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Impaired word-stem completion priming but intact perceptual identification priming with novel words: evidence from the amnesic patient H.M.

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Abstract—We hypothesized that word-stem completion (WSC) priming and perceptual identification (PI) priming, two types of repetition priming, rely on different cognitive and neural mechanisms: WSC priming on a modification mechanism that influences lexical retrieval, and PI priming on plasticity in pre-lexical perceptual systems. We compared the priming performance of the amnesic patient H.M. with words that came into common usage after the onset of his amnesia, and thus were novel to him (post-1965 words), and with familiar (pre-1953) words. We also tested age- and education-matched normal control subjects (NCS) and a patient with anterograde amnesia of recent onset (P.N.). The modification hypothesis predicted that H.M. would fail to show WSC priming with post-1965 words because pre-existing lexical representations of the test stimuli would be necessary for priming to occur. H.M.'s WSC priming score in the post-1965 condition did not differ from 0, and was inferior to the performance of NCS and of P.N. In contrast, H.M. displayed normal WSC priming in the pre-1953 condition. H.M. also showed robust and equivalent levels of PI priming in both conditions. A final experiment demonstrated preserved post-1965 word PI priming in H.M. when his baseline performance was matched with his post-1965 WSC priming baseline score. Our results challenge models that assume that most kinds of verbal repetition priming rely on the same or similar perceptual mechanisms. © 1998 Elsevier Science Ltd. All rights reserved.

Introduction

Taxonomies of human memory distinguish declarative (explicit) memory, conscious recollection of facts and past events, from nondeclarative (implicit) memory, the influence of previous experience on task performance without conscious referral to stored information [1–3]. Declarative memory relies on the medial temporal-diencephalic system [4–12]. Many disparate mnemonic phenomena fall under the rubric of nondeclarative memory, including the acquisition of motor, perceptual, and problem solving skills, sensorimotor adaptation, classical conditioning, and repetition priming. The neural substrates for these phenomena are not well defined. The dissociation between declarative and nondeclarative memory derives in large part from studies of global amnesia, in which declarative memory is severely impaired, but nondeclarative memory can be intact, compared to the performance of healthy control subjects [6, 8, 13, 14]. The evidence to date suggests that every kind of nondeclarative memory depends upon brain areas outside the medial temporal-diencephalic system (but see [15]).

One type of nondeclarative memory, repetition priming, occurs when prior exposure to a stimulus biases or facilitates the processing of and response to the stimulus on subsequent exposures. This report will examine two kinds of repetition priming: word-stem completion (WSC) priming and perceptual identification (PI) priming. WSC priming is demonstrated when exposure to a word in a study list increased the likelihood that subjects will complete a three-letter stem to that word. Previous work has shown that severely amnesic subjects (including H.M.) show normal WSC priming with common nouns (e.g., [16–18]). The sparing of WSC priming in amnesia indicates that the medial temporal-lobe diencephalic system is not critical for WSC priming. Subjects with Alzheimer's disease (AD), however, whose pathology relatively spares primary sensory and motor cortices but disrupts high-order cortex in the temporal and parietal

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lobes [19], can be impaired on tests of WSC priming [16, 20–24] (but see [25]), suggesting that high-order (heteromodal) cortical areas may be an important neural substrate for this type of priming.

PI priming is demonstrated when subjects can identify previously studied words or pictures at shorter exposure durations than unstudied words or pictures. Research by Keane and colleagues [26] suggests that PI priming is mediated by posterior cortical areas: a patient with bilateral lesions in peristriate cortex, but with relatively intact heteromodal cortex in the parietal lobes, showed impaired performance on this task (but intact cross-modal WSC priming). In contrast, subjects with AD perform normally on tests of PI priming [22], suggesting that peristriate visual cortex can support learning on this task. Subsequently, Gabrieli *et al.* [27] reported impaired PI priming, but largely spared WSC priming,† in a patient with a right occipital-lobe lesion.

Some researchers have posited that WSC priming, like PI priming, is a perceptually based phenomenon [28–32]. For example, Squire and colleagues [28, 33] have argued that this kind of priming relies on transient change in perceptual circuits in posterior visual cortex when the task is administered in the visual modality. This view is consistent with reports from PET studies of decreased blood flow in occipital cortex when subjects performed WSC priming tasks [33–36]. These findings have been interpreted as suggestive that the processing of repeated presentations of a stimulus requires less neural activity than was required for the initial processing. Similarly, Schacter [32] has proposed that WSC priming is supported by a presemantic perceptual representation system that is housed in posterior cortex. Investigators in our laboratory have argued, however, that in addition to perceptual mechanisms, WSC priming relies on a lexical-semantic memory system localized in temporal and parietal circuits [16, 22, 37].

An early model of WSC priming, the trace activation model, proposed a lexical explanation of WSC priming [17, 38, 39]. According to this view, activation of the mnemonic representations of words in a study session [40, 41] would bias subsequent WSC by increasing the probability that the studied stimulus would be retrieved during the test session (a "hot tubes" effect [42]). Subsequent developments in our understanding of the physiological mechanisms and computational principles underlying cortical learning impel us to adopt "modification" [43] as a more appropriate characterization of this theorized mechanism than "activation". We will use the term "modification" to refer to this theorized mechanism of plasticity throughout this report. The modification hypothesis would predict that amnesic subjects would need a premorbid representation of a word in order to prime with that word in a WSC priming test.

The modification explanation of WSC priming may seem inconsistent with recent reports of intact repetition priming in H.M. and other amnesic patients with novel stimuli, including priming of perceptual grouping tendencies with novel geometric patterns [44–47], PI priming with pseudowords (e.g., [28, 48, 49]), and priming of "possible/impossible" judgments with novel objects [50]. These examples of intact repetition priming in amnesia employ stimuli that cannot have been represented in memory prior to the testing session, and therefore must arise from the establishment of new perceptual representations by the study episode (for examples of this argument, see [28, 32, 33, 51]). However, the repetition priming paradigms that reveal intact priming in amnesia with novel stimuli (PI, pattern completion, 3-dimensional object judgment) all rely on low-level perceptual processing of stimuli.

A considerable body of evidence suggests that the mechanisms underlying WSC priming have an important lexical component. Reports of robust cross-modal WSC priming (e.g., [27, 52–55]) and of robust WSC priming when studied words were inferred by the subjects from clues or from definitions (i.e., the studied words were neither visually nor auditorily presented) [52, 56], indicate that the WSC priming effect does not rely exclusively on perceptual continuity of stimuli between study and test.‡ Many studies have suggested that semantic elaboration of words at study enhances the WSC priming effect [17, 53, 57, 58] (but see [29, 59]). Finally, the evidence of impaired WSC priming (but intact PI priming) in AD [22, 27, 37], is consistent with the idea that WSC priming depends upon non-perceptual (perhaps lexical) processes. The empirical evidence cited in this paragraph is consistent with a modification model of WSC priming.

We also have theoretical motivation to consider a modification model of WSC priming. We believe that many examples of nondeclarative memory arise as byproducts of plasticity in brain systems whose primary function is not mnemonic. For example, motor learning (e.g., [13, 60]) and incomplete picture priming (e.g., [8, 61]) each can be interpreted as manifestations of bias or facilitation in an information processing system (the motor system or the visual system) that performs an operation (a movement or a visual discrimination) repeatedly. Thus, we do not characterize nondeclarative memory phenomena as reflective of a memory system (or systems), but rather as the result of memory in brain systems whose primary function is not mnemonic (e.g., the motor system or the visual system). This contrasts with the declarative

† Cross-modal WSC priming was intact in subject L.H. [26] and in subject M.S. [26], but intramodal priming was impaired for both subjects. We believe that the modality-shift manipulation isolates the lexical contribution to WSC priming, which we propose in this paper is mediated by a modification mechanism.

‡ The results from this type of study also indicate that WSC priming can have an important perceptual component, because changing case, font, or modality between study and test does reduce significantly the WSC priming effect (e.g., [27, 51, 53–55]).

memory system, a dedicated memory system that depends on circuitry in the medial temporal lobes that is specialized for the encoding and consolidation of associations into long-term memory. This theoretical orientation impels one to analyze carefully the processes (cognitive and/or neural) that are engaged by a task if one seeks to understand the mechanisms that support nondeclarative learning expressed through that task. In the case of WSC priming, the modification model is compelling because it takes into account the processes engaged by the WSC priming task: when asked to complete a three-letter stem to a word, a subject must engage in a lexical search and select an exemplar from among the lexical entries in this word-initial cohort [62]. Because lexical search is an important component of the WSC task, it is reasonable to hypothesize that the priming that can be expressed in the WSC task results from the biasing of this lexical search procedure. The modification model posits just such a mechanism. Our theoretical approach is best characterized as a component processes approach [63–65], and is consistent with a proceduralist view that "memory storage for an experience resides in the same neural units that processed that experience when it happened in the first place" [66].

