Double dissociation of memory capacities after bilateral occipital-lobe or medial temporal-lobe lesions

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Summary

Memory for recently encountered information can be reflected in conscious recall and recognition of that material, or in facilitated reprocessing of that material, an effect known as repetition priming. Repetition priming may be perceptual (form-based) or conceptual (meaning-based). A patient with bilateral occipital-lobe lesions (L.H.) and a patient with bilateral medial-temporal lobe lesions (H.M.) showed a double dissociation between visuo-perceptual priming (impaired in L.H. and intact in H.M.) and visual recognition memory (intact in L.H. and impaired in H.M.). L.H. showed intact conceptual priming for visually presented words; his pattern of impaired visuo-perceptual priming and intact conceptual priming is the reverse dissociation to that observed in prior studies of patients with Alzheimer’s disease, in whom occipital cortices are relatively spared. These double dissociations suggest that a memory system localized to the occipital lobe mediates visuo-perceptual priming effects, and that this system is independent of neural circuits mediating conceptual priming effects, and independent of the limbic–diencephalic system supporting conscious recognition of recently encountered information.

Key words: memory systems; priming; amnesia

Abbreviations: ANOVA = analysis of variance; SPECT = single photon emission computed tomography; WAIS-R = Wechsler Adult Intelligence Scale—Revised; WMS-R = Wechsler Memory Scale—Revised

Introduction

One of the most compelling insights to emerge from neuropsychological studies of human memory is that distinct kinds or components of memory are mediated by separable neural systems. This notion rests on a wealth of evidence demonstrating that memory capacities dissociate in patients with brain lesions. The first reports of such dissociations came from studies of amnesic patients with limbic–diencephalic lesions (for reviews, see Moscovitch et al., 1993; Squire et al., 1993), who exhibited severe deficits in recall and recognition memory tasks (classified as direct or explicit measures of memory), but who often showed normal performance on skill-learning and repetition priming tasks (classified as indirect or implicit measures of memory [Graf and Schacter, 1985; Schacter, 1987; Richardson-Klavehn and Bjork, 1986]). It has been argued, therefore, that performance on explicit memory tasks depends critically upon the integrity of limbic–
diencephalic circuits, whereas performance on implicit memory tasks depends upon the integrity of neural structures outside of those circuits (e.g., Squire et al., 1993).

Subsequent studies revealed that implicit memory task performance can be fractionated into components that reflect the operation of distinct neural systems. For example, skill learning in a rotary pursuit task and repetition priming in a word-stem completion task appear to depend upon separate neural systems that are differentially affected in Huntington’s disease and Alzheimer’s disease (Eslinger and Damasio, 1986; Shimamura et al., 1987; Heindel et al., 1988; Heindel et al., 1989).

Furthermore, studies of Alzheimer’s disease patients have revealed that repetition priming effects may be the product of at least two neurally separable components, only one of which is compromised in Alzheimer’s disease. Priming tasks typically comprise two phases: (i) a study phase in which subjects are exposed to words or pictures; and (ii) a test phase, in which subjects are asked to perform a task with studied and unstudied words or pictures. The measure of priming is the study-induced change in test performance, i.e. the difference in speed, accuracy, or bias in performance with studied items compared with unstudied items. Alzheimer’s disease patients often show impaired priming on word-stem completion tasks (Shimamura et al., 1987; Salmon et al., 1988; Heindel et al., 1989; Bondi and Kaszniak, 1991; Keane et al., 1991; Gabrieli et al., 1994; but see Partridge et al., 1990; Deweer et al., 1994), on word association tasks (Brandt et al., 1988; Huff et al., 1988; Salmon et al., 1988), and on category exemplar generation tasks (Monti et al., 1995). In contrast, Alzheimer’s disease patients show normal priming on tasks requiring identification of briefly presented words or pseudowords (Keane et al., 1991, 1994), lexical decision (Ober and Shenaut, 1988; Ober et al., 1991), or identification of intact or fragmented pictures (Park et al., 1991; Gabrieli et al., 1994). On the basis of these results, we (Keane et al., 1991; Gabrieli et al., 1994) hypothesized that one class of priming tasks (including word completion, word association, and category exemplar generation) indexes conceptual memory processes localized to temporoparietal circuits that are impaired in Alzheimer’s disease, and another class (including identification of words and pictures) indexes perceptual memory processes localized to occipital circuits that are relatively spared in Alzheimer’s disease (Arnold et al., 1991).

The present study examined the neural separability of implicit and explicit memory processes, and of perceptual and conceptual priming processes. To date, the evidence that these forms of memory depend upon independent neural systems comes from single dissociations, i.e. a single patient group’s showing impaired performance on one kind of task and normal performance on the other. Specifically, amnesic patients show impaired performance on explicit memory tasks and intact performance on implicit memory tasks; Alzheimer’s disease patients show intact perceptual priming and impaired conceptual priming. Such single dissociations should be interpreted with caution, because, rather than indicating the participation of separate neural circuits in different kinds of memory tasks, they may be indicating differences in difficulty between two tasks that depend upon a unitary neural system. Thus, performance on the ‘harder’ (explicit memory or conceptual priming) task may be compromised by any damage to that neural system, whereas performance on the ‘easier’ (implicit memory or perceptual priming) task may survive damage to that system.

If these alternative ‘unitary mechanism’ accounts were correct, then it would not be possible to observe the reverse dissociations (impaired implicit memory performance and intact explicit memory performance, or impaired perceptual priming and intact conceptual priming) because impairment on the easier task would necessitate impairment on the more difficult task. Demonstrations of such double dissociations (Teuber, 1955) would require the postulation of separate neural circuits mediating implicit and explicit memory processes, and separate neural circuits mediating perceptual and conceptual priming processes.

The present study sought evidence for such double dissociations. In Experiments 1A and 1B we examined the status of visuoconstructural priming and explicit memory in a patient with bilateral posterior cerebral lesions (patient L.H.), and contrasted his performance with that of the amnesic patient H.M., whose amnesia resulted from bilateral resection of medial temporal-lobe structures. We hypothesized that L.H.’s lesion would impair visuoconstructural priming processes (presumed to be localized to posterior brain areas), but would spare explicit memory processes (localized to diencephalic and medial temporal-lobe regions spared in L.H.). In contrast, we expected that the amnesic patient H.M. would show normal perceptual priming (due to the fact that his lesion spared visual cortices), but impaired explicit memory performance (due to the medial temporal-lobe lesion). Such a pattern of results would constitute a double dissociation between implicit and explicit memory processes in L.H. and H.M.

In Experiments 2 and 3 we sought evidence for the dissociability of visuoconstructural and conceptual priming effects by examining L.H.’s performance on priming tasks that depend in whole or in part upon conceptual processes. Although we hypothesized that L.H.’s lesion would compromise the neural substrate of visuoconstructural priming, we hypothesized that it would spare the neural substrate of conceptual priming. Such a pattern of results in L.H. would be the reverse of that observed in Alzheimer’s disease patients, and would constitute a double dissociation between visuoconstructural and conceptual priming.

**Experiment 1A**

Prior exposure to words enhances subsequent identification of those words (compared with unstudied words) upon brief visual presentation (Postman and Solomon, 1949/50; Neisser,
1954; Ross et al., 1956; Winnick and Daniel, 1970; Murrell and Morton, 1974; Jacoby and Dallas, 1981; Clarke and Morton, 1983; Kirsner et al., 1983). This priming effect is based largely upon a perceptual (rather than an abstract conceptual or lexical) representation of the word; the effect is attenuated or abolished when the perceptual modality of stimuli differs at study and test (Jacoby and Dallas, 1981; Clarke and Morton, 1983; Kirsner et al., 1983; Keane et al., 1991), when stimuli are studied and tested in different lexical/pictorial formats (Winnick and Daniel, 1970), when the typeface of stimuli differs at study and test (Jacoby and Hayman, 1987), and when stimuli are generated rather than read at study (Winnick and Daniel, 1970; Clarke and Morton, 1983; Jacoby, 1983; Schwartz, 1989). Further, perceptual priming effects are not limited to real-word stimuli, but have been demonstrated with pseudoword stimuli as well (Postman and Rosenzweig, 1956; Sprague, 1959; Feustel et al., 1983; Rucekl, 1990). Real-word and pseudoword perceptual priming effects can be dissociated from explicit memory (Jacoby and Dallas, 1981; Jacoby, 1983; Haist et al., 1991; Keane et al., 1991; Keane et al., 1994). Thus, these tasks provide useful indices of the operation of implicit visuo-perceptual memory processes. Experiment 1A examined priming in perceptual identification of words, and recognition memory for words, in L.H. and H.M.

Methods

All of the experiments reported in this paper had the approval of a human subjects committee, and all patients and control subjects gave their informed consent to participate.

Subjects

L.H. L.H. [who was case 10 in Koerner and Teuber (1973) and patient 1 in Levine et al. (1985)] was a 41-year-old, right-handed man, who suffered a severe closed-head injury in an automobile accident at the age of 18 years. The injuries sustained in that accident required him to undergo an extensive right temporal lobectomy, and to have a ventriculovenous shunt inserted for hydrocephalus.

