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JOURNAL OF MEMORY AND LANGUAGE **36**, 382–405 (1997)
ARTICLE NO. ML962489

Morphological Priming, Fragment Completion, and Connectionist Networks

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Long-term morphological priming is a form of repetition priming in which the identification of a word is primed by the prior presentation of a morphologically related word. We investigated morphological priming using a variant of the fragment completion task in which a word is briefly presented with one of its letters replaced by a pattern mask and subjects attempt to identify the letter "hidden" by the mask. In Experiment 1 a levels-of-processing manipulation at study was found to affect free recall but not masked fragment completion, suggesting that repetition priming in the latter task is not the result of explicit memory processes. Subsequent experiments revealed that both masked and standard fragment completion are influenced by morphological priming and that, although this effect cannot be attributed to the orthographic and phonological similarity of morphologically related words, it does vary in magnitude as a function of orthographic similarity. These results are consistent with a connectionist account of morphological priming in which morphological effects arise from the activation dynamics of a connectionist network even though morphological relationships are not explicitly represented in this network. © 1997 Academic Press

Readers are influenced by the morphological structure of the words that they read. Although the effects of morphology on reading have been demonstrated in a variety of experimental tasks (see Feldman, 1991, Henderson, 1985, and Stolz & Feldman, 1995, for reviews), few paradigms have played as important a role in the study of morphological effects in reading as has long-term repetition priming. In the repetition priming paradigm, the identification of a target word is measured as a function of recent experiences with the word itself or with words related along a dimension of interest. For example, a target might be preceded by itself (e.g., *car–car*), by a morphologically related word (e.g., *cars–car*), or by a word that is not related to the target morphologically but is similar to the target in spelling and pronunciation (e.g.,

This research was supported by Grant HD-01994 from the National Institute of Child Health and Development to Haskins Laboratories. We thank Laurie Feldman and Carol Fowler for their comments concerning this work and Billy Crawford and Jay St. Jean for their assistance in collecting the data. Portions of this research were presented at the Annual Meeting of the Canadian Society for Brain, Behavioral, and Cognitive Science, Halifax, Nova Scotia, June, 1995, and the Annual Meeting of the Psychonomic Society, Los Angeles, CA, November, 1995.
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0749-596X/97 $25.00

card–car). Numerous studies have demonstrated that the speed and accuracy with which a word is read are facilitated not only by the prior presentation of that word but also by the prior presentation of a morphologically related word (see Feldman, 1994, and Tenpenny, 1995, for reviews).

Although repetition priming has played an important role in the study of both memory and word identification (see Schacter, 1987, for discussion of this point), investigations of morphological priming largely have been limited to the literature on word identification. Thus, whereas memory theorists have investigated the effects of repetition priming on a variety of tasks, including lexical decision, speeded naming, perceptual identification, fragment completion, and stem completion (see Richardson-Klavehn & Bjork, 1988, and Roediger & McDermott, 1993, for reviews), most studies of morphological priming have used facilitation in the lexical decision task as an index of priming (e.g., Feldman, 1994; Fowler, Napps, & Feldman, 1985; Napps, 1989; Stanners, Neiser, Hernon, & Hall, 1979). Consequently, although morphological priming has had a significant impact on the development of theoretical accounts of the processes involved in word identification, its implications for theories of memory have largely been ignored.

In this paper we attempt to bring recent developments in both literatures to bear on the study of morphological priming. One purpose of the present research is to extend our understanding of morphological priming by investigating its effects in several variants of the fragment completion task, a task used primarily in the study of memory. This research is guided by a connectionist approach to cognitive modeling that offers an alternative to other, perhaps more widely accepted, accounts of the role of morphology in reading.

Previous Research on Morphological Priming

The first study to investigate morphological effects in repetition priming was reported by Murrell and Morton (1974). In the priming phase of their experiment, subjects studied a short list of words with the expectation that their memory for these words would later be tested. Shortly after the study phase, an identification task was administered. The accuracy with which words were identified during this task varied as a function of their relationships with words on the study list. Specifically, repeated words were identified more easily than unprimed words (i.e., words that were not related to any of the study words), and to a lesser extent, so were words that had been preceded by a morphologically related prime (e.g., *cars* at study, *car* at test). Thus, both repetition priming and morphological priming facilitated identification. In contrast, no priming was observed for words that were preceded by morphologically unrelated primes that were similar in spelling and pronunciation (e.g., *card–car*).