In order to test the modification hypothesis, we studied WSC priming in the amnesic patient H.M., using words that came into common usage after the onset of his anterograde amnesia, and thus were novel to him. This hypothesis predicted that H.M. would fail to show learning in this experiment because the necessary pre-existing lexical representations of the test stimuli would be lacking. In contrast to the modification hypothesis, perceptually oriented explanations of WSC priming [30, 32, 33, 59] would predict that amnesic subjects should perform normally on a test of WSC priming with unfamiliar words, because low-level perceptual mechanisms would be engaged equally by familiar and by unfamiliar letter strings. All previous experiments that have found intact WSC priming in amnesic subjects (e.g., [16–18]) have used words that were familiar to the subjects. Therefore, the results of these experiments were equally consistent with the modification model and with perceptual models. The present experiment was designed to provide a definitive test between these two models because they predicted different results.

Experiment 1a: Word-Stem Completion Priming with Post-1965 Words

One earlier study has been performed to test a modification model by investigating WSC with unfamiliar words in amnesia and dementia [38]. This study employed a cued-recall procedure, and found impaired performance with pseudowords in the memory-impaired group. These results have no bearing on models of WSC priming, however, because control subjects in this study must have used declarative memory retrieval strategies when performing the WSC test [28]. The present study therefore represents the first methodologically clean test of the modification model of WSC priming.

Methods

Subjects

Two amnesic subjects, H.M. and P.N., and 10 NCS participated in this study (Table 1). H.M. underwent bilateral medial temporal lobectomy in 1953, at age 27, to alleviate intractable epilepsy (see [6, 7] for a summary of H.M.'s clinical and research history). P.N. was diagnosed with herpes simplex encephalitis in 1992, at age 58. In 1994 (approximately four months prior to testing), seizure activity and an associated hypoxic episode resulted in damage to both medial temporal-lobe regions; this episode has been linked to the onset of dense anterograde amnesia in P.N. The severity of P.N.'s amnesia was comparable to that of H.M. as indexed by the difference between the Full Scale I.Q. and the Memory Quotient or General Memory Score. For P.N. the difference was 38 (WAIS-R, F.S.I.Q. = 121; WMS-R, General Memory Score = 83; tested 5/94), and for H.M. the difference was 38.6 (Wechsler-Bellevue, II, F.S.I.Q. = 111.6; WMS, Memory Quotient = 73; tested 10/90). Like H.M., P.N. denied any familiarity with the testing procedures and apparatus despite repeated testing. None of the NCS had a history of neurological or psychiatric disorders, and all had a normal neurological examination at the time of testing. All subjects were born in the United States and were native English speakers.

Stimuli

The stimuli were 156 words that first appeared after 1965 in *Webster's Third New International Dictionary* or in *The American Heritage Dictionary* (assembled from the publication *12,000 Words: a supplement to the Webster's Third New International Dictionary*) (see Appendices). These words were presumed to be novel to H.M. because they came into popular usage after the onset of his amnesia. In contrast, these words were presumed to be familiar to P.N. because her amnesia was of recent onset. The words were chosen so as to be familiar to any native English speaker who had lived in the United States and had obtained a high school diploma there. The three-letter stem corresponding to each of the words could be completed to at least five common words. Of the 156 stimuli, 120 were divided randomly into six lists of 20 words each; each list was balanced for word length and for alphabetical position of the first letter. The mean frequency of the words was 16.9 per 44 million,§ and the mean length was 7.1 letters. The remaining 36 words were used as filler words. Each NCS, as well as P.N., was tested for priming on two lists, and for cued recall on two others; for the NCS, the lists were counterbalanced for both tests. H.M. was tested for priming using four of the lists, and for cued recall using the remaining two. To reduce the likelihood that NCS could invoke declarative memory strategies, we: (a)

§ Word frequency was determined using a database of every wire story issued by the Associated Press during the period February, 1988–December, 1988, using a stochastic part-of-speech analyzer [67]. We used this database rather than more conventional published corpora because the post-1965 words do not appear in corpora that were published several years prior to the appearance of these words.

Table 1. Subject characteristics for Experiment 1a

Group	Number of subjects (M/F)	Age (mean (and S.D.) for NCS)	Education (mean (and S.D.) for NCS)	Vocabulary sub-section of WAIS-R (mean (and S.D.) for NCS)	Snellen acuity (range for NCS)
NCS	10 (4/6)	68 (2.8)	12.4 (0.8)	11.6 (1.3)	20/20–20/30
H.M.	1 (M)	67	12	10	20/40
P.N.	1 (F)	60	16	16	20/30

used long study and test lists; (b) gave only brief presentation(s) of stimuli at the study phase, and just single presentations of each stem at test phase; and (c) administered all nondeclarative memory tests before testing declarative memory. (H.M. was administered two additional priming tests after taking the Cued Recall and Vocabulary Recognition Tests.)

Procedure

Subjects participated in two priming tests, followed by a test of cued recall and a test of recognition of the definitions of the words in our stimulus set (H.M. participated in additional testing, as discussed below). The WSC Priming Tests and WSC Cued Recall Test differed only in the instructions that were delivered immediately before the WSC portion of each test.

Study session

Subjects read words aloud as they were presented one-by-one for 5 s each on a computer screen. If a subject mispronounced a word, the experimenter gave the correct pronunciation and instructed her to repeat the correct pronunciation aloud. Half of the words of a 20-word list occurred once, and half occurred three times. We included this manipulation of study-repetitions because it has been used successfully in previous studies to draw inferences about the processes underlying the creation and strengthening of memory traces [68, 69]. Additionally, three filler words (taken from the remaining 36 stimuli) were inserted at the beginning and three filler words at the end of each list to control for primacy and recency effects, giving a total of 46 stimuli in each study list.

WSC Priming Test 1

Approximately 1 min following the study session, subjects viewed 40 three-letter stems one-by-one on a computer screen. Half of the stems corresponded to words in the study list, and half to words in another of the six lists that served as unstudied words. Word stems corresponding to the two lists were interleaved randomly. Subjects were asked to complete each stem with the first word that came to mind. Each stem remained on the screen until the subject responded, and response latency was recorded.

WSC Priming Test 2

The stimuli, study procedure, and test procedure for WSC Priming Test 2 were identical to those for WSC Priming Test 1, except that the studied and unstudied lists were reversed. In this way, each of the two lists served as a priming list and as an unstudied control list for each subject. This test followed WSC Priming Test 1 by at least 4 weeks (with the exception of subject P.N., who, 24 h after WSC Priming Test 1, performed WSC Priming Test 2). This delay minimized the likelihood that NCS would remember the procedure from the previous test, and thus minimized the likelihood that they would employ declarative retrieval strategies.

WSC Cued Recall Test

The study procedure was identical to that for the priming tests, except that new lists were used. The testing procedure differed from the priming tests in one respect only: after the study procedure, subjects were instructed to remember the words from the study list and to complete the word stems to the studied words. This test followed WSC Priming Test 2 by at least 4 weeks (with the exception of P.N., who performed the WSC Cued Recall Test 24 h after WSC Priming Test 2).

Vocabulary Recognition Test

Immediately following the WSC Cued Recall Test, subjects were administered a 4-alternative forced-choice vocabulary test, measuring their understanding of the meanings of the 120 words used as test stimuli. An example of a Vocabulary Recognition Test question is: "*biathlon*: (a) a marathon held annually in Boston; (b) a river with two tributaries; (c) a mansion with columns and arches characteristic of Roman architecture; (d) a composite athletic contest consisting of cross-country skiing and rifle sharp shooting".

Additional testing with H.M.

To gather more data from H.M., he received WSC Priming Test 3 and WSC Priming Test 4 after he performed the WSC Cued Recall Test and the Vocabulary Recognition Test. For these additional priming tests, we used the two word lists that had not been used previously in priming tests with H.M., but had been included in the Vocabulary Recognition Test, which preceded the administration of WSC Priming Test 3 by 14 weeks, and the administration of WSC Priming Test 4 by 21 weeks. H.M. also performed a test of Recall-of-Definitions of all 114 words used in this experiment. In this test, he viewed each word individually and gave the definition of that word. He performed this test the day after he performed WSC Priming Test 3, i.e., 7 weeks before he performed WSC Priming Test 4.

Scoring

We calculated priming and cued recall scores as the number of stems completed to studied words minus the baseline score of stems completed to unstudied words from the word list (completions to words other than those on the studied and unstudied list were not scored). In order to assess the subjects' familiarity with the words, the experimenter noted whether they pronounced the words in the study lists correctly, before receiving assistance from the experimenter.

After the experiment was concluded, we discarded six words from the analysis, one from each list. Most NCS (and in some cases H.M.) completed stems to five of these words in several unstudied trials, and thus decreased our confidence that we were measuring nondeclarative memory for these words in priming trials. We discarded an additional word when we realized, after the administration of the tests, that the three-letter stem of that word was itself a word ("codon").