Although initially he exhibited a variety of cognitive impairments and appeared nearly blind during the weeks following the accident, his condition improved dramatically over the subsequent months and years. He completed his undergraduate education and went on to receive two Master's degrees. In Koerner and Teuber's (1973) study (performed 2 years after L.H.'s injury), kinetic perimetry revealed a left upper homonymous quadrantanopia, which extended slightly into the lower left quadrant. The perifoveal region was spared.

Brain MRIs were obtained 18 months prior to the current study, using a 1.5 Tesla System (General Electric Co., Milwaukee, Wis., USA). T1 - (TR = 600 ms/TE = 20 ms) and T2 - (TR = 2200 ms/TE = 40, 80 ms) weighted images were acquired with a 5 mm slice thickness. Single photon emission computed tomography (SPECT) images were obtained within 2 months of the current study, using a digital brain SPECT system (ASPECT, Digital Scintigraphics Inc., Waltham, Mass., USA). Images were acquired 20 min after intravenous injection of 20.0 mCi (±1.0 mCi) of Tc-99m-hexamethylene propylene amine oxime, a radiolabelled tracer of cerebral perfusion (Ceretec, Amersham Ltd, Amersham, UK), with the patient supine, at rest, with eyes open, in a darkened room.

MRI and SPECT images showed the structural and functional evidence, respectively, of the original injury and the surgical resection of anterior right temporal lobe. Tissue had been removed from the superior extent of Heschl's gyrus postero-inferiorly to the midportion of the inferior temporal gyrus. Adjacent medial temporal-lobe structures, including the parahippocampal gyrus and hippocampal-amygdaloid complex, had been spared gross structural damage and were perfused, but at a decreased level compared with homologous left medial temporal structures. White matter underlying the right second and third frontal and orbital gyri contained abnormally high signal on long TR/TE images, probably representing tissue damage in the border-zone between middle and anterior cerebral artery territories. This may have resulted from vascular compromise during the acute period. Damage to white matter of right parietal and occipital lobes was severe, and extended from the grey/white junction to the ventricular surface, from the resection margin to including the inferior parietal lobe and adjacent lateral occipital lobe. Superior parietal structures were spared. In addition, there was a left-hemispheric lesion involving primarily white matter, which extended posteriorly from the inferior temporal gyrus and adjacent fusiform gyrus to white matter below the occipital horn. Perfusion in these structures was severely reduced. These findings are shown in Fig. 1. Medial occipital structures were normal. There was a mild degree of symmetric enlargement of the lateral, third and fourth ventricles, which was greater than expected for a 41-year-old man, and was probably attributable to the trauma.

At the time of the present studies, L.H.'s most prominent deficit was an inability to recognize faces. He could not recognize his parents', wife's, children’s’ or acquaintances’ faces, although he could recognize individuals from the sounds of their voices or by means of other characteristic features. His visuo-perceptual impairment was evident on other demanding perceptual tasks, e.g. on an overlapping figures test (taken from Ghent, 1957) with nine displays each containing three to five overlapping figures. L.H. showed impaired performance, being unable to discern two of the 36 figures, and requiring an average of 96 s per display to identify (by tracing) the individual figures. Levine and Calvanio (1989) reported that L.H. had a severe impairment in visual closure tests in which he was required to identify objects and words presented in incomplete form or embedded in visual white noise, but performed normally on tests in which he was required to unscramble letters to form a word, to fill in one or more letters to form a word, or to find words embedded in apparently random sequences of letters. L.H.'s
perceptual impairments do not appear to reflect deficits in basic visual sensory function, e.g. he showed normal central acuity (20/30) with correction, and normal contrast sensitivity. He showed a slight impairment in stereocuity.

In the context of the present studies, it is notable that L.H. showed no evidence of alexia. He performed normally in a timed reading test containing lists of high- and low-frequency words; regular and irregular words; abstract and concrete words; and nonwords. The words in this test were four to seven letters in length, and the nonwords were three or four letters in length. L.H.'s mean reading time for eight 20-item word lists was 20.6 s (compared with a mean of 20.3 s for three control subjects from the present studies), and his time to read a 48-item nonword list was 72 s (compared with a mean of 70.7 s for three control subjects). Thus, there was no indication that L.H. was a letter-by-letter reader.

On the Wechsler Adult Intelligence Scale—Revised (WAIS-R; Wechsler, 1981), L.H. had a verbal IQ of 123, a performance IQ of 95, and a full-scale IQ of 111. On the Wechsler Memory Scale—Revised (WMS-R; Wechsler, 1987) he had a Verbal Memory Index of 108, a Visual Memory Index of 87, a General Memory Index of 101, an Attention/Concentration Index of 130 and a Delayed Memory Index of 92.

**H.M.** The well-studied amnesic patient H.M. was a 62-year-old man with 12 years of education, who underwent a bilateral temporal lobectomy at the age of 27 years for treatment of intractable epilepsy (Scoville and Milner, 1957; Milner et al., 1968; Corkin, 1984). MRI evidence (Corkin et al., 1994) indicated that the bilateral lesion included the medial temporal pole, amygdala and entorhinal cortex. Approximately the anterior 2–2.5 cm of the dentate gyrus, hippocampus and subicular complex were removed, and approximately the posterior 2 cm of these fields were intact but shrunken. The rostral perirhinal cortex was also removed, but at least some of the posterior perirhinal and parahippocampal cortex may be intact. H.M. had a profound and pervasive anterograde amnesia. On the Wechsler–Bellevue Scale, Form I, H.M. had a verbal IQ of 107, a performance IQ of 128, and a full-scale IQ of 117. On the WMS-R, he had a Verbal Memory Index of 72, a Visual Memory Index of 73, a General Memory Index of 63, an Attention/Concentration Index of 77, and a Delayed Memory Index of <50. Table 1 shows raw scores and percentiles on individual tests from the WMS-R for L.H. and H.M.

### Table 1 Performance on tests from the WMS-R

<table>
<thead>
<tr>
<th>Test</th>
<th>Patient L.H.</th>
<th>Patient H.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw score</td>
<td>Percentile</td>
</tr>
<tr>
<td>Digit Span Forward</td>
<td>12</td>
<td>99</td>
</tr>
<tr>
<td>Digit Span Backward</td>
<td>12</td>
<td>99</td>
</tr>
<tr>
<td>Visual Memory Span Forward</td>
<td>11</td>
<td>94</td>
</tr>
<tr>
<td>Visual Memory Span Backward</td>
<td>9</td>
<td>81</td>
</tr>
<tr>
<td>Logical Memory I</td>
<td>31</td>
<td>78</td>
</tr>
<tr>
<td>Logical Memory II</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>Visual Reproduction I</td>
<td>36</td>
<td>79</td>
</tr>
<tr>
<td>Visual Reproduction II</td>
<td>36</td>
<td>88</td>
</tr>
</tbody>
</table>

**Normal control subjects.** Six control subjects for L.H. (three women and three men) were recruited via advertisements and flyers on the MIT campus. The group had a mean age of 41.3 years (range 39–46 years), a mean educational level of 16.7 years (range 16–18 years), and a
mean WAIS-R age-scaled vocabulary score of 12.5. (The vocabulary subscale score for L.H. was 12.) H.M.'s performance was compared with that of a control group of similar age (mean 64.6 years, range 52–75 years) and years of education (mean 14.1 years, range 12–20 years) whose performance in this experimental task was reported in a prior study (Keane et al., 1991, experiment 2).

**Materials**

The stimuli were 140 four- and five-letter words, of which half were high-frequency (with at least 96 occurrences per million; mean 280) and half were low-frequency (with no more than 10 occurrences per million; mean 3.5) (Kucera and Francis, 1967). Twelve of the 140 words were used as filler items, and the remaining 128 words were divided into two lists that were balanced for word frequency and word length. Each 64-word list included: 16 high-frequency four-letter words; 16 low-frequency four-letter words; 16 high-frequency five-letter words; and 16 low-frequency five-letter words. One list was used in the perceptual priming task; the other was used in a recognition memory task.

**Procedure**

In the following order, each subject studied one list of words; performed a perceptual identification task with studied and unstudied words; studied a second new list of words; and performed a yes/no recognition task with studied and unstudied words. All stimuli were presented on the screen of an IBM personal computer. Subjects sat ~20 inches from the screen.

The procedure in the study phase was identical for the perceptual identification and the recognition tasks. Subjects were told that they would see a series of words presented one at a time, and that they were to read each word aloud. They saw 32 different words presented singly; half were presented one time and the other half were presented three times (once within each third of the list). In addition to these 64 trials, three filler words were presented at the beginning and end of the list (to blunt any primacy and recency effects upon later memory for the stimuli), yielding a total of 70 trials. The study phase was followed immediately by a perceptual identification or recognition task.

In the perceptual identification task, subjects were told that a series of words would be presented very briefly, and that they were to identify each word. Each trial was preceded by the appearance of a fixation character (+) at the location where the word was to appear. Subjects were instructed to fixate this character in preparation for the brief appearance of a word. On each trial, a word was flashed and then replaced by a backward mask (####) of 250 ms duration. The initial presentation time was 1.67 ms. If the subject was unable to identify the word at this exposure duration, it was presented in the next trial for 33.4 ms. The same word was presented in additional increments of 16.7 ms on successive trials (to a maximum presentation time of 635 ms) until subjects correctly identified it. The computer recorded the exposure duration at which the subject correctly identified each word. The perceptual identification task consisted of 64 different words, 32 of which had appeared in the prior study list (16 once, 16 three times). The other 32 words had not appeared in the prior study list. Within each of the control groups, stimuli were counterbalanced across subjects so that each word appeared equally often as a studied or unstudied item in the perceptual identification task.