In a subsequent study, Stanners et al. (1979) investigated morphological priming in the lexical decision task. They found that less time was needed to decide that a letter string was a word if a morphological relative of that word had recently been seen. One advantage of using lexical decision to study morphological priming is that it avoids a form of response competition inherent in the tachistoscopic identification task. Specifically, incorrect responses in the identification task are often similar to the correct response. Thus, for a target word primed by a morphological relative, one of the incorrect responses (i.e., the morphologically related prime) has also been primed, and, to the degree that this word is reported during the test phase, the true effect of the priming event on the accessibility of the target word's representation may be obscured.

Since the pioneering research of Stanners et al. (1979), a number of studies have investigated the effects of long-term morphological priming in the lexical decision task. This research has revealed a number of important characteristics of morphological priming. First, morphological priming has been found in several languages other than English, including Italian (Laudanna & Burani, 1986), Hebrew (Bentin & Feldman, 1990), and

Serbo-Croatian (Feldman & Fowler, 1987), and thus is not an artifact of any peculiarities of English morphology. In addition, although morphologically related words are usually related in form (i.e., spelling and pronunciation) and meaning, morphological priming cannot be attributed solely to similarity along these dimensions. That is, lexical decisions are facilitated more by morphologically related primes than by unrelated primes matched with the morphological relatives on either formal (Hanson & Wilkenfeld, 1985; Napps, 1989; Napps & Fowler, 1987; Stolz & Feldman, 1995) or semantic (Bentin & Feldman, 1990; Stolz & Feldman, 1995) similarity to the target. Finally, morphological priming varies with the morphological relationship of the prime and target (Feldman, 1994; Stanners et al., 1979; although see Fowler et al., 1985). Morphologically complex words (e.g., *manager*) tend to prime their base forms (e.g., *manage*) more than they prime other related words (e.g., *management;* Fowler et al., 1985), and regular inflections (e.g., *runs*) are generally more effective primes than either irregular inflections (e.g., *ran*) or derivations (e.g., *runner*).

A number of theoretical proposals have been advanced to account for morphological priming. In general, these accounts take one of two forms. In decompositional accounts (e.g., Taft & Forster, 1975), reading a morphologically complex word involves parsing that word into its constituents in order to access the lexicon. Thus, morphemes serve as the "access units" in reading, and morphologically related words are identified via the same access unit. As a consequence, if the identification of a word results in the activation of a given access unit, the identification of other words sharing this unit (i.e., morphologically related words) will be facilitated for as long as this activation persists. In contrast, "whole-word" accounts of morphological priming (Feldman & Fowler, 1987; Lukatela, Gligorijevic, Kostic, & Turvey, 1980) assume that although each word has its own lexical entry, the lexicon is organized so that morphological relationships are explicitly represented (e.g., by direct connections among the entries for morphologically related words). On this view, morphological priming occurs because the activation of a given word results in the partial activation of morphologically related words (e.g., via their interconnections).

The decompositional and whole-word models differ in many respects and, indeed, there are important differences among models of each class. Nonetheless, these models are alike in their assumption that the lexicon is organized around morphological principles, and in all of these models the explicit representation of morphological relationships plays a key role in the account of morphological effects in visual word identification. The advent of connectionist models has opened the door to an alternative account—one that denies that morphology is explicitly represented but instead claims that morphological effects emerge from the activation dynamics of a network that computes the orthographic, phonological, and semantic codes associated with a visual stimulus.

Network Dynamics and Morphological Priming

From a connectionist perspective, word identification involves the establishment of mutually consistent patterns of activation over sets of processing units that represent the various (e.g., phonological, orthographic, semantic) properties that constitute a word. This occurs through a dynamic process in which the activation of one set of units influences, and in turn is influenced by, the activation of other sets of units. Over time, this interactive flow of activation results in a resonant state (often referred to as an attractor) such that the patterns of activation over the various sets of nodes are mutually reinforcing. Many possible states can occur—which one actually develops depends both on the input to the network (e.g., the visual stimulation) and the configuration of the connection matrices that link the processing units. These configurations are acquired through a learning process that attunes the reader to the statistical regularities (at various grain-sizes) that exist among linguistic structures. (For detailed explications of such models, see Grossberg & Stone, 1986, Hinton & Shallice, 1991, Kawamoto, Farrar, & Kello, 1994, Masson, 1995, Plaut & Shallice, 1993, Seidenberg & McClelland, 1989, and Stone & Van Orden, 1994.)