Results

Vocabulary

NCS achieved 84.8% correct on the Vocabulary Recognition Test, which was significantly higher than H.M.'s score of 43.9% ($t=19.12$; $P=0.0001$), and significantly lower than P.N.'s score of 95.6% ($t=-5.13$; $P<0.001$). NCS recognized significantly more definitions of correctly pronounced (89.3% correct) than of mispronounced (73.4% correct) words ($t=2.64$; $P<0.05$). When subsequently asked to provide the definitions of the 114 words used in this experiment, H.M. correctly gave the definition of 13.2% of them.

WSC Priming vs WSC Cued Recall

In order to establish that NCS completed more stems to studied words on the WSC Cued Recall Test than on the WSC Priming Tests, we analyzed the NCS data with a factorial repeated measures ANOVA, with the factors of session (WSC Priming Test 1, WSC Priming Test 2, Cued Recall) and repetitions-at-study (0, 1, 3); the dependent measure was percentage of stems completed to target words. A significant Session × Repetition interaction ($F=6.24$; $P<0.001$), indicated that the difference between the number of completions to target words for 0 repetitions vs 1 and 3 repetitions for the Cued Recall session was significantly greater than that for the Priming sessions ($F=23.96$; $P<0.001$). Similarly, repetition of words at study had a stronger effect on the WSC Cued Recall Test than on the Priming Tests. The mean score for the 3-repetition study condition was significantly higher than that for the 1-repetition study condition ($F=6.31$; $P<0.05$). The mean scores for the 0-repetition condition, i.e., the unstudied condition, were virtually identical across sessions. We then performed separate ANOVAs to examine performance in the Priming Tests and the Cued Recall Test separately.

WSC priming

NCS showed a repetition priming effect by completing 16.1% more word stems to studied words than to unstudied words (mean total completions to studied words, collapsed across sessions and repetitions, = 20.8%; mean total completions to unstudied words, collapsed across sessions, = 4.8%) (Fig. 1). A factorial repeated-measures ANOVA with the factors of session (WSC Priming Test 1 and WSC Priming Test 2) and repetitions-at-study (0, 1, 3) revealed a main effect of repetition ($F=20.71$; $P<0.0001$). The absence of a main effect of session and of an interaction indicated that priming levels did not differ between WSC Priming Test 1 and WSC Priming Test 2, so subsequent comparisons of NCS with the amnesic subjects in this study employed NCS priming scores collapsed across the two priming tests. NCS completed significantly more stems to studied words (1 and 3 repetitions) than to unstudied words (0 repetitions) ($F=45.09$; $P<0.0001$) and significantly more stems to words with 3 repetitions than with 1 ($F=9.48$; $P<0.05$).

An additional analysis of NCS performance examined the percentage of stems completed to studied words by whether the words were pronounced correctly during the Study Session. Paired t tests indicated that completion of stems to correctly pronounced 1-repetition words (mean completion score = 16.7%) was significantly greater than completion of stems to mispronounced 1-repetition words (mean completion score = 3.3%), ($t=2.34$; $P<0.05$), and that completion of stems to correctly pronounced 3-repetition words (mean completion score = 32.6%) was significantly greater than completion

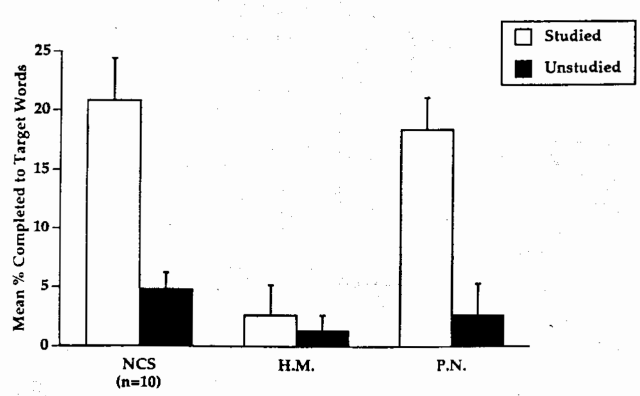

Fig. 1. WSC priming performance with post-1965 words by NCS, P.N., and H.M.; H.M. was significantly impaired relative to NCS.

of stems to mispronounced 3-repetition words (mean completion score = 0%), ($t = 13.00$; $P = 0.0001$) (Fig. 2). Many of the 3-repetition words that were mispronounced by NCS were mispronounced more than once: NCS made a total of 90 pronunciation errors over the total of 900 single-word reading trials of 3-repetition words; 51% of the errors occurred on just one exposure of the word; 28% of errors occurred on two exposures of the word; and 21% of errors occurred on three exposures of the word.

H.M. completed only 1.3% more word stems to studied than to unstudied words (mean total completions to studied words = 2.6%; mean total completions to unstudied words = 1.3%) (Fig. 1). A t test indicated that H.M.'s mean priming score did not differ from 0 ($t = 0.4$; $P > 0.7$). It is important to note, however, that although H.M. did not show a priming effect, he completed word stems fluently and had no difficulty producing an appropriate completion for virtually every word stem. We compared H.M.'s performance with the performance of NCS by subtracting H.M.'s mean priming score from the score of each NCS, and then performing a t-test to determine whether the mean of these difference scores was significantly different from 0. This analysis indicated that the mean net priming score of NCS differed significantly from the value for H.M. ($t = 6.58$; $P = 0.0001$). H.M. mispronounced a study word on 49% of the 228 reading trials presented to him in the course of his testing.

P.N. completed 15.8% more stems to studied than to unstudied words (mean total completions to studied words = 18.4%; mean total completions to unstudied words = 2.6%) (Fig. 1). The mean net priming score for P.N. did not differ significantly from the mean score for NCS. She did not mispronounce any words.

WSC Cued Recall

On the WSC Cued Recall Test, NCS benefited from study by completing 35.3% more word stems to studied words than to unstudied words (mean total completions to studied words, collapsed across repetition, = 39.5%; mean total completions to unstudied words = 4.2%) (Fig. 3). A factorial repeated-measures ANOVA examining performance on the WSC Cued Recall Test with the factor of repetitions-at-study (0, 1, 3) revealed a main effect of repetition ($F = 45.79$; $P < 0.0001$). NCS completed significantly more stems to studied words (1 and 3 repetitions) than to unstudied words (0 repetitions) ($F = 55.48$; $P = 0.0001$), and significantly more stems to words with 3 repetitions than with 1 ($F = 32.93$; $P < 0.0005$).

NCS correctly completed 3-letter stems to 57.9% of correctly pronounced 3-repetition words and to 30.2% of mispronounced words; they correctly completed 3-letter stems to 24.1% of correctly pronounced 1-repetition words and to 10% of mispronounced 1-repetition words. During the WSC Cued Recall Test only 5 NCS made pronunciation errors while studying 1-repetition words, and only 8 NCS made pronunciation errors while studying 3-repetition words, so significance tests comparing the results for correctly pronounced vs mispronounced words were not carried out.

H.M. showed only a slight advantage of study on the WSC Cued Recall Test, correctly completing 5.3% more word stems to studied words than to unstudied words (mean total completions to studied words = 5.3%, mean total completions to unstudied words = 0%) (Fig. 3). P.N. completed 15.8% more word stems to studied words than to unstudied words (total completions to studied words = 15.8%; total completions to unstudied words = 0%) (Fig. 3). Nonparametric Wilcoxon Signed Rank tests indicated that H.M.'s value and P.N.'s value were significantly lower than that for NCS ($P < 0.005$ for both).

Discussion

We tested the hypothesis that WSC priming in amnesia depends upon modification of premorbid representations of the stimuli with which priming is tested, and thus

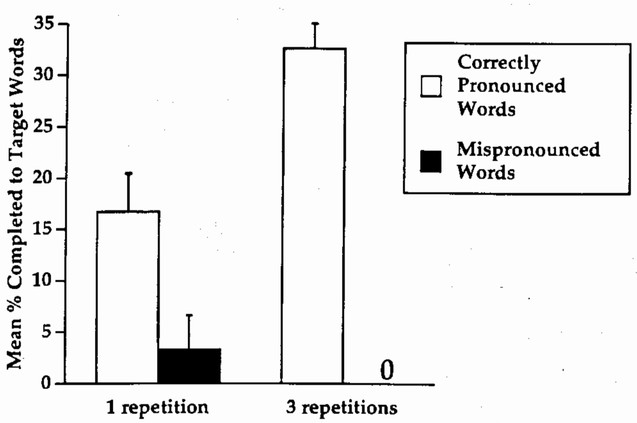

Fig. 2. Post-1965 WSC priming: NCS correctly completed significantly more correctly pronounced one-repetition words than mispronounced one-repetition words; they correctly completed significantly more correctly pronounced three-repetition words than mispronounced three-repetition words.