In the recognition test, subjects were told that they would see a series of words, some of which had appeared in the preceding study list. Subjects were asked to respond 'yes' if they had seen the word on the prior list and 'no' if they had not. The recognition test comprised 64 words; half had appeared in the prior study list (once or three times) and half were new. Across subjects within each of the two control groups, the stimuli were counterbalanced so that each word appeared equally often as a studied or unstudied item in the recognition task.

**Results**

**Priming in perceptual identification of words**

The dependent measure was the stimulus exposure duration at which subjects correctly identified words. The mean exposure duration (in milliseconds) needed to identify unstudied (no prior exposures) and studied (one or three prior exposures) words of high and low frequency was calculated (Table 2). Priming was indicated by the reduction...
in exposure duration needed to identify studied words relative to unstudied words.

Normal control subjects for L.H. L.H.'s control group showed perceptual priming. They required a mean exposure time of 25.7 ms to identify unstudied words, and 21.6 ms to identify words that had appeared in the prior study list. The priming effect was not merely the result of averaging across the group as each of the six individual control subjects required less exposure time to identify studied than unstudied words. In a two-way repeated-measures analysis of variance (ANOVA) with factors of prior exposure (zero, one and three prior exposures) and word frequency (high or low), the priming effect was indicated by a main effect for prior exposure \(F(2,10) = 15.36, P < 0.001\). Planned contrasts to examine the source of this effect indicated that studied items were identified at shorter exposure durations than unstudied items [zero exposures versus one or three exposures; \(F(1,10) = 25.39, P < 0.001\)]; and that priming was greater for words with three prior exposures than for words with one prior exposure [one exposure versus three exposures; \(F(1,10) = 5.34, P < 0.05\)]. There was no main effect of word frequency (\(P > 0.10\)), and no interaction between prior exposure and word frequency (\(P > 0.10\)), indicating that the magnitude of the priming effect was similar for high- and low-frequency words.

L.H. L.H. performed two versions of the priming task on two separate occasions, separated by 4 weeks, in order to obtain a measure of his performance with items counterbalanced across studied and unstudied conditions. In both testing sessions, during the perceptual identification task, he became fatigued and was able to complete only the first half (i.e. 32) of the trials. The perceptual identification task was designed so that the first 32 and the second 32 trials were balanced with respect to numbers of studied and unstudied words, and numbers of words studied once or three times. Therefore, the data from the first 32 items in two different testing sessions (for a total of 64 data points), allowed an examination of performance with equal numbers of words in the studied and unstudied conditions, and equal numbers of words studied once or three times. On average, L.H. required 263.6 ms (range 116.9–484.3 ms) to identify unstudied words, and 268.3 ms (range 100.2–501.0 ms) to identify words that had appeared in the prior study list. These results indicate an absence of priming in L.H. In contrast to that of his control subjects, L.H.'s perceptual identification performance was not enhanced by prior exposure to words.

In order to compare the performance of L.H. and his control group on just those trials that L.H. had completed (i.e. the first 32 items in each of two counterbalanced versions of the perceptual identification task), we recalculated the mean scores for the control group in each of the six experimental conditions for just those 32 trials. For these items, the control group required a mean of 27.6 ms to identify unstudied words, and 22.8 ms to identify words that had appeared in the prior study list. Again, the benefit in identification of studied relative to unstudied words was present for each individual control subject. In a two-way repeated-measures ANOVA with factors of prior exposure (zero, one or three) and word frequency, the priming effect was indicated by a main effect of prior exposure \(F(2,10) = 7.43, P < 0.05\). Planned contrasts indicated that studied items were identified at shorter exposure times than unstudied items [zero exposures versus one and three exposures; \(F(1,10) = 8.75, P < 0.05\)] and that the priming effect was greater for words with three prior exposures than for words with one prior exposure [one exposure versus three exposures, \(F(1,10) = 6.12, P < 0.05\). There was no main effect of word frequency, and no interaction between prior exposure and word frequency, indicating that priming was similar for high- and low-frequency words. In summary, the control group for L.H. showed significant perceptual priming (reliable at the level of individual subjects), under conditions in which L.H. showed no perceptual priming.

H.M. H.M. performed two different versions of the priming task in two sessions separated by 9 days in order to obtain a measure of performance with items counterbalanced across studied and unstudied conditions. H.M. required a mean exposure duration of 43.3 ms to identify unstudied words, and 34.2 ms to identify studied words. The priming effect resembled that of the control group (Keane et al., 1991, experiment 2), whether the effect was expressed in terms of absolute magnitude (9.1 ms for H.M. versus 8.7 ms for the control group), or as a proportion of baseline performance (21.0% for H.M. versus 18.5% for the control group). Thus, H.M. showed normal perceptual priming in the present task.

Recognition For each subject, we calculated the proportion of words correctly recognized from the study list (hits) in each of the four conditions defined by crossing repetition (one versus three exposures) with word frequency (high versus low), and the proportion of unstudied words incorrectly attributed to the study list (false alarms) in each of the two word frequency conditions. These proportions were used to determine a \(d'\) score for studied words in each of the four study conditions defined by repetition and word frequency (Table 3).

Normal control subjects for L.H. The mean \(d'\) scores for L.H.'s control group were submitted to two-way repeated measures ANOVA with factors of prior repetition (one versus three) and word frequency. This analysis revealed a main effect for repetition \(F(1,5) = 9.42, P < 0.05\), reflecting better recognition of words that had appeared three times in the prior study list than those that had appeared once. Although recognition memory performance was numerically better for low- than for high-frequency words, this difference did not reach significance (\(P > 0.09\)). There was
Table 3  Word recognition (mean d’ score)

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Word frequency</th>
<th>1 exposure</th>
<th>3 exposures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient L.H.</td>
<td>High</td>
<td>1.55</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>2.02</td>
<td>3.50</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>1.79</td>
<td>3.69</td>
</tr>
<tr>
<td>L.H. control group</td>
<td>High</td>
<td>2.05 (SD 0.86)</td>
<td>3.18 (SD 0.54)</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>3.01 (SD 1.22)</td>
<td>3.87 (SD 0.43)</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>2.53</td>
<td>3.53</td>
</tr>
<tr>
<td>Patient H.M.</td>
<td>High</td>
<td>-0.68</td>
<td>-0.34</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>2.17</td>
<td>0.52</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.75</td>
<td>0.09</td>
</tr>
<tr>
<td>H.M. control group*</td>
<td>High</td>
<td>1.16 (SD 0.58)</td>
<td>2.62 (SD 1.01)</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>2.53 (SD 0.82)</td>
<td>3.51 (SD 0.74)</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>1.85</td>
<td>3.07</td>
</tr>
</tbody>
</table>

*Data for H.M. control group taken from Keane et al. (1991, Experiment 2).

no interaction between repetition and word frequency ($P > 0.50$).

L.H. L.H.’s recognition performance was similar to that of his control group. His mean recognition performance across all conditions ($d' = 2.74$) was within the range of his control group (range 2.65–3.66), and within 1 SD of the mean of the control group (mean $d' = 3.03$, SD = 0.38). Like his control group, L.H. showed better recognition memory performance for words with three study list exposures than for those with one exposure.

H.M.H.M.’s recognition memory performance was markedly impaired. His mean performance across all experimental conditions ($d'' = 0.42$) was well outside of the range of the control group (range 1.53–3.17) and >3 SD below the mean of the control group (mean $d'' = 2.46$, SD = 0.60).

Experiment 1B

The aim of Experiment 1B was to replicate the double dissociation between visuo-perceptual priming and recognition memory in L.H. and H.M., using pseudowords as stimuli.

Methods

Subjects

L.H. and H.M. participated in the present experiment (see descriptions above). The six control subjects for L.H. were recruited from the MIT community and via newspaper advertisements. The five men and one woman comprising this group had a mean age of 41.5 years (range 37–44 years), a mean education level of 17.8 years (range 15–20 years), and a mean WAIS-R Vocabulary score of 14.8. H.M.’s performance was compared with that of a control group of similar age (mean 64.5, range 53–80) and education (mean 13.0, range 8–20) whose performance in this experimental task was reported in Keane et al. (1994).

Table 4  Mean exposure time (milliseconds) to identify pseudowords

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Unstudied pseudowords</th>
<th>Studied pseudowords</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 exposure</td>
<td>3 exposures</td>
</tr>
<tr>
<td>Patient L.H.</td>
<td>187.9</td>
<td>203.6</td>
</tr>
<tr>
<td>L.H. control group</td>
<td>27.4</td>
<td>24.5</td>
</tr>
<tr>
<td>Patient H.M.</td>
<td>101.9</td>
<td>97.4</td>
</tr>
<tr>
<td>H.M. control group*</td>
<td>54.3</td>
<td>51.6</td>
</tr>
</tbody>
</table>

*Priming is indicated by a reduction in the exposure time to identify studied pseudowords compared with unstudied pseudowords. Data for H.M. control group taken from Keane et al. (1994).

