory/motor tasks (for review, see Thach et al 1992). Additional evidence for a dissociation between priming and skill learning has been provided in studies of college students and elderly adults (Hashtroudi et al 1992; Schwartz & Hashtroudi 1991).

CONCLUDING COMMENTS

Although the systematic study of implicit memory is a recent development, it has generated an impressive amount of new information and ideas about the nature of mnemonic function. Nevertheless, much remains to be learned and many puzzles need to be solved. For example, although data on skill learning and corticostriatal function in patient populations fit well with data from animal studies (e.g. Cohen & Eichenbaum 1992; Mishkin et al 1984), animal models of priming have yet to be developed, and our knowledge of the neural basis of priming is still rather rudimentary. Given the rapid progress during the past decade, however, we suspect that these and other problems will likely be illuminated during the coming years.

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