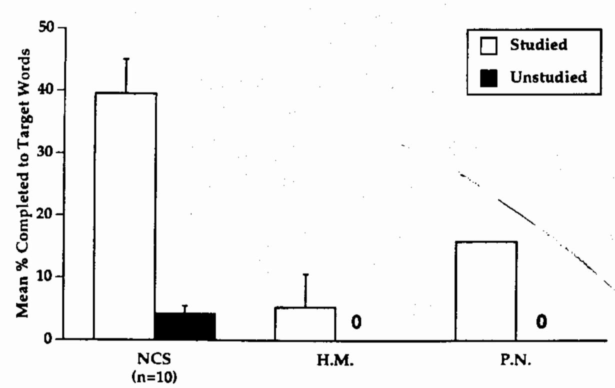

Fig. 3. Post-1965 cued recall performance of NCS, P.N., and H.M.; H.M. and P.N. were significantly impaired relative to NCS.

that it depends upon lexical memory. Using words that entered the dictionary a minimum of 12 years after the onset of H.M.'s amnesia, we compared his priming performance to that of a group of NCS and to a patient with amnesia of recent onset (P.N.). H.M. did not prime with the post-1965 material, as contrasted with robust priming for the NCS and for P.N. P.N.'s normal WSC priming performance indicates that dense amnesia alone cannot explain H.M.'s results. H.M. was also significantly impaired relative to NCS on a declarative memory test of WSC, as well as on a test of the meanings of the 114 words in the post-1965 stimulus set. His multiple-choice Vocabulary Recognition Test score of 43.9%, which was well above chance, illustrates his use of his intelligence when he did not know the meanings of words. For example, when asked to define the words, he said *biathlon* is: "A Greek word for a foot race between two people"; and that *psychedelia* is: "Study of the mind—*psyche* is the mind, *delia* is the study of it". These responses suggest that, when he did not know the meaning of a word, H.M. attempted to derive it by analyzing the components of the word. We believe that H.M.'s score of 13.2% correct on the test of recall of the definitions of the 114 post-1965 words is a more accurate index of his familiarity with them. P.N. was also impaired relative to NCS on the WSC Cued Recall Test. She scored significantly higher than NCS on the Vocabulary Recognition Test, a reflection of her higher overall intelligence.

The results of Experiment 1a were consistent with the modification hypothesis of WSC priming, but inconsistent with strong versions of perceptual hypotheses of WSC priming. We concluded from this result that modification of pre-existing lexical representations is partly responsible for the WSC priming effect, and necessary for this effect to be expressed. This conclusion was prompted by our task analysis, which indicated that the WSC task requires subjects to engage in lexical retrieval.

There are three possible alternative interpretations of these results. First, it is possible that the absence of a WSC priming effect for H.M. is an artifact of the test instructions to "complete each stem to the first *word* that comes to mind". That is, completion of a three-letter stem by H.M. to a post-1965 word that is not represented in his mental lexicon might be interpreted (by H.M.) as a violation of the WSC instructions. We do not have data from experiments with H.M. that address this concern directly. We have, however, rejected this alternative explanation of the null result in unfamiliar WSC priming in tests of college students [70], by instructing subjects to complete 3-letter stems to "the first *sound* that comes to mind", and to "the first *letter-string* that comes to mind". The results of these experiments [70] replicate the results presented in Experiment 1a in this report. Second, interpretation of H.M.'s WSC priming performance is complicated by a mean baseline score of 0. Because there is no way to raise baseline performance with unfamiliar words on the WSC task we could not take any simple steps to make interpretation of the results of Experiment 1a more straightforward. The important theoretical point of this paper, however, derives from the dissociation between WSC priming and PI priming that is produced by the manipulation of stimulus familiarity. We were able, therefore, to strengthen our theoretical argument by producing post-1965 word PI priming data in H.M. with baseline scores comparable to those produced by Experiment 1a. These data are presented in Experiment 2b in this report. Third, the failure of H.M. to display WSC priming with post-1965 words might have resulted from a simple inability on the part of H.M. to produce priming in the WSC task, rather than from our experimental manipulation of word familiarity. A test of this alternative hypothesis is presented in Experiment 1b.

Experiment 1b: Word-stem Completion Priming with Pre-1953 Words

Although previous research had demonstrated that H.M. can exhibit normal WSC priming with words that are familiar to him [16], we sought with this experiment to confirm that H.M. could show WSC priming with familiar words that were matched for length and frequency with the post-1965 words used in Experiment 1a, and presented with the same testing procedures. The modification model and the perceptual models of WSC priming each predicted that H.M. would show normal WSC priming with words for which he *did* have a premorbidly acquired lexical representation.

Methods

Subjects

H.M. and 10 NCS participated in this study (Table 2). None of the NCS had a history of neurological or psychiatric disorders, and all had a normal neurological examination at the time of testing. All subjects were born in the United States and were native English speakers. Four of the NCS had participated in Experiment 1a.

Stimuli

The stimuli were 80 words that had been in common usage in the United States long before 1953 (first appearance of each word was determined from its entry in *Webster's Third New International Dictionary* or *The American Heritage Dictionary*) (Appendix B). The words were matched closely for frequency (mean = 16.7/44 million) and length (mean = 6.8 letters) to the post-1965 words used in Experiment 1a, and were judged to be familiar to any native English speaker who had lived in the United States and had obtained a high school diploma there. These words were presumed to be familiar to H.M. because he would have learned them before the onset of his amnesia. The three-letter stem corresponding to each of the words could be completed to at least five common words. The 80 words were divided randomly into four lists of 20 words each; each list was balanced for word length and for alphabetical position of the first letter. An additional 24 "pre-1953" words were used as

Table 2. Subject characteristics for Experiment 1b

Group	Number of subjects (M/F)	Age (mean (and S.D.) for NCS)	Education (mean (and S.D.) for NCS)	Vocabulary sub-section of WAIS-R (mean (and S.D.) for NCS)	Snellen acuity (range for NCS)
NCS	10 (4/6)	68.9 (2.4)	11.8 (0.7)	12.0 (1.9)	20/20–20/30
H.M.	1 (M)	67	12	10	20/40

filler words. Each NCS was tested for WSC priming with one list.

Procedure

The procedures for administering and scoring the WSC priming test were identical to those used for the WSC priming tests in Experiment 1a.

Additional testing with H.M.

To gather more data from H.M., he was administered 10 WSC priming tests.

Vocabulary Recognition Test

Immediately following the WSC priming test, subjects were administered a 4-alternative forced-choice vocabulary test, measuring their understanding of the meanings of the 80 words used as test stimuli. H.M. was administered the test upon completion of the 10th WSC priming test.

Results

Vocabulary

The NCS achieved a mean score of 97.5% correct on the Vocabulary Recognition Test; H.M. scored 80.2% correct, confirming that the majority of the pre-1953 words were familiar to him.

WSC priming

NCS showed a repetition priming effect by completing significantly more word stems to studied words (mean = 28.5%) than to unstudied words (mean = 10%) ($t = 6.2$, $P < 0.0005$) (Fig. 4). Similarly, H.M. showed a repetition priming effect by completing significantly more word stems to studied words (mean = 35%) than to unstudied words (mean = 14.2%) ($t = 4.3$, $P < 0.01$) (Fig. 4). The mean net priming score of NCS (18.5%) did not differ significantly from the value for H.M. (20.8%) (Wilcoxon Rank Sums test $P > 0.6$).

Discussion

The results of Experiment 1b confirmed that H.M. shows normal WSC priming when tested with words that are familiar to him. This result strengthens our conclusions from Experiment 1a, that WSC priming arises from the modification of lexical representations, because H.M. showed normal WSC priming on words for which he had a lexical representation, and showed no WSC priming with words for which he lacked a lexical representation.