Materials

The stimuli were 140 three-letter pronounceable pseudowords, all consonant-vowel-consonant strings. Of these pseudowords, 12 were used as filler items, 64 were used in the perceptual identification task, and 64 were used in the recognition task.

Procedure

The procedure in this experiment was identical to that used in Experiment 1A.

Results

Primming in perceptual identification of pseudowords

The results are shown in Table 4.

Normal control subjects for L.H. Perceptual priming was evident in L.H.’s control group in that they required a shorter exposure duration to identify studied pseudowords (24.3 ms) than unstudied pseudowords (27.4 ms). Five of the six subjects in this group required less exposure time to identify studied than unstudied pseudowords. The one subject who failed to show this effect required the shortest exposure duration of all subjects to identify unstudied items (20.7 ms); thus, the absence of priming in that subject may have been due to a performance ceiling. A one-way repeated-measures ANOVA for the three experimental conditions (zero versus one versus three prior exposures) failed to reveal a significant difference among conditions ($P > 0.20$). However, because the comparison critical to the priming effect was that between studied and unstudied items, the data were collapsed across two study conditions (one and three prior exposures), and the mean exposure durations required to identify studied and
Table 5  Pseudoword recognition (mean d’ score)

<table>
<thead>
<tr>
<th>Subjects</th>
<th>1 exposure</th>
<th>3 exposures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient L.H.</td>
<td>0.50</td>
<td>1.33</td>
</tr>
<tr>
<td>L.H. control group</td>
<td>1.16 (SD 0.97)</td>
<td>2.09 (SD 1.27)</td>
</tr>
<tr>
<td>Patient H.M.</td>
<td>0.30</td>
<td>0.48</td>
</tr>
<tr>
<td>H.M. control group*</td>
<td>0.93 (SD 0.55)</td>
<td>1.61 (SD 0.87)</td>
</tr>
</tbody>
</table>

*Data for H.M. control group taken from Keane et al. (1994).

unstudied items were compared. This analysis indicated significant priming \( t(5) = 2.63, P < 0.05 \).

L.H. L.H. failed to show any evidence of perceptual priming in the current task. His mean exposure time to identify unstudied pseudowords was 187.9 ms, and to identify studied pseudowords was 197.6 ms.

H.M. Priming in H.M. was reflected in a mean exposure time of 101.9 ms to identify unstudied pseudowords compared with 93.2 ms to identify studied pseudowords. H.M.’s priming effect was comparable to his control group, whether that effect was expressed in terms of absolute magnitude (4.9 ms for the control group versus 8.7 ms for H.M.) or as a percentage of baseline (unstudied) performance (8.4% for the control group versus 8.5% for H.M.).

Recognition
For each subject, proportions of hits and false alarms were used to determine \( d' \) scores for pseudowords in each of the two experimental conditions (one versus three prior exposures) (Table 5).

L.H. and normal control subjects for L.H. For L.H.’s control group, a paired \( t \) test indicated that recognition performance was better for pseudowords with three prior exposures than for those with one prior exposure \( t(5) = 6.3, P < 0.001 \). Like his control group, L.H. showed better recognition memory for words with three than with one prior exposure. His mean performance across the two conditions (\( d' = 0.92 \)) was within the range of his control group (range 0.08–3.30), and within 1 SD of the control group mean (mean \( d' = 1.63, SD = 1.10 \)).

H.M. H.M.’s mean performance across the two experimental conditions (\( d' = 0.39 \)) was outside of the range of his control group (0.59–2.46), and >1 SD from the mean of his control group (mean \( d' = 1.27, SD = 0.66 \)).

Recognition memory performance with pseudowords in Experiment 1B was notably worse than recognition memory performance with real words in Experiment 1A, for both of the control groups and for L.H. (H.M.’s recognition memory performance was at similarly low levels in both experiments). This difference in performance across experiments was likely due to differences in the memorability of words versus pseudowords, and to the fact that the pseudowords used in Experiment 1B were highly confusable with one another because they were all three-letter consonant–vowel–consonant strings. Thus, although H.M.’s recognition performance was closer to that of his control group in Experiment 1B than in Experiment 1A, that narrowing of the gap in performance may have been due to the fact that some of the control subjects in Experiment 1B were operating closer to a performance floor due to the difficult discriminations required in the recognition memory task.

Discussion of Experiments 1A and 1B
In two separate experiments, visuo-perceptual priming and recognition memory were found to be doubly dissociated in L.H. and H.M.. L.H. showed impaired priming in perceptual identification of words and pseudowords, but normal recognition memory for words and pseudowords. In contrast, H.M. showed normal priming in perceptual identification of words and pseudowords, but impaired recognition memory for both sorts of stimuli. [The presence of normal priming with pseudoword stimuli in H.M. has critical implications for theoretical accounts of preserved memory function in amnesia. These issues are beyond the scope of this paper. For extended discussions of the implications of priming with novel stimuli see Gabrieli et al. (1990); Haist et al. (1991); Schaeter et al. (1991); Keane et al. (1995).] This double dissociation is incompatible with the notion that implicit and explicit memory performance depend (to different degrees) upon a unitary memory system. Rather, these results provide strong evidence that at least one kind of implicit memory (visuo-perceptual priming) depends upon a neural system distinct from the system that supports explicit memory performance.

The absence of perceptual priming in L.H. is particularly striking when considered in the context of a prior study (Keane et al., 1991). In the present study, L.H.’s performance differed from that of other subjects in that he required longer exposure durations than did the control subjects to identify words. One might be concerned that such impaired baseline performance precludes the possibility of priming (i.e. that there might be a scaling problem such that priming effects are not observable at high levels of baseline performance). Furthermore, one could question any conclusion based on the performance of a single patient on a single test: an unreliable measure could fail to elicit priming in a single subject even if no real deficit were present. Both of these issues may be addressed by referring to the earlier study (Keane et al., 1991) in which perceptual priming of words using the current priming task were examined. In Experiments 2 and 3 of that study, there were three patients with Alzheimer’s disease whose baseline performance was similar to (or worse than) that of L.H.: all three of these patients showed substantial perceptual priming in the current task, arguing against the notion that elevated baseline performance precludes the possibility of normal priming. In Experiment
1 of the prior study, perceptual priming was examined in 32 college students. All 32 of those subjects required shorter exposure durations to identify studied compared to unstudied words. These findings suggest that priming in perceptual identification of words is robust at the level of individual subjects. Thus, the absence of perceptual priming in L.H. in the present study is likely due to the disruption of neural circuits critical to this expression of memory.

Experiment 2A
In Experiment 2A we aimed to demonstrate that L.H.'s priming deficit was a selective one, restricted to tasks that depend upon visuo perceptual priming processes. We examined priming on a conceptual priming task: category exemplar production. In this task, subjects studied a word list that included low- and high-frequency exemplars from a variety of categories (e.g., 'MANGO'), and were subsequently asked to generate exemplars from a number of categories (e.g., 'FRUIT') as quickly as they could in a given amount of time. Priming was reflected in the tendency to generate exemplars from the prior study list more often than would be expected by chance. Patients with global amnesia show normal priming on this kind of task (Gardner et al., 1973; Graf et al., 1985; Keane et al., 1993), indicating that the effect does not depend upon recall and recognition memory processes that are impaired in global amnesia.

Priming in this task does not depend upon the perceptual mechanisms that subserve priming in identification of briefly presented words because in a category exemplar production task, the primed stimulus (e.g., 'MANGO') shares no perceptual features with the test cue (e.g., 'FRUIT'); the study and test stimuli are related only in meaning. Experimental evidence supports the idea that priming in a category exemplar production task depends upon conceptual processes that do not play a role in a perceptual identification task: categorical organization of words in a study list enhances priming in the former, but not the latter task (Rappold and Hashtroudi, 1991), and the level of semantic processing at study influences priming in the former (Hamann, 1990; Keane et al., 1993) but not in the latter task (Jacoby and Dallas, 1981; Kirsner et al., 1983). Because the category exemplar production task does not depend upon perceptual priming mechanisms, but provides a relatively pure measure of conceptual priming processes, we predicted that it would elicit normal priming in L.H.

Methods
Subjects
L.H. and his control group from Experiment 1A participated in this experiment.

Materials
The target stimuli were low-typicality exemplars of 16 categories (Battig and Montague, 1969). From eight of the 16 categories, five exemplars were selected; from the other eight categories, 10 exemplars were selected. Each of the exemplars was listed by at least 10 out of 442 subjects asked to generate members of that category (but none of the exemplars was among the 10 most frequent responses for that category) (Battig and Montague, 1969). In terms of response frequency, the mean rank of the target exemplars was 26.4 (range 11–48) (Battig and Montague, 1969). Three exemplars from each of eight additional categories served as filler items.

Procedure
The experiment proceeded in two sessions. In Session 1, the experimenter spoke aloud the names of each of the 16 target categories, and subjects were asked to generate (aloud) as many exemplars of each category as possible in 1 min. Their responses provided a baseline measure of category exemplar production for each subject.