The connectionist view of word recognition leads to a straightforward account of repetition priming: Repetition priming is one consequence of a learning process that modifies the weights of the connection matrices after a resonant state has been set up, thus strengthening that state's "basin of attraction" (Becker, Behrmann, & Moscovitch, 1993; McClelland & Rumelhart, 1985; Rueckl, 1990). One effect of the weight changes that occur after a word has been processed is to facilitate the subsequent processing of that word. In addition, because connectionist networks employ superimpositional storage processes (i.e., many memory traces are superimposed on the same set of weights), the subsequent processing of other stimuli should also be affected by these weight changes. Indeed, experimental results have borne out this prediction. Feustel, Shiffrin, and Salasoo (1983) and Rueckl (1990) found that the identification of a word can be primed by the prior presentation of orthographically and phonologically similar words. Moreover, pseudowords can also be primed by formally similar primes (Feustel et al., 1983; Rueckl, 1990; Rueckl & Olds, 1993).

Form-based similarity priming resembles morphological priming in that the identification of a word is primed by the presentation of a related word. The connectionist account suggests that this resemblance is not superficial but instead reflects the fact that both forms of priming are manifestations of the same underlying process—the strengthening of attractors via the learning mechanism. However, morphological priming differs from form-based similarity priming in that in morphological priming the prime and target are typically related both formally and semantically, whereas in similarity priming the primes and targets are semantically unrelated (e.g., *card–car*). Thus, the identification of both morphologically and formally similar words will benefit from the weight changes made within the orthographic and phonological layers (as well as in the pathway between them), but only the identification of morphologically related words will benefit from weight changes made within the semantic layer and in the pathways between that layer and the orthographic and phonological layers.

This account predicts that morphological priming effects should vary in strength depending on the degree to which the prime and target are formally and semantically similar. Thus, for example, root forms (e.g., *teach*) would be expected to be primed more strongly by regular inflections (e.g., *teaching*), which are highly similar to their root forms along both formal and semantic dimensions, than by irregular inflections (e.g., *taught*), which are usually formed by changing the orthographic and/or phonological properties of their base forms, or by derivations (e.g., *teachable*), which are less similar to their root forms semantically than are inflections. This prediction is, in fact, consistent with experimental results (Feldman, 1994; Stanners et al., 1979). However, this pattern of results can also be accounted for by models that assume that morphological relationships are explicitly represented in the lexicon, provided that different classes of morphological relationships are represented in different ways (Stanners et al., 1979). Thus, the contrast between priming effects involving regular inflections, irregular inflections, and derivations is not particularly diagnostic.

A more telling case involves variability in formal or semantic similarity when the morphological relationship between the prime and target is held constant. For example, some irregular past tense forms are fairly similar to their root forms (e.g., *made–make, swam–swim*), whereas others are less similar (e.g., *took–take, bought–buy*). From a connectionist perspective, more morphological priming would be expected in the former case. In contrast, models that link morphological priming to the explicit representation of morphology in the lexicon would be hard pressed to explain an effect of formal similarity within morphological class.

Although their findings are equivocal, several studies provide data relevant to this issue. The first of these was reported by Stanners et al. (1979), who conducted several experiments investigating the effects of orthographic similarity on morphological priming. For example, in one of their experiments (Experiment 2) the morphological primes were irregular past-tense forms that differed from their base-form targets by either one letter (the similar condition; e.g., *hang–hung*) or more than one letter (the dissimilar condition; e.g., *shake–shook*). Morphological priming was obtained, although the magnitude of this effect was significantly smaller than that of repetition priming. In addition, the difference between identity and morphological priming was 25 ms larger in the dissimilar condition than in the similar condition. However, this difference was not statistically significant.

This pattern of results is typical of experiments that have investigated the effects of orthographic similarity on morphological priming. In all, at least eight experiments addressing this issue have been reported. These include Experiments 2, 3, and 4 of Stanners et al. (1979), Experiments 3a, 3b, and 4a of Fowler et al. (1985), Experiment 1 of Napps (1989), and Experiment 1 of Stolz and Feldman (1995). In each of these experiments, the effect of orthographic similarity on morphological priming was not statistically significant, but in each case the numerical trend was toward less priming with less orthographic similarity.[1] It is possible, of course, that statistics don't lie, and that morphological priming is, in fact, invariant across variations in formal similarity. Indeed, a number of theorists (e.g., Fowler et al., 1985; Stolz & Feldman, 1995) have reached just this conclusion. However, given that morphological priming has consistently been found to be greater numerically, if not statistically, for more similar prime-target pairs,[2] an alternative interpretation is that formal similarity does influence morphological priming, but that, as we suggest in the following section, the lexical decision task provides a relatively insensitive measure of this effect. With this in mind, it is worth considering whether other, potentially more sensitive, tasks might be used in the study of morphological priming.