Experiment 2a: Perceptual Identification Priming with Pre-1953 and Post-1965 Words

After finding a clear dissociation in H.M.'s WSC priming performance with pre-1953 and post-1965 words, we

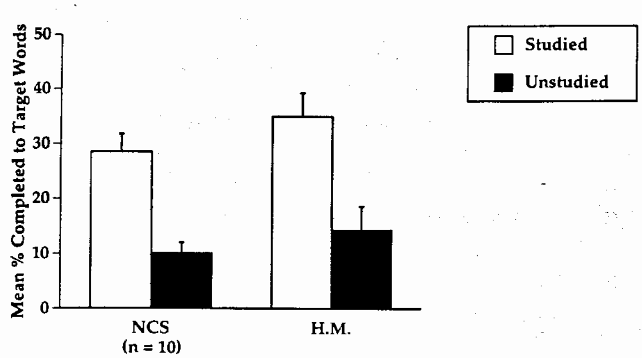

Fig. 4. WSC priming performance with pre-1953 words by NCS, P.N., and H.M.; H.M. was significantly impaired relative to NCS.

sought to measure his performance with the same words using a repetition priming task that relied on perceptual mechanisms: perceptual identification (PI) priming. Task analysis suggested to us that the PI task, in which subjects are asked to identify visually presented words whose perception is rendered difficult by a short exposure duration or by visual noise, places heavy demands on early (prelexical) stages of the visual system. We reasoned that, because subjects participating in such a test typically either perceive the word immediately or cannot discern it at all, an active, deliberate search of the lexicon is never required. Therefore, we hypothesized that the learning that is expressed in PI priming experiments results from plastic changes that occur at a locus different from the locus of the WSC priming effect, and that different mechanisms might mediate these two kinds of nondeclarative learning. The preponderance of published data supports the view that the learning observed in PI priming experiments depends on unambiguously perceptual mechanisms. For example, the PI priming effect is largely abolished when the modality of stimulus presentation is changed between study and test (e.g., [22, 30, 71]). Additionally, intact PI priming is found in normal and memory impaired subjects tested with pseudowords (e.g., [28, 43, 49, 70, 72–75]), indicating that the learning is supported by the biasing of pre-semantic perceptual mechanisms (i.e., the learning *cannot* take place at the level of lexical representations). Preserved PI priming by H.M. with the post-1965 words used in Experiment 1a would demonstrate a dissociation from WSC priming, and would be consistent with our hypothesis that the two types of priming rely on different mechanisms. Intact PI priming with pseudowords by H.M. in earlier experiments from our laboratory [26, 48] led us to predict that H.M. should show robust PI priming with post-1965 words.

Methods

Subjects

Two amnesic subjects, H.M. and P.N., and 19 NCS participated in this study (Table 3). None of the NCS had a history of neurological or psychiatric disorders, and all had a normal neurological examination at the time of testing. All subjects were born in the United States and were native English speakers. Three of the NCS had participated in Experiments 1a and 1b; two had participated in 1a, and two had participated in 1b.

Design

The experimental design of Experiment 2a was formally identical to the design of the WSC priming experiments, with the exception that each subject was tested in both conditions (pre-1953 and post-1965), permitting repeated measures analyses of the data. Testing sessions for NCS were separated by at least 4 h for all subjects, and the order of testing was counterbalanced across NCS. Additional dependent measures for the PI priming experiment were threshold exposure duration by word length ("short" words were $<$ or $=$ 8 letters; "long" words were $>$ 8 letters) and priming score by word length. The Vocabulary Recognition Test was not administered in Experiment 2a.

Materials

The word stimuli used in Experiment 2a were the same as those in the previous experiments.

Procedure

Apparatus. The words were presented sequentially using two high speed random access slide projectors (Kodak EktaPro 7000) fitted with high speed shutters (Gerbrands G1166) that were controlled by a computer (Macintosh IIcx). The words were flashed on a rear projection screen in a dimiy lit room. Word stimuli were presented in the same font and the same size as in Experiments 1a and 1b, as well as at the same level contrast. Each subject sat approximately 24 in. from the screen.

Threshold session. This session determined for each subject the stimulus exposure duration that would result in 50% correct identification performance with unstudied words. An unstudied baseline performance of approximately 50% correct would insure that the performance of subjects on the PI priming test would not be contaminated by floor or ceiling effects. Subjects were told that each word would appear briefly on the screen, and they were asked to read each word aloud. Each trial consisted of a fixation cross (+) signaling the beginning of the trial (1000 ms), followed by a 900 ms blank interval, followed by a word presented for a variable exposure duration, followed immediately (ISI $=$ 0 ms) by a pattern mask of 250 ms in duration. During the Threshold Session we determined the 50% correct

Table 3. Subject characteristics for Experiment 2a

Group	Number of subjects (M/F)	Age (mean (and S.D.) for NCS)	Education (mean (and S.D.) for NCS)	Vocabulary sub-section of WAIS-R (mean (and S.D.) for NCS)	Snellen acuity (range for NCS)
NCS	19	68.5	12.4	11.4	20/20–20/30
	(10.9)	(2.8)	(0.9)	(1.3)	
H.M.	1 (M)	69	12	10	20/40
P.N.	1 (F)	62	16	16	20/30

performance exposure threshold for each subject at each word length (long and short) by using an adaptive staircase procedure (the Step Method [76]). After each trial, the experimenter entered a score of "correct" or "incorrect" into the computer that controlled the shutters on the slide projectors, and the Step Method algorithm governing the computer used this information to adjust the exposure duration for the subsequent trial. Each block contained 45 trials, and the mean of the results of two threshold blocks yielded the exposure duration that was used to test subjects during the Priming Test. Two threshold blocks used short words and two used long words. The word stimuli used in the Threshold Session in both conditions were pre-1953 words (different from the words used in the priming tests). Because these words were familiar to H.M., the Step Method underestimated his 50% thresholds for words in the post-1965 condition, particularly for long words. We determined the long word exposure duration for H.M. in the post-1965 condition by increasing the estimate from the Threshold Session by approximately 190%, a factor that we determined during pilot testing.

Study session. The study session was identical to that described in Experiment 1.

Priming test. Subjects were shown 40 words one-by-one on the screen using the same presentation procedure as in the Threshold Session. The exposure durations for short words and for long words had been determined for each subject during the Threshold Session. Half of the words in each test had been presented in the previous study session. The other half were words that had not been studied. The priming effect was the number of correctly identified studied words minus the baseline score of correctly identified unstudied words. We discounted data from tests in which baseline scores were <20% or >80% correct in order to avoid floor and ceiling effects. In these instances, subjects were retested (with a different test form) during a later session.

Additional testing for amnesic subjects

To increase the number of observations with the amnesic subjects, H.M. was tested 11 times in the pre-1953 condition and 14 times in the post-1965 condition; P.N. was tested 4 times in the pre-1953 condition and 4 times in the post-1965 condition. For each subject, each testing session was separated by at least 6 h, and each test in the same condition was separated by at least one day. Because H.M.'s testing was performed during 4 separate multi-day visits to our laboratory over a period of 13 months, we considered each of his PI priming scores to be an independent observation for the purpose of our analyses.¶

Results

Threshold session

Analysis of the NCS, mean exposure durations with a 2×2 mixed factors ANOVA revealed main effects of condition ($F(1,18)=9.9$; $P>0.005$) and word-length ($F(1,18)=29$; $P<0.001$), and a tendency toward an interaction ($F(1,18)=3$; $P=0.1$) (Table 4). H.M.'s mean exposure duration data were also submitted to a 2×2 mixed factors ANOVA, that revealed main effects of condition ($F(1,24)=120.3$; $P>0.0001$) and word-length ($F(1,24)=116.4$; $P<0.0001$) and an interaction ($F(1,24)=70.9$; $P<0.0001$). Because P.N. was only tested 4 times in each condition, her data were not analyzed with inferential statistics (Table 4).

Table 4. Mean exposure durations for Experiment 2a (ms)

	Pre-1953		Post-1965	
Group	Short (S.D.)	Long (S.D.)	Short (S.D.)	Long (S.D.)
NCS	53.1 (19.8)	75.5 (36.4)	68.5 (27.8)	99.7 (49.5)
H.M.	74.1 (19.7)	99.9 (40.3)	126.6 (29.5)	336.1 (66.4)
P.N.	25.8 (3.0)	33.0 (7.4)	49.5 (7.9)	69.0 (15.1)

Priming test

The NCS, in both conditions, correctly identified more studied words (pre-1953 mean=75.2%; post-1965 mean=69.2%) than unstudied words (pre-1953 mean=50.5%; post-1965 mean=35.3%) (Fig. 5). A 2×2 between- and within-factors ANOVA, with the factors of study-type and condition, revealed a main effect of study ($F(1,18)=154.9$; $P<0.0001$), a main effect of condition ($F(1,18)=7.6$; $P<0.05$), and an interaction ($F(1,18)=5.2$; $P=0.05$). Planned comparisons confirmed that there was a significant priming effect with pre-1953 words (24.7%) ($t(18)=7.8$; $P<0.0001$) and with post-1965 words (33.9%) ($t(18)=11.8$; $P<0.0001$). A post-hoc t test indicated that the source of the interaction was the difference in baseline scores for the two conditions (post-1965 baseline score=37.2; pre-1953 baseline score=49.5) ($t(18)=3.4$; $P<0.005$) (Fig. 5). The difference in baseline

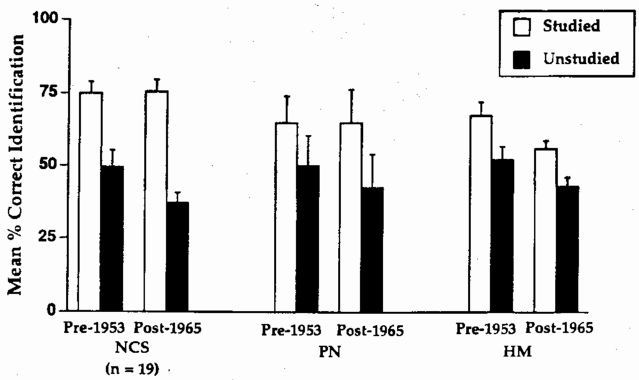

Fig. 5. PI priming by NCS, P.N., and H.M. H.M. was significantly impaired relative to NCS in both conditions; and H.M.'s corrected priming scores did not differ across conditions.