Session 2 (separated from Session 1 by at least 24 h) proceeded in three study-test phases. In Phase 1, the experimenter read aloud a list of 28 words. The list included five exemplars from each of four target categories (presented in a random order), as well as four filler exemplars at the beginning and the end of the list. Subjects were asked to decide whether each word was the name of something natural or man-made. After this study task, subjects performed a category exemplar production task like the one they performed in Session 1, i.e. the experimenter spoke aloud the names of four target categories (whose exemplars constituted the prior study list), and subjects were asked to generate (aloud) as many exemplars of that category as possible in 1 min.

Phase 2 was identical to Phase 1, except that the target stimuli were five exemplars from each of four new categories.

In Phase 3, as in Phases 1 and 2, subjects performed the study task with five exemplars from each of four new categories. However, in Phase 3 (unlike Phases 1 and 2), the study task was followed by a four-choice recognition task, i.e. on each of 20 trials, the experimenter spoke aloud four words, and subjects had to indicate which of the four words had appeared in the prior study list. The four choices included the target exemplar, an unstudied exemplar from the same category, and two exemplars from a different (unstudied) category. In total, the stimuli in the recognition task included five studied exemplars from each of four categories, five unstudied exemplars from each of four studied categories, and 10 unstudied exemplars from each of four unstudied categories. This task served as a recognition memory measure and also as a study task for the category exemplar production task that followed. In the category exemplar production task (as in Phases 2 and 3), the experimenter spoke aloud the names of eight categories (whose exemplars had appeared in the prior study list and/or in the prior recognition task).
subjects were asked to list as many exemplars of that category as possible in 1 min.

Results

Category exemplar production priming

For each subject, we calculated the percentage of target exemplars produced in the category exemplar production task in Session 1. This score provided a measure of baseline performance in the absence of prior exposure to exemplars. Across the three phases in Session 2, we calculated the percentage of target exemplars generated following exposure to those exemplars in the study list or in the recognition task. Priming was reflected in an increase in the mean percentage of target exemplars generated in the primed condition relative to the baseline condition (Fig. 2).

Normal control subjects. The mean percentage of target exemplars produced in the primed condition (35.0%) was greater than the mean percentage produced in the baseline condition (23.3%), t(5) = 3.4, P < 0.01, indicating significant priming in category exemplar production.

L.H. L.H. performed this task in its entirety twice, in two separate testing sessions separated by 4 weeks. His results represent the mean of his performance across the two sessions. For L.H., the mean percentage of target exemplars produced in the baseline condition was 11.3%, and in the primed condition was 28.8%. The baseline score for L.H. was below the range of the control group (12.5-30.0%), and >1 SD below the control group mean (mean 23.3%, SD = 7.0). His priming score (17.5%) was within the range of his control group (4.0-26.7%), and was within 1 SD of the control group mean (mean 11.7%, SD = 8.4), indicating normal priming in category exemplar production.

Recognition

The recognition score for each subject was the percentage of studied exemplars correctly identified in the four-choice recognition test. The mean score for the control group was 95.8% (SD = 5.8); the mean score for L.H. across the two testing sessions was 92.5%. His score was within the normal range (85.0-100%), and within 1 SD of the normal mean.

Discussion

L.H. showed normal priming in category exemplar production. His normal performance in this conceptual priming task contrasts with his lack of priming in the two perceptual priming tasks in Experiment 1.

Before considering the implications of these findings, we considered one other feature (in addition to the perceptual/conceptual nature of the priming tasks) that distinguishes the tasks used in Experiments 1 and 2. In the perceptual identification tasks in Experiment 1, the stimuli were presented visually at study and test, whereas in the category exemplar production task in Experiment 2, the stimuli were presented auditorily at study and test. In order to demonstrate directly that L.H.'s normal category exemplar production priming in Experiment 2A was due to the conceptual nature of the priming task (and not to the auditory modality of presentation), a second experiment was conducted which compared priming in category exemplar production under auditory and visual study conditions.

Roediger and colleagues (Roediger and Blaxton, 1978; Roediger et al., 1989) have argued that one of the hallmarks of a conceptual (or conceptually driven) priming task is that performance in the task is uninfluenced by manipulations of the perceptual format of stimuli. Further, they have demonstrated (Srinivas and Roediger, 1990) that priming in category exemplar production is insensitive to such manipulations, consistent with the notion that it indexes conceptual rather than perceptual priming processes. By examining the effect of a modality manipulation on category exemplar-production priming, Experiment 2B accomplished two aims: (i) it allowed us to demonstrate empirically that priming in the current category exemplar production task was unaffected by a perceptual manipulation, indicating that performance reflects conceptual priming processes; (ii) it allowed us to test the prediction that L.H. would show normal conceptual priming, irrespective of the perceptual modality in which stimuli were presented.

Experiment 2B

Methods

Subjects

L.H. and six normal control subjects participated in this experiment. The control group consisted of four men and
two women whose mean age was 41.2 years (range 37–43 years), mean education level was 17.2 years (range 15–20 years), and mean WAIS-R Vocabulary score was 15.2.

Materials
The critical stimuli in this experiment were 80 low-typicality exemplars, five exemplars from each of 16 different categories (Battig and Montague, 1969). Each of these exemplars was listed by at least 10 out of 442 subjects asked to generate members of that category (but none of the exemplars was among the eight most frequent responses for that category) (Battig and Montague, 1969). In terms of response frequency, the mean rank of the target exemplars was 28.4 (range 9–48) (Battig and Montague, 1969). Four exemplars from each of eight additional categories served as filler items.

Procedure
The experiment proceeded in three sessions. In Session 1, baseline performance was measured, in Session 2, the (implicit) priming task was administered, and in Session 3, an (explicit) cued recall task was administered.

In Session 1, the names of each of the 16 target categories were presented on a computer screen; subjects were asked to generate (aloud) as many exemplars of each category as possible in 1 min.

Session 2 (separated from Session 1 by at least 24 h) proceeded in four study-test phases. In each phase, a study task was followed by a category exemplar production task. In the study task, subjects either saw (visual condition) or heard (auditory condition) a series of words, and were asked to decide whether each word was the name of something natural or man-made. In the visual study condition, exemplars were presented on the screen of an IBM personal computer; in the auditory study condition, the exemplars were read aloud by the experimenter. Each study list consisted of 28 exemplars, i.e., five exemplars from each of four target categories (presented in a random order), as well as four filler exemplars at the beginning and end of the list. After each study task, subjects performed a category exemplar production task like the one they performed in Session 1, i.e., the names of four target categories (whose exemplars constituted the prior study list) were presented on a computer screen; subjects were asked to generate (aloud) as many exemplars of that category as possible in 1 min.

A different set of 20 target exemplars (five from each of four categories) was used in each of the four study-test phases. Two of the study-test phases were administered under visual study conditions, and the other two were administered under auditory study conditions. Across subjects in the control group, the four different stimulus sets were counterbalanced across visual and auditory conditions, and the order of administration of the visual and auditory conditions was counterbalanced.

Session 3 was separated from Session 2 by at least 4 weeks. The materials and procedure used in Session 3 were identical to those used in Session 2 with the exception that in the test portion of each study-test phase, subjects were instructed explicitly, for each category, to try to recall exemplars of that category that had appeared in the prior study list.

Results
Priming in category exemplar production
For each subject, we calculated the percentage of target exemplars produced in the category exemplar production task in Session 1 separately for categories that would subsequently appear in the auditory or visual priming conditions. These percentages provided a measure of baseline performance in the absence of prior exposure to exemplars. From the data obtained in Session 2, we calculated the percentage of target exemplars generated following visual exposure to those exemplars in the prior study condition across the two administrations of the visual condition, and following auditory exposure to those exemplars in the prior study condition across the two administrations of the auditory condition. Priming in each condition (auditory or visual) was reflected in an increase in the mean percentage of target exemplars generated in the primed condition (i.e., following study list exposure) relative to the baseline condition (Fig. 3).

Normal control subjects. For exemplars which appeared in the visual or auditory study conditions, the baseline scores were 32.1 and 25.4%, respectively. The mean percentage of target exemplars produced following visual study was 56.7%, and following auditory study it was 52.5%. In order to examine the effect of the modality manipulation on category exemplar-production priming, these data were submitted to
a two-way repeated-measures ANOVA with factors of test condition (baseline versus primed) and study-phase presentation modality (visual versus auditory). Priming was indicated by a main effect for test condition [$F(1.5) = 28.8$, $P < 0.01$], indicating that a higher percentage of target exemplars were produced in the primed than in the baseline conditions. Critically, there was no interaction between test condition and presentation modality ($P > 0.50$), indicating that the magnitude of priming was similar following visual (24.6%) and auditory (27.1%) study exposure.

**L.H.** For exemplars which appeared in the visual or auditory study conditions, L.H. had baseline scores of 10.0 and 15.0%. His mean baseline score (12.5%) was below the range of the control group (range 21.3–40.0%), and >2 SD below the mean baseline score of the control group (mean 28.8%, $SD = 6.6$). For L.H. the mean percentage of exemplars produced following visual study was 32.5% and following auditory study was 32.5%. The resulting priming score in the visual condition (22.5%) was within the control group range (12.5–40.0%) and within 1 SD of the control group mean (mean 24.6%, $SD = 10.9$). Similarly, L.H.’s priming score in the auditory condition (17.5%) was within the control group range (10.0–50.0%), and within 1 SD of the control group mean (mean 27.1%, $SD = 14.8$). Thus, L.H. showed normal priming in category exemplar production regardless of the perceptual modality in which the stimuli were presented for study.

**Category exemplar cued recall**

For each subject, the cued recall score was the percentage of target exemplars produced in Session 3 following auditory or visual exposure in a study list. For the normal control group, a paired $t$ test revealed that cued recall performance did not differ for the visual (63.8%) and auditory (56.3%) conditions ($P > 0.30$). L.H.’s cued recall performance was reduced relative to that of his control group. His score in the visual condition (47.5%) was slightly below the range of his control group (range 52.5–82.5%), and >1 SD from the control group mean (mean 63.8%, $SD = 11.7$). Similarly, his cued recall score in the auditory condition (37.5%) was slightly below the range of the control group (range 42.5–72.5%), and >1 SD below the control group mean (mean 56.3%, $SD = 11.1$).

**Discussion**

In Experiment 2B, priming in category exemplar production was equivalent following auditory or visual presentation of stimuli at study, demonstrating that the priming effect reflected the operation of conceptual (rather than perceptual) processes. Furthermore, priming in L.H. was normal regardless of the perceptual modality in which the stimuli were presented. We may therefore conclude that the performance dissociation in L.H. between (impaired) priming in perceptual identification of words and pseudowords in Experiment 1, and (normal) priming in category exemplar production in Experiment 2A, was not due to the perceptual modality in which stimuli were presented (visual in Experiment 1 versus auditory in Experiment 2A), but to the distinct mechanisms underlying priming in the two tasks; L.H. showed impaired priming in Experiment 1 in a task that depended upon visuo perceptual priming processes, and normal priming in Experiment 2 in a task that depended upon conceptual priming processes.

The results of the explicit memory measure in Experiment 2B (category exemplar cued recall) differed from those of the earlier experiments in that L.H.’s performance was reduced relative to his control group. Unlike the recognition memory measures used in Experiments 1A, 1B and 2A, the explicit memory measure in Experiment 2B was a cued recall task. Although L.H.’s performance was impaired, it was not at a level comparable to that of amnestic patients. In a separate study, amnestic patients’ mean performance in a comparable category cued recall task averaged 8.3% (Keane et al., 1993) compared with a mean of 42.5% for L.H. in the present study.

A clue about the basis of L.H.’s reduced cued recall performance comes from an examination of his performance in the baseline sessions, in which subjects were asked simply to generate exemplars in response to a category cue (without prior exposure to exemplars). As stated in Results, L.H. produced fewer target exemplars at baseline than did the control subjects. This reduced baseline performance appears to reflect an overall reduction in fluency. L.H. produced fewer (target or non-target) exemplars per category than did the control group (L.H. mean 9.4; control group mean 17.5, $SD = 3.1$). L.H. has a right frontal lesion (in addition to the posterior lesions), but fluency deficits are typically associated with left frontal lesions. Prior studies of L.H. have revealed deficits in visual imagery as well as visual perception (Levine et al., 1985). Because most of the categories in the present study corresponded to concrete, visualizable stimuli (e.g., fruits, animals, vehicles), normal subjects may have used imagery as an aid to generate category exemplars, putting L.H. at a relative disadvantage. In any case, L.H.’s reduced output in the category cued recall task may reflect the same non-nmenmonic deficit that underlies his diminished output in the category fluency task.

**Experiment 3**

Experiments 1 and 2 demonstrated a dissociation between (impaired) visuo perceptual priming and (intact) conceptual priming in L.H. This dissociation occurred in the context of two tasks which differed on a number of dimensions. One important dimension concerns the characteristics of the test cues in the two tasks. In the perceptual identification task, the test cue (i.e. the stimulus to be identified) appeared very briefly; in the category exemplar production task, the test cue (i.e. a category name) was available until the subject’s response was complete. One might ask whether L.H.’s
priming deficit is restricted to priming tasks in which test cues are presented very briefly, or whether it extends to perceptual priming tasks in which test cues are available until the subject has responded. Experiment 3 addressed this question, and sought convergent evidence for the dissociation between two forms of priming in L.H., by examining priming in a word-stem completion task, in which subjects study a list of words and are asked subsequently (in the test phase) to complete three-letter word-stems with the first word that comes to mind. Because priming in this task depends in part upon perceptual processes (see below), and because the test cues (i.e., word stems) are available until a response is made, the task allowed us to determine whether L.H.'s visuo perceptual priming impairment generalizes beyond tasks in which test cues are presented very briefly. Furthermore, because priming in word-stem completion draws upon nonvisuo perceptual processes as well as visuo perceptual processes, and because those processes can be teased apart without altering the nature of the cues or response demands at test (as described below), this task afforded the opportunity to demonstrate a dissociation in L.H. under conditions in which only the basis of the priming effect (and not the nature of the test cues or response demands) varied.

Priming in word-stem completion is normal in amnesic patients (Warrington and Weiskrantz, 1970; Graf et al., 1984) and, therefore, independent of the limbic-diencephalic system supporting recall and recognition memory. Evidence that word-stem completion priming includes a perceptual contribution comes from demonstrations that the priming effect is reduced when the perceptual overlap between stimuli at study and test is minimized, e.g., when stimuli are presented in different perceptual modalities at study and test (Graf et al., 1985; Bassili et al., 1989; McClelland and Pring, 1991; Rajaram and Roediger, 1993). Evidence that the priming effect is not mediated solely by visuo perceptual processes comes from the fact that the effect is not eliminated when the perceptual overlap between stimuli at study and test is minimized (Graf et al., 1985; Bassili et al., 1989; McClelland and Pring, 1991; Rajaram and Roediger, 1993); this robust cross-modal effect indicates the participation of nonvisuo perceptual processes in word-stem completion priming.

In order to tease apart the contributions from two sources to priming in word-stem completion, we examined visual word-stem completion following visual or auditory study of words. Thus, in the study phase, words were presented either auditorily or visually, and in the test phase, each word stem was presented visually until the subject was able to generate a word to complete it. Normal subjects were expected to show (as they have in prior studies) greater priming in the within-modality (visual study-visual test) condition than in the cross-modality (auditory study-visual test) condition, due to the contribution of perceptual processes in the within-modality condition that do not contribute to performance in the cross-modality condition.

We predicted that L.H.'s performance would reflect an impairment of visuo perceptual priming processes, and sparing of nonperceptual priming processes. Specifically, we predicted that (i) he would show impaired priming in the within-modality condition (because that condition depends in part upon visuo perceptual priming processes impaired in L.H.); (ii) he would show normal priming in the cross-modality condition (because performance in that condition does not require the operation of the perceptual priming processes that are impaired in L.H.); (iii) he would show similar levels of priming in the two conditions (because his performance in both conditions would reflect only the contribution of nonperceptual priming processes). We also administered within- and cross-modality recognition memory tests, expecting that L.H. would show normal recognition memory performance as he did in the prior experiments. Further, because recognition memory in normal subjects is relatively insensitive to variations in the surface format (e.g., perceptual modality) of stimuli at study and test (Kirsner et al., 1983; Roediger and Blaxton, 1987; Keane et al., 1991), we expected that recognition memory performance would be similar within and across modalities.

Methods

Subjects
L.H. and his control group from Experiment 1A participated in this experiment.

Materials
The stimuli were 120 four- to seven-letter words, of medium frequency (mean = 97 per million) (Kucera and Francis, 1967). The stem (i.e., the first three letters) of each word was unique among the 120 words and constituted the beginnings of at least 10 entries in the Merriam-Webster Dictionary (1974). None of the 120 words was the most common completion given for its stem in a pilot study of 60 normal subjects. Twenty-four additional words served as filler items in the study task; none of these words began with the same stem as any of the test words. Of the 120 test words, 80 were used in the word-completion tasks, and 40 were used in the recognition memory tasks. For each of the 40 words to be used in the recognition memory tasks, we selected two other words that began with the same three-letter stem. These words were used as distractor items in a three-choice recognition test.

Procedure
The experiment comprised four study-test phases. In Phases 1 and 2, subjects studied a list of words presented visually (in one phase) or auditorily (in the other phase), and then performed a word-stem completion task in which word stems were presented visually. In Phases 3 and 4, subjects studied a list of words presented visually (in one phase) or auditorily (in the other phase), and then performed a three-choice
recognition task with visually presented words. The priming tasks (Phases 1 and 2) always preceded the recognition tasks (Phases 3 and 4) in order to minimize the likelihood that subjects would treat the word-stem completion task as a cued recall task. However, for the two priming phases and the two recognition phases, the order of administration of the within-modality (visual–visual) and cross-modality (auditory–visual) phases was counterbalanced across subjects. Further, within each of the two priming tasks (visual–visual and auditory–visual), the stimuli were counterbalanced across subjects so that each word appeared equally often in the studied or unstudied condition. Finally, in the recognition tasks, the stimuli were counterbalanced across subjects so that each word appeared equally often in the visual–visual or auditory–visual task.