¶The autoregressive-moving average (ARMA) analysis that could be used to remove the autocorrelative component from multiple scores obtained from one subject requires a minimum of 50 observations, and therefore we did not use it.

scores, which also appeared in the data of the two amnesic subjects, will be considered in the Discussion section.

The analysis of NCS' mean correct identification of studied words by repetitions-at-study (pre-1953: 3 repetitions = 81.8%, 1 repetition = 68.7%; post-1965: 3 repetitions = 70%, 1 repetition = 64.7%) with a 2×2 between- and within-factors ANOVA with factors of condition and repetitions-at-study revealed a main effect of repetition ($F(1,18)=5.8$; $P<0.05$), a borderline significant effect of condition ($F(1,18)=3.3$; $P=0.09$), and no interaction.

Pronunciation errors during the Study Session were made by 10 NCS in the pre-1953 condition (total of 20 words mispronounced), and by 13 NCS in the post-1965 condition (total of 44 words mispronounced). In the pre-1953 condition, NCS correctly identified 79.8% of studied words that were pronounced correctly at study, and identified correctly 60.4% of studied words that were mispronounced at study; in the post-1965 condition, NCS correctly identified 78% of studied words that were pronounced correctly at study, and 46.6% of studied words that were mispronounced at study. These percentages, however, are skewed by the small number of observations in the "mispronounced" category. In the pre-1953 condition, 7 of the 10 subjects who mispronounced at study made just one pronunciation error, and thus their percentage identification of mispronounced words was either 100% ($n=4$) or 0% ($n=3$). Similarly, in the post-1965 condition, 4 of the 13 subjects who mispronounced at study made just one pronunciation error, and thus their percentage identification of mispronounced words was either 100% ($n=1$) or 0% ($n=3$). The small number of observations and high degree of variability in these data prevented meaningful statistical analysis.

H.M., in both conditions, correctly identified more studied words (pre-1953 mean = 67.4%; post = 1965 mean = 55.9%) than unstudied words (pre-1953 mean = 52.1%; post-1965 mean = 42.9%). A 2×2 between- and within-factors ANOVA, with the factors of condition and study, confirmed that this priming effect was significant, and revealed that H.M.'s performance did not differ between the two conditions (main effect of study ($F(1,24)=18.9$; $P<0.0005$), and main effect of condition ($F(1,24)=6.2$; $P<0.05$), with no interaction (Fig. 5). H.M.'s mean priming score was significantly lower than the NCS mean priming score in the pre-1953 condition ($t(17)=3.1$; $P<0.001$) and in the post-1965 condition ($t(17)=7.3$; $P<0.0001$).

Analysis of H.M.'s mean correct identification of studied words by repetitions-at-study (pre-1953: 3 repetitions = 65.5%, 1 repetition = 66.5%; post-1965: 3 repetitions = 62.1%, 1 repetition = 49.6%) with a 2×2 between- and within-factors ANOVA with factors of condition and repetitions-at-study revealed no significant effects, although the mean effect of condition ($F(1,22)=2.6$; $P=0.12$), and the interaction ($F(1,22)=2.5$; $P=0.13$) approached significance. Because the results of an earlier study [70] predicted a significant interaction, we performed planned t-tests to compare H.M.'s performance by repetition category across conditions. The across-conditions difference in 1-repetition performance was marginally significant ($t(22)=1.9$; $P=0.07$) whereas there was no suggestion of a difference in 3-repetition performance.

The limited number of observations with P.N. precluded statistical analysis of her data. Inspection of her results, however, indicated that she displayed comparable levels of priming in the two conditions (pre-1953 studied identification = 65%; unstudied identification = 50%; post-1965 studied identification = 65%, unstudied identification = 42.5%) (Fig. 5).

Discussion

The result from Experiment 2a with the most theoretical importance, that H.M.'s PI priming performance was insensitive to the manipulation of familiarity, stands in stark contrast to the clear effect that this manipulation had on his WSC priming performance (reported in Experiments 1a and b). This result, confirming many previous reports of comparable (though not always equivalent) PI priming with familiar and unfamiliar stimuli (e.g., [28, 43, 48, 49, 70, 72, 74, 75]), is consistent with the claim that the learning observed in PI priming arises primarily from plasticity in perceptual, pre-lexical mechanisms. We believe that we found comparable PI priming in H.M. with pre-1953 and post-1965 words because the early visual system treats meaningful and nonmeaningful letter strings in the same way.|| The fact that H.M.'s mean PI priming score in the post-1965 condition was significantly lower than the NCS mean score does not weaken our interpretation, because H.M.'s mean PI priming score was also significantly lower than the NCS mean score in the pre-1953 condition; that is, his PI priming performance was insensitive to the manipulation of familiarity. The variance of this result from previous reports of intact (vis-a-vis NCS) PI priming in H.M. (e.g., [26]) may be explained by the difference in PI methods (single presentation at test vs repeated, progressively longer presentations [26]), in dependent variables (percentage-correct vs exposure-time [26]), or by the discrepancy in his age at the time of testing (69 years vs 62 years in [26]). In the present study, H.M. also required longer exposure durations than NCS at both word lengths in both conditions. This result reflects his overall slowness [6], which exists despite normal selective attentional capabilities [6]. Generalized slowness and passivity has also been observed in Penfield and Milner's [77] amnesic patient P.B. (Milner, B., pers. commun.). P.B.'s pro-

|| The model of PI priming proposed by Bowers [43], although concurring that a low-level perceptual mechanism supports PI priming with unfamiliar words, would posit that a *modification* mechanism supports PI priming with familiar words.

found amnesia was attributed to a large removal of the left hippocampus and left temporal (lateral) neocortex for the relief of intractable epilepsy, paired with unsuspected atrophy of his right hippocampus [78]. P.B. and H.M. are similar in that both also have amygdala lesions, unilaterally in P.B. and bilaterally in H.M.

The NCS' performance on the priming test also suggests differences from WSC priming. In the post-1965 condition of the WSC priming test, NCS completion rate for studied words that were mispronounced was lower than baseline completion rates. In the post-1965 PI priming test, in contrast, NCS identified correctly words that had been mispronounced at study at a rate that was numerically higher than the unstudied identification rate.

A distinctive pattern of the PI priming results for all subjects was that baseline identification was lower in the post-1965 condition than in the pre-1953 condition. We believe that this pattern in the data is an artifact resulting from the fact that 50% performance thresholds were determined using pre-1953 words. Although the two groups of words were matched carefully for frequency and for length, results of the Vocabulary Recognition Tests in Experiments 1a and b indicated that the pre-1953 words were more familiar to *all* subjects than the post-1965 words (dramatically so for H.M., subtly so for NCS). This difference in familiarity resulted in inaccuracies in estimating the exposure duration needed to achieve 50% baseline performance in the post-1965 condition (even though we took steps to account for this in determining post-1965 exposure durations for H.M.). This methodological complication does not detract from the result of principal theoretical importance of this study, however, because H.M.'s priming scores did not differ significantly across conditions.

Of greater concern for the overall theoretical goal of this report, however, is the difference between H.M.'s mean baseline score for post-1965 WSC priming (Experiment 1a) and for post-1965 PI priming. This concern is addressed in Experiment 2b.

Experiment 2b: "Floor-effect" Perceptual Identification Priming with Post-1965 Words

Our claim that WSC priming and PI priming rely primarily on different mechanisms depends on an interaction of nondeclarative memory test (WSC vs PI) and stimulus-type (pre-1953 vs post-1965) in H.M.'s data. Although the comparison of Experiments 1a and 2a demonstrates such an interaction, the possibility remains that this interaction is the spurious product of a scaling artifact [79, 80]. According to this alternative hypothesis, a WSC priming effect for post-1965 words might be concealed by the floor effect (mean baseline score of 0) in H.M.'s post-1965 WSC data, and if WSC with post-1965 words could be made less difficult, such that H.M. would complete a reasonable number of unstudied word-stems to target words, a post-1965 WSC priming effect might emerge. It is not possible, however, to test this alternative hypothesis by raising WSC baseline performance with unfamiliar words. We designed Experiment 2b, therefore, to generate an alternative solution to this problem: to produce post-1965 word PI data in H.M. with a floor effect. This approach does not avoid the difficulties of interpreting data contaminated by floor effect [79, 80]. It does, however, permit a direct comparison of post-1965 WSC priming and post-1965 PI priming, which represents an important test of our hypothesis. A demonstration of robust PI priming with post-1965 words in floor-effect conditions would permit a qualified rejection of the "scaling-artifact" alternative interpretation of the interaction that emerged from Experiments 1a and 2a.

Methods

Subjects

H.M. was the sole participant in this experiment. He was 70 years old at the time of testing.