In the visual study task, target words were presented one at a time on the screen of an IBM personal computer. In the auditory study task, words were spoken aloud by the experimenter. For each word, subjects were instructed to answer the question, “Is this word the name of an object that you could touch?” The study list contained 20 target words, in addition to three filler words at the beginning and end of the list.

In the word-completion task, 40 three-letter word stems were presented one at a time on a computer screen; subjects were asked to complete each stem with the first word that came to mind. Twenty of the stems corresponded to words that had appeared in the prior study list, and the other 20 corresponded to words that had not appeared in the study list. Performance with the unstudied stems provided a baseline measure of word-stem completion, i.e., a measure of the likelihood that stems would be completed to target words in the absence of recent exposure to those words.

In the recognition task, on each of 20 trials, three words appeared on a computer screen. One of these words had appeared in the study list; the other two words began with the same three-letter stem as the studied word. Subjects were instructed to read the words aloud and to select the word that had appeared in the study list.

Results

Word-completion priming

For each subject, and for each of the two study-test phases (visual–visual and auditory–visual), we calculated the percentage of target words produced in the baseline condition (i.e., the percentage of unstudied stems completed to target words), and the percentage of target words produced in the primed conditions (i.e., the percentage of studied stems completed to words from the prior study list) (Fig. 4). The priming score was the difference between the percentage of target words produced in the baseline and primed conditions.

Normal control subjects. The mean baseline scores for the control group were 9.2% in the visual–visual condition and 15.0% in the auditory–visual condition. The proportions of target exemplars produced following exposure to those words in a study list were 37.5% in the within-modality (visual study–visual test) condition, and 24.2% in the cross-modality (auditory study–visual test) condition. These data were submitted to a two-way repeated-measures ANOVA with factors of test condition (baseline versus primed) and study modality. Priming was indicated by a main effect of test condition \( F(1, 5) = 25.8, P < 0.01 \). An interaction between test condition and study modality \( F(1, 5) = 7.49, P < 0.05 \), indicated that priming was greater in the within-modality (28.3%) than in the cross-modality condition (9.2%).

L.H. L.H. performed two versions of the priming task on two separate occasions, separated by 4 weeks, so that we could obtain a measure of his performance with the same items counterbalanced across studied and unstudied conditions within each of the priming tasks (visual–visual and auditory–visual). The baseline scores for L.H. were 15.0% in the visual–visual task and 7.5% in the auditory–visual task. His scores in the primed conditions were 32.0% in the visual study–visual test priming task, and 27.5% in the auditory study–visual test priming task. L.H.’s priming in the within-modality condition (17%) was outside of the normal range (range 20–35%), and >2 SD below the normal mean (28.3%, SD = 5.16). His priming in the cross-modality condition (20%) was within the normal range (-10–40%), and within 1 SD of the normal mean (9.2%, SD = 16.9).

Recognition

For each subject, we calculated the percentage of correct responses in the three-choice visual recognition tests.
following visual or auditory study of words. Scores for L.H. represented means across two testing sessions (separated by 4 weeks), in which test stimuli were counterbalanced across studied and unstudied conditions. In the control group, the mean scores in the visual–visual (96.7%) and auditory–visual (92.5%) conditions did not differ by t test (P > 0.30). L.H.’s mean scores in the visual–visual (92.5%) and auditory–visual (87.5%) conditions were within the normal range (visual–visual condition = 85–100%; auditory–visual condition = 80–100%), and within 1 SD of the normal mean (visual–visual SD = 6.1; auditory–visual SD = 8.2).

Discussion

In Experiment 3, control subjects showed greater word-stem completion priming in a within-modality than in a cross-modality study-test condition. This finding replicates prior reports (Graf et al., 1985; Bassili et al., 1989; McClelland and Pring, 1991; Rajaram and Roediger, 1993), and demonstrates that priming in visual word-stem completion depends in part upon visuo-perceptual processes. L.H. showed impaired priming in the (within-modality) condition that depended upon the operation of those visuo-perceptual processes, and normal priming in the (cross-modality) condition that did not require the operation of those processes. L.H.’s impaired priming in the within-modality condition replicates the visuo-perceptual priming impairment observed in Experiments 1A and 1B, and demonstrates that this impairment is not restricted to tasks in which test cues are presented briefly, but extends to tasks in which test cues are available until a response is made. Furthermore, the dissociation between impaired within-modality and intact cross-modal word-stem completion priming in L.H. parallels the dissociation between visuo-perceptual priming and conceptual priming observed across Experiments 1 and 2, and demonstrates that this dissociation can be obtained when cues and response demands are held constant at test.

There is some debate about the nature of the mechanism underlying cross-modal word-completion priming. We have argued that the effect may reflect conceptual mechanisms (Keane et al., 1991; Gabrieli et al., 1994), whereas others have argued that the effect may reflect phonological or articulatory processes (Kirsner et al., 1989; Schacter, 1992). There is general agreement, however, that cross-modal word-completion priming does not require the participation of visuo-perceptual processes, and that the boost to the priming effect in the within-modality condition reflects the additional contribution of those visuo-perceptual processes. Therefore, regardless of the mechanism underlying cross-modal word-completion priming, L.H.’s performance suggests sparing of a non-visuo-perceptual priming process (reflected in the intact cross-modal priming effect) and impairment of a visuo-perceptual priming process (reflected in his failure to show the within-modality boost in priming).

The present experiment replicated the dissociation in L.H. between implicit and explicit memory performance that was observed in Experiment 1 in which L.H. showed impaired within-modality word-stem completion priming, but normal within-modality recognition performance. Coupled with prior reports in amnesic patients of normal within-modality word-stem completion priming and impaired within-modality recognition memory (Warrington and Weiskrantz, 1970; Graf et al., 1984), these results represent a double dissociation between implicit and explicit memory performance in L.H. and amnesic patients.

Finally, recognition memory (unlike word-stem completion priming) was unaffected by the perceptual manipulation in that visual recognition memory for words studied visually was equivalent to that for words studied auditorily. The lack of a perceptual effect is consistent with prior reports (Kirsner et al., 1983; Roediger and Blaxton, 1987; Keane et al., 1991), and provides a clue about why visual recognition memory is intact in L.H. Visual recognition memory judgments do not appear to draw upon information about the perceptual format of stimuli, and therefore, do not depend upon visuo-perceptual processes that underlie visuo-perceptual priming effects, and that are impaired in L.H.

General Discussion

Two major findings emerged from this study. First, implicit and explicit memory processes were doubly dissociated in L.H. and H.M. L.H. showed impaired priming in perceptual identification of words and pseudowords, but normal recognition memory for words and pseudowords. In contrast, H.M. showed normal priming in perceptual identification of words and pseudowords, but impaired recognition memory for those stimuli. In addition, L.H. showed impaired within-modality word-stem completion priming, and intact within-modality recognition memory, whereas amnesic patients have shown the opposite pattern of performance (Warrington and Weiskrantz, 1970; Graf et al., 1984). These double dissociations between visuo-perceptual priming and recognition memory provide compelling evidence that implicit and explicit memory processes are not subserved by a single neural system, but that at least one form of implicit memory (measured by visuo-perceptual priming) is supported by a neural system separate and independent of the system that supports explicit memory (measured by recognition memory).

Secondly, perceptual and conceptual priming effects were dissociated in L.H., providing the opposite dissociation to that observed in Alzheimer’s disease patients. L.H. demonstrated an absence of priming in two perceptual priming tasks (perceptual identification of words and pseudowords), but normal priming in a conceptual priming task (category exemplar production). Alzheimer’s disease patients, on the other hand, have shown impaired priming in category exemplar production (Monti et al., 1995), but normal priming in perceptual identification of words (Keane et al., 1991) and pseudowords (Keane et al., 1994). This double dissociation between perceptual and conceptual priming effects provides
strong evidence for the existence of two priming processes that depend upon separate neural systems.

Further, the present results demonstrated that these two priming processes can be dissociated from each other within one task. For example L.H. showed impaired within-modality stem-completion priming (an effect that depends in part upon visuo perceptual priming processes), but normal cross-modal stem-completion priming (an effect that does not depend upon visuo perceptual priming processes). L.H.’s within-modality stem-completion priming deficit suggests that his visuo perceptual priming impairment is not restricted to tasks in which stimuli are presented briefly (i.e. Experiment 1), but is evident also on a perceptually based priming task in which test stimuli are available until a response is generated.

Given the fact that L.H.’s lesion produced significant visuo perceptual impairments (e.g. an inability to recognize faces) one might ask whether his visuo perceptual priming deficit was a trivial consequence of a failure to perceive adequately the words during the study phases. Several pieces of evidence argue against this possibility. First, L.H. was able to read aloud the words presented at study, secondly, he showed normal conceptual priming for visually studied words and, thirdly, he showed normal recognition memory for visually studied words. These findings suggest that, despite his visuo perceptual impairments, L.H. was able to process and represent words through visual channels in a way that was sufficient to support some forms of memory for those words. Critically, however, those processes and representations were insufficient to support visuo perceptual priming effects.

The pattern of dissociations described above has also been demonstrated in a patient with a right occipital lesion (M.S. in Gabrieli et al., 1995). The similarity of the findings in L.H. and M.S. suggests that this pattern of dissociations is not spurious, but that it reflects a fractionation of implicit and explicit memory processes in the nervous system.

**Relationship between repetition priming and explicit memory**

The current findings demonstrate a double dissociation between visuo perceptual priming and recognition memory in L.H. and H.M., providing strong evidence that the processes supporting visuo perceptual priming do not make a necessary contribution to explicit memory performance. This double dissociation has a parallel in studies of normal cognition: priming in visuo perceptual identification is influenced by manipulations of the perceptual similarity of stimuli at study and test (e.g. Jacoby and Dallas, 1981; Jacoby, 1983; Kirsner et al., 1983; Keane et al., 1991; Rajaram and Roediger, 1993), but uninfluenced by manipulations of the level of semantic processing of stimuli at study (Jacoby and Dallas, 1981; Kirsner et al., 1983; Graf and Ryan, 1990), whereas recognition memory performance is often insensitive to perceptual manipulations (Kirsner et al., 1983; Roediger and Blaxton, 1987; Keane et al., 1991), but reliably affected by level-of-processing manipulations (Craik and Lockhart, 1972; Craik and Tulving, 1975). Thus, just as different brain lesions have opposite effects on visuo perceptual priming and recognition memory, so do two different kinds of experimental manipulations have opposite effects on these measures in normal cognition. Together, these findings provide convergent evidence that explicit memory can operate independently of the processes that support visuo perceptual priming.

These double dissociations impose constraints on dual-process theories (e.g. Mandler, 1980; Jacoby and Dallas, 1981), which postulate that recognition memory is based in part upon the same perceptual memory mechanisms that underlie perceptual priming effects. Two predictions follow from such models: (i) recognition memory, like perceptual priming, should be sensitive to manipulations affecting the perceptual similarity of stimuli at study and test; (ii) an impairment in perceptual priming should be accompanied by an impairment in recognition memory. The first prediction is countered by findings in normal cognition demonstrating that recognition memory is often insensitive to perceptual manipulations (Kirsner et al., 1983; Roediger and Blaxton, 1987; Keane et al., 1991). The second prediction is countered by the present findings demonstrating impaired visuo perceptual priming and intact recognition memory in L.H. Thus, contrary to dual-process theories, these findings suggest that recognition memory is not necessarily dependent upon perceptual memory processes of the kind that support perceptual priming.

It could be, however, that most recognition memory measures (including those used in the present study) are insufficiently sensitive to detect perceptual effects in normal cognition, or to detect a recognition memory deficit in L.H. Thus, it is possible that perceptual processes consistently make a contribution to recognition memory, but that the magnitude of that contribution (relative to other mechanisms) is too small to be detected in tasks like those used in the present study. According to this view, L.H. may have a subtle recognition memory deficit that was not detectable in the present tasks. Alternatively, it may be that perceptual processes make a critical, measurable contribution to recognition memory performance only under perceptually demanding conditions, or when other routes to recognition are unavailable (Johnston et al., 1985, 1991). Under such conditions, a perceptual component in normal recognition memory is detectable, and a recognition memory impairment in L.H. might be observable. Thus, the present findings in L.H. and prior findings in normal cognition (Kirsner et al., 1983; Roediger and Blaxton, 1987; Keane et al., 1991) do not disprove dual-process theories of recognition memory, but place constraints on such theories, demonstrating that visuo perceptual processes do not necessarily (i.e. under all conditions) make a measurable contribution to recognition memory.

Unlike visuo perceptual priming, conceptual priming has not been doubly dissociated from explicit memory. Amnesia
provides single dissociations between (intact) conceptual priming and (impaired) explicit memory (Shimamura and Squire, 1984; Graf et al., 1985), but no patient group has shown the reverse dissociation. Thus, although the processes that support conceptual priming can operate independently of explicit memory, it is not clear that explicit memory can operate in the absence of the processes subserving conceptual priming. Likewise, in normal cognition, it is difficult to dissociate conceptual priming from explicit memory. Like explicit memory task performance, conceptual priming effects are sensitive to levels-of-processing manipulations (Humann, 1990; Srinivas and Roediger, 1990; Keane et al., 1993) and are insensitive to perceptual manipulations (Srinivas and Roediger, 1990). These findings leave open the possibility that the processes supporting conceptual priming may be critical to explicit memory performance.

In summary, the evidence-to-date from studies in normal subjects and neurologically impaired patients suggests that the ability to remember explicitly recently encountered information does not necessarily rely on the processes and brain structures that support visuoafferential priming. It remains an open question whether explicit memory processes can operate independently of the processes and structures that support conceptual priming.

**Memory systems of the human brain**

The results of the present study add to a growing body of neuropsychological evidence demonstrating that the brain comprises multiple memory systems. The well-documented memory impairments in patients with circumscribed amnesia suggest that a limbie–diencephalic system is critical to the establishment and conscious retrieval of memories for recent experiences and for recently encountered information. Damage to this system produces deficits on explicit (direct) memory measures, such as recall and recognition tasks, but typically spares performance on implicit (indirect) measures, such as repetition priming and skill-learning tasks (Moscovitch et al., 1993; Squire et al., 1993). Thus, the limbie–diencephalic system plays a critical and unique role in explicit memory task performance.

The impairment of visuoafferential priming in L.H., coupled with the sparing of such effects in Alzheimer’s disease (Keane et al., 1991, 1994) and in amnesia (Cermak et al., 1985; Haist et al., 1991), suggests that visuoafferential priming depends upon neural circuits that are compromised in L.H., but spared in Alzheimer’s disease and in amnesia. L.H.’s lesions included the right temporal- and frontal-lobes, as well as the occipital lobe bilaterally. Although the neuropathology in early-stage Alzheimer’s disease patients is largely confined to medial-temporal lobe structures (Braak and Braak, 1991), the neuropathology in moderately demented Alzheimer’s disease patients typically includes the frontal and temporal lobes (Arnold et al., 1991; Braak and Braak, 1991). Because normal visuoafferential priming has been demonstrated even in moderately or severely demented Alzheimer’s disease patients (Keane et al., 1991, 1994), it is unlikely that frontal and temporal regions form the neural substrate of that form of memory. It is more plausible that visuoafferential priming depends upon the integrity of occipital circuits that are compromised in L.H., but relatively spared in Alzheimer’s disease (Arnold et al., 1991) and in amnesia (Squire, 1986). Several pieces of evidence support and refine this proposal, and highlight a critical role for the right posterior cortex in visuoafferential priming. First, a patient with a lesion restricted to the right occipital cortex exhibited a selective deficit in visuoafferential priming (Gabrieli et al., 1995), demonstrating that a right posterior lesion alone is sufficient to disrupt visuoafferential priming effects. Secondly, in a PET study in normal subjects (Squire et al., 1992), an area in right extrastriate cortex was selectively activated during performance of a visual word-stem completion priming task. Thirdly, in a study of work-completion priming with stimuli lateralized to the left or right visual field in normal subjects, the perceptually specific component of the priming effect appeared to be mediated by the right hemisphere (Marsiske et al., 1992). However, visuoafferential priming with words does not depend exclusively on right posterior cortices: Carlesimo et al. (1994) reported impaired visuoafferential priming in a dyslexic patient with a left posterior lesion. It is possible that left and right posterior cortices make qualitatively distinct contributions to visuoafferential priming effects. Further work will be needed to clarify the nature of these contributions.

Most of the neuropsychological evidence concerning the neural substrate of conceptual priming effects comes from behavioural studies of Alzheimer’s disease patients, who have shown impaired priming in category exemplar production (Monte et al., 1995), word association (Brandt et al., 1988; Huff et al., 1988; Salmon et al., 1988), and word-stem completion (Shimamura et al., 1987; Salmon et al., 1988; Heindel et al., 1989; Bondi and Kaszniak, 1991; Keane et al., 1991; Gabrieli et al., 1994). Because patients with circumscribed amnesia have shown normal performance on each of these tasks (Warrington and Weiskrantz, 1970; Graf et al., 1984, 1985; Shimamura and Squire, 1984; Keane et al., 1993), the priming deficit in Alzheimer’s disease patients must not reflect the medial-temporal lobe pathology common to Alzheimer’s disease and amnesia. Instead, the deficit may reflect neocortical pathology present in Alzheimer’s disease but absent in amnesia. Alzheimer’s disease patients have widespread neocortical pathology which includes higher-order (hetero-modal) cortices in temporal, parietal and frontal lobes (Arnold et al., 1991; Braak and Braak, 1991). Any of these regions could plausibly form the neural substrate of conceptual priming effects. Future studies will determine whether conceptual priming effects in different tasks (e.g. cross-modal word-stem completion, category exemplar production) reflect the operation of the same cognitive and neural mechanisms.
Conclusion
This study demonstrated a double dissociation between visuo-perceptual priming (an implicit memory measure) and recognition memory (an explicit memory measure) in L.H. and H.M., and, coupled with prior findings, a double dissociation between visuo-perceptual and conceptual priming in L.H. and Alzheimer’s disease patients. These results indicate that a memory system localized to the occipital lobe mediates visuo-perceptual priming effects. This system is independent of a limbic–diencephalic system supporting explicit memory task performance, and independent of neural circuits mediating conceptual priming effects.

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References


Roediger HL, Blaxton TA. Retrieval modes produce dissociations in memory for surface information. In: Gorfine DS, Hoffman


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