Design, materials, and procedure

The experimental design of Experiment 2b was identical to the design of Experiment 2a, with the exception that H.M. was only tested with post-1965 words. Experiment 2b consisted of 15 floor-effect PI tests performed with H.M. over the course of seven consecutive days. We planned to conduct 15 test sessions before beginning the experiment, in order to permit comparison of the data from Experiment 2b with those from H.M. in Experiment 2a. Testing sessions were separated by at least 5 h; on two occasions H.M. was tested with the same stimulus list twice in the same day. The procedure and apparatus were identical to those used in Experiment 2a with the exception that, in the Threshold Sessions, we did not employ the Step Method, but determined the exposure duration that would product 0% correct identification of baseline words in H.M. by varying manually the exposure duration of a few preliminary trials.

Results

Threshold session

H.M.'s mean exposure duration data were: short 44 ms (S.D. = 10); long 59.7 (S.D. = 23.9).

Priming test

We limited our analyses to a test of the significance of the "floor-effect" PI priming effect, because this result was the only result required for hypothesis testing. H.M. identified correctly more studied words (mean = 10.0%) than unstudied words (mean = 5.3%). (Despite our efforts to determine the tachistoscopic exposure durations that would produce baseline identification rates of 0, H.M. identified correctly 3 baseline words on 2 of the tests in Experiment 2b, 2 baseline words on 1 of the tests, and 1 baseline word on 8 of the tests.) A paired *t*-test confirmed that the mean priming effect of 4.7% was significant ($t(14)=2.3$; $P<0.03$).

Discussion

The result of Experiment 2b, the persistence of a post-1965-word PI priming effect for H.M. under floor-effect baseline conditions, is at variance with the result of Experiment 1a, the absence of post-1965-word WSC priming at floor-effect baseline conditions. This is illustrated in Table 5, which compares directly H.M.'s post-1965 WSC priming performance with the sub-set of his post-1965 PI priming tests in which his baseline identification score was 0. This result palliates the concern that the absence of WSC priming in the post-1965 condition may have occurred artifactually due to a floor effect.

Finally, if we accept the validity of the Task × Familiarity interaction produced in these experiments, we are left with the challenge of interpreting a single dissociation. Single dissociations are vulnerable to the possibility that they merely reflect a disparity in the difficulty of two tasks, rather than an important qualitative difference. We are confident about the theoretical claims advanced in this report, however, because the pairing of our results, with those of a previous experiment in our laboratory [26] yields a double dissociation. In the present study a patient with disrupted lexical memory but an intact visual system demonstrated impaired WSC priming but (relatively) intact PI priming. Conversely, Keane and colleagues [26] have reported intact WSC priming (in a cross-modality condition) but absent PI priming in the visual agnosic patient L.H., who has intact lexical memory and a severely damaged visual system. This pattern of results is consistent with the assertion that WSC priming and PI priming arise from plasticity in disparate brain systems.

General Discussion

The finding with H.M. of impaired WSC priming, but robust PI priming, with novel stimuli is consistent with the view that distinct mechanisms support the learning that can be measured in each task. Although preserved PI priming with pseudowords has been reported previously in H.M. [26, 48], in patients with Alzheimer's disease [22], in Korsakoff's amnesics [73], and in a group of amnesic subjects with mixed etiologies [28], our study represents the first methodologically clean investigation of WSC priming with unfamiliar word stimuli in amnesia. A dissociation between these two tasks has also been reported in patients with Alzheimer's disease by Gabrieli, Keane, and colleagues [16, 22, 37]. They proposed that WSC priming relies on a lexical–semantic system, whereas PI priming relies on a structural–perceptual system, both of these memory systems operating in the domain of nondeclarative memory [16, 22, 37]. The component processes model that we promote in this paper offers a mechanistically more precise level of explanation of this dissociation: we proposed that a modification mechanism [17, 38, 42] mediates the lexical plasticity that underlies WSC priming, whereas acquisition mechanisms operating at relatively low levels of the visual system are responsible for PI priming [22, 43, 80]. Our reasoning is prompted by a consideration of the demands of the WSC and the PI tasks.

In the WSC test, subjects are asked to produce "the first word that comes to mind" that completes a three-letter stem. Subjects are thus confronted with a lexical retrieval task that, from their perspective, has little to do with "memory". As they search their lexicons for a word beginning with a particular combination of three letters, the probability that they will first retrieve the target word increases if the lexical representation of that word was recently modified by exposure to the word during a study session. If the target word was not presented during the study session (i.e., if it is an unstudied word), then that word's representation in the subject's lexicon has *not* been modified, and the word's stem is less likely to be completed to that word. (At the present time we can only speak of "modification" metaphorically because the neural mechanisms underlying lexical retrieval are poorly understood.) This model is consistent with the results routinely obtained from healthy and amnesic subjects on tests of WSC priming with *familiar* words. If, however, a representation of the word in question does *not* exist in the subject's lexicon, or exists in a degraded form, then no modification can take place during the study session, and the word will not be retrieved during the subsequent word-finding procedure in which the subject engages during the priming test. This reasoning can explain H.M.'s impaired performance with the post-1965 word stimulus set employed in our experiment. We interpret the robust repetition effect that we see in the NCS results to indicate that the state of modification of a lexical entry may be a graded quality, depending in part on the number of times that the word corresponding to the entry is read during the study session. Additional support for this view comes from Carlesimo [53], who has reported a level-of-processing effect in WSC priming (although other studies e.g., [28, 59] have not found this effect). In this respect,

Table 5. Comparison of H.M.'s post-1965 WSC priming (from Experiment 1a) and "floor-effect" PI results from Experiment 2b

Group	WSC priming ($n=4$ obs.) (S.D.)	PI priming ($n=4$ obs.) (S.D.)
H.M.	2.6 (1.3)	7.5 (2.9)

our view departs from that of Graf and Mandler [91], who posited that activation of a lexical representation is an all-or-none state, and who therefore predicted that there would be no level-of-processing effect in WSC priming. Alternatively, the repetition effect in WSC priming may reflect a strengthened contribution of perceptual learning with increased repetitions.

Task analysis suggests that a different procedure is critical in the PI task. In PI, subjects are asked to read words (or pseudowords) whose perception is rendered difficult by a short exposure duration or visual noise. Because subjects participating in such a test either perceive the word immediately or cannot discern it at all, an active, deliberate search of the lexicon is never required. Clearly, lexical access plays an important role in the PI task, because baseline identification thresholds are lower with familiar words than with unfamiliar words. The learning that is expressed in PI priming, however, must result from facilitation at a low, pre-lexical level, because the priming effects with unfamiliar words are comparable to those with familiar words (see [43] for an alternative view). Thus, in our conception of the requirements of the WSC task and the PI task, subjects follow different procedures in order to perform successfully, and the priming that can be observed in each task arises from the biasing of two different processes. Further, results of previous studies from our laboratory [16, 22, 37, 49] indicate that these two types of priming also arise from two disparate parts of the brain: the neural mechanisms for WSC priming are located in high-order temporal and parietal cortex (likely candidate brain areas for lexical memory), whereas the neural substrate for PI priming is striate and/or peristriate cortex.

Our task analyses must incorporate the fact that the study portion of WSC and PI tasks is identical: visually presented word reading. In both tasks, study can be assumed minimally to induce plastic change at the level of (1) visual perception, (2) lexical memory, (3) phonological coding and motor preparation, and (4) motor output. Step #2 is skipped if stimuli are unfamiliar words. It follows from this assumption that study induces priming in the same neural and information-processing systems in these two tasks. The two tasks differ *at test*, however, because the WSC priming and PI tasks require different operations at test. Thus, the two tasks probe for plasticity at different levels of neural and information processing at test. The WSC priming effect is weighted toward plastic change at the level of lexical memory, whereas the PI priming effect is weighted toward plastic change at the level of visual perception. And because the study portion of the WSC task produces plasticity at the level of visual perception, there is a component of the WSC priming effect that can be ascribed to visual perceptual plasticity (as evidenced in the reduction of WSC priming in manipulations of study–test continuity (e.g., [27, 53–56]), and the reduced PET signal reported in extrastriate areas during primed WSC ([33, 34, 36])).

The proposition that the WSC priming effect arises primarily from lexical retrieval procedures is supported by evidence from AD. When Keane and colleagues [22] found impaired WSC priming but intact PI priming in AD, they observed that WSC priming, but not PI priming, was correlated with verbal fluency performance. This finding supports a view that WSC priming relies on intact lexical retrieval, and, indeed, the authors suggested that "the mechanism underlying impaired verbal fluency in AD is related to the mechanism underlying impaired word-completion priming in AD but is unrelated to the mechanism supporting perceptual priming" [20] (p. 335). Consistent with this claim is the well-documented deficit of subjects with AD on tests of lexical retrieval, such as confrontation naming tests (e.g., [81–83]). Chertkow and colleagues have recently reported that AD subjects showed reduced WSC priming with words that they had failed to produce during a naming test [20]. These results indicate that impaired lexical retrieval predicts impaired WSC priming, an observation consistent with the modification hypothesis.

Further support for our conception of the mechanisms underlying WSC priming (and for our interpretation of H.M.'s performance in this study) comes from the performance of the NCS in our study. They primed at a robust level with words that they pronounced correctly during the study sessions in the post-1965 condition, but showed virtually no priming with words that they mispronounced at study. In the test of PI priming, in contrast, NCS showed *enhanced* identification of words that they had mispronounced at study in comparison to unstudied words. We assume that mispronouncing a word indicates a lack of familiarity with that word, that is, that the word is not represented in the subject's lexicon or is only weakly represented. Our finding of no WSC priming with mispronounced words suggests one of two possibilities: (a) that NCS did not show WSC priming with words that they did not know, or (b) that mispronouncing words at study interfered with the process of "modifying" the lexical representation of those words (despite the fact that when subjects mispronounced a word, they were given the correct pronunciation and were subsequently asked to repeat it). The first possibility is supported by our observation that NCS recognized the correct definitions of words that they pronounced correctly at study more often than of words that they mispronounced.

This pattern in the NCS data in the present study is reminiscent of other work by our group using unfamiliar words [70] and pseudowords [48]. These two studies indicated that healthy subjects do not show WSC priming with unfamiliar stimuli but, when a cued recall (declarative) testing procedure is used, they can complete stems to these novel stimuli. These results are consistent with the claim that, for NCS as well as for amnesic subjects, the modification of a pre-existing lexical representation of a word is necessary in order for study of that word to enhance the subject's ability to complete its three-letter stem to the word.

The dissociation of WSC priming and PI priming is consistent with an earlier proposal that the former is an example of conceptual priming, whereas the latter is an example of perceptual priming [22]. Although the conceptual/perceptual distinction can be a useful way to organize different types of priming into general categories, it does not provide an explanation of the mechanisms that underlie different types of priming. Overinterpretation of this organizational scheme can lead to theoretical confusion if it is assumed that all types of priming falling under a particular rubric rely on common mechanisms. For example, Maki and Knopman [84] recently challenged the validity of the perceptual/conceptual distinction by comparing the performance of AD subjects and NCS on a "*perceptual*" rhyme exemplar general task and a *conceptual* category exemplar generation task. They noted that Keane and colleagues [22] had proposed that AD subjects perform normally on perceptual priming tests, but are impaired on conceptual priming tests. The results of their experiment indicated that AD subjects performed as well as NCS on both tasks when they generated target items at study, but were impaired on both tasks when they repeated target items at study [84]. They concluded that methodological factors (level of processing at study) were more important than the conceptual or perceptual nature of the task at determining the results. We suggest, however, that the two tasks used in the Maki and Knopman experiment shared an important common characteristic: each required subjects to engage in a search of stored representations of words (one search done by phonology, the other done by semantics). Therefore the status of the rhyme exemplar generation task as a perceptual task is tenuous, and it is not surprising that predictions based on strict adherence to the perceptual/conceptual organizational scheme were not borne out. The status of WSC priming as a "perceptual" or a "conceptual" task is also not absolute, because perceptual and lexical mechanisms can each contribute to the learning that can be observed in this task. In our view, careful analysis of the mechanisms and procedures that are engaged by a specific task yield greater analytic precision and greater predictive power than can memory systems models, such as the perceptual/conceptual model.

The component processes approach to memory research has yielded other reports of important differences between different types of repetition priming, similar to the WSC/PI dichotomy that we have described in this report. Many recent studies, for example, have proposed an important nonperceptual contribution to the word-fragment completion priming effect [64, 85, 86] suggesting that the priming observed with this task, too, has components that are qualitatively different from low-level acquisition mechanisms that are presumed to underlie many examples of perceptual priming. Furthermore, the word-fragment completion and WSC tasks have been shown, themselves, to differ in important ways: comparison of the demands of the word-fragment completion and WSC tasks suggests that the former emphasizes perceptual matching processes; whereas the latter relies to a much greater extent on lexical search [87]. Empirical support for this conclusion derives from the dissociation of WSC priming and word-fragment completion priming in patients with frontal-lobe lesions [88]. The component processes approach to memory research [63–65] is best viewed not as rejecting the more established traditions of memory systems or transfer-appropriate processing theorizing, but as incorporating ideas from each to yield an approach with greater predictive power. Mnemonic phenomena are viewed as "composed of various component processes" [89] (p. 68), some shared and some unique, that adhere to principles laid out in transfer-appropriate processing theory, and that are often supported by discrete brain systems. The power of the component processes approach comes from its appreciation of the fact that plasticity is a characteristic of virtually every process and system in the brain, and thus that careful attention must be paid to the processes and systems that are engaged by tasks that can reveal nondeclarative memory.

The differing pattern of results obtained by testing amnesic subjects on WSC and PI priming tests is inconsistent with theoretical models suggesting that both of these priming paradigms rely solely on perceptual mechanisms (e.g., [15, 28, 31, 33]). These models reflect the fact that most experiments demonstrating intact repetition priming with novel verbal information in amnesia have been tests of perceptual priming, and have not included WSC priming in their testing protocols (see [90] for a review). Based on the results reported here, we propose that the pre-existence of lexical representation of words in a stimulus set is a *sine qua non* of exhibiting normal WSC priming, and thus that a modification mechanism makes a critical contribution to this kind of nondeclarative memory.

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Appendix A: Post-1965 Words

AEROBICS
AFRO
AMARETTO
AMNIOCENTESIS
APARTHEID
AQUARIAN
ARUGULA
ASTROTURF
AWACS
BEANIE
BIATHLON
BIKINI
BIONICS
BIRIANI
BISCOTTI
BLEEP
BLOCKBUSTER
BONG
CASTROISM
CELLULITE
CHARBROILER
CHICANO
CHUGALUG
CILANTRO
COBOL
CODON
CORTISONE
COUTH
CROCKPOT
CRUDITES
CYBORG
DECATHLETE
DEFOGGER
DELI
DEPROGRAM
DERAILLEUR
DISKETTE
DOMINATRIX
DORK
DREADLOCKS
DUMPSTER
EUROCRAT
FALAFEL
FICHE
FLACKERY
FLOOZY
FRACTAL
FREEBEE
FRISBEE
FUTON
GIMMICK
GLASPHALT
GLITZ
GLOP
GONZO
GRANOLA
GRIDLOCK
GRUNGE
GULAG
HACKER
HAVARTI
HOLOGRAM
HOMOPHOBIA
HUCKSTER
JACUZZI
HONCHO
HYPE
INTERFERON
KAYAK
KLICK
KUDO
LAMAZE
LIBBER
LUMPECTOMY
MACHO
MAMMOGRAM
MARGARITA
MAVEN
MEDICARE
MELATONIN
MOTOCROSS
NAUGAHYDE
NERD
NEUROSCIENCE
NOSH
PAPARAZZI
PARAMEDIC
PHEROMONE
PICOGRAM
PIZZAZZ
PLASMID
PREPPY
PSYCHEDELIA
PULSAR
QUASAR
RASTAFARIAN
REGGAE
REPO
REVERB
SALSA
SANDINISTA
SASQUATCH
SCAM
SCHLOCK
SLEAZE
SONOGRAM
SPRITZ
STAGFLATION
SUSHI
TAHINI
TELETHON
TERIYAKI
TRIATHLON
TOKE
VALIUM
VELCRO
WIMP
YUPPIE
ZINGER

Appendix B: Pre-1953 Words

ABOLITIONIST
ACCREDITATION
AFFIRMATION
AQUEDUCT
ARBOR
ASTERISK
BALM
BENT
BLIZZARD
BLUSTER
BOTANY
BRIAR

CHECKMATE
CLAPPER
CRABAPPLE
CRUMB
DAREDEVIL
DECANTER
DEODORANT
DESPERADO
DOMICILE
DRAM
ESCAPADE
FILLET
FLAMINGO
FOSSIL
GLITTER
GLOSSARY
GROUCH
HARPOON
HUSK
INFINITY
LAIR
MEAD
MERIDIAN
MILDEW
MIME
MONOGRAM
MORASS
MUSTARD
OCTAVE
ORIOLE
PECK
PEDESTRIAN
PHARMACY
PILING
PISTACHIO
PRETZEL
QUICKSILVER
RECIPROCAL
REGALIA
ROULETTE
SALUTATION
SAUSAGE
SCALLION
SCONCE
SHAD
SIMILE
SLOP
SMUDGE
SNEEZE
SPIDERWEB
SQUAWK
STEW
STUPIDITY
SUFFIX
TASSEL
THIMBLE
THUMB
TIDBIT
TRAMPOLINE
TREBLE
TRIAGE
TROT
TRUANT
VASE
VELOUR
WEAKLING
WRANGLER
YARN