Measures of Repetition Priming

Repetition priming has been observed in a variety of experimental paradigms, including tachistoscopic identification (Jacoby & Dallas, 1981; Rueckl, 1990), stem completion (Graf, Squire, & Mandler, 1984; Mandler, Hamson, & Dorfman, 1990), fragment completion (Tulving, Schacter, & Stark, 1982; Weldon, 1991), and word association (Shimamura & Squire, 1984). Yet, as noted above, studies of morphological priming have relied almost exclusively on the lexical decision task. This contrast reflects the fact that, whereas repetition priming has played an important role in the study of both memory and word recognition, investigations of morphological priming have been linked almost exclusively to the latter. As a result, the study of morphological priming has not benefited much from recent developments in the memory literature, including, in particular, the emphasis on gathering converging evidence across a variety of tasks to elucidate the nature of the processes that underlie priming effects (see Schacter, 1987, and Roediger & McDermott, 1993, for reviews).

Overreliance on the lexical decision task is potentially problematic. For example, al-

[1] In some of these experiments, phonological similarity was also varied, but in this case even the numerical effects were small and inconsistent. Because we assume that phonology has an important influence on the activation dynamics of word identification, our account predicts that phonological similarity should matter. However, it is not unreasonable to suppose that visual lexical decision is a relatively insensitive measure of this effect.

[2] To our knowledge, the eight experiments cited above are the only published experiments that investigated the effects of orthographic similarity on morphological priming. The probability that, by chance, the numerical effect of orthographic similarity was in the same direction in all eight experiments is less than .004.

though long-term form-based similarity priming has been found in several studies employing identification tasks (Feustel et al., 1983; Rueckl, 1990; Rueckl & Olds, 1993), it has never been found using lexical decision (Hanson & Wilkenfeld, 1985; Napps, 1989; Napps & Fowler, 1987; Stolz & Feldman, 1995). This suggests that the lexical decision task is a relatively insensitive measure of orthographic similarity effects. If so, it is not the most appropriate tool for investigating issues such as whether morphological priming effects vary with the formal similarity of the prime and target. In addition, problems arise because it is relatively difficult to link performance in the lexical decision task to specific underlying processes. Although the lexical decision task was originally intended to provide a window on the process of lexical access, it is now clear that lexical decisions can be based on any of a number of sources of information (Balota, Ferraro, & Connor, 1991; Rueckl, 1995a; Seidenberg & McClelland, 1989). Coupled with findings suggesting that lexical decisions are made on the basis of different kinds of information in different experimental contexts (cf. Pugh, Rexer, & Katz, 1994; Stone & Van Orden, 1993), it seems unlikely that results from lexical decision studies alone will reveal whether the locus of morphological priming effects involves structural (i.e., orthographic and phonological) and/or semantic levels of representation. (See Henderson, 1985, for a discussion of the possible loci of morphological effects.)

Given the above considerations, we decided to widen the range of tasks that have been used to study morphological priming. We discovered, however, that many of the tasks that have been used in the study of repetition priming are not well suited for the investigation of morphological priming. For example, as noted earlier, one problem with using the tachistoscopic identification task to study morphological priming is that it is open to a form of response competition—because they tend to resemble their targets, morphologically related primes may be produced as incorrect responses. Stem completion suffers from a similar problem. In the stem completion task a word stem (e.g., ele____) is presented and the subject is asked to name the first word that comes to mind that completes the stem. Because morphologically related words often share the same stem (particularly in a language such as English, where most inflections and derivations are formed through suffixation), only a greatly restricted range of morphologically related word pairs can be used in this task without introducing the possibility of response competition.

Another commonly used paradigm is the fragment completion task. In this task, subjects are presented with a fragmented form of a word (e.g., _l_ph_n_) and are asked to think of a word that completes the fragment. By constructing the fragments appropriately, a morphologically related prime can be ruled out as a possible completion for a particular fragment, thus eliminating the form of response competition plaguing the tachistoscopic identification and stem completion tasks. Although the fragment completion task looks promising in this respect, other characteristics of this task are less than ideal if it is to be used as a tool for investigating the word identification process. In particular, whereas the duration of the identification process is typically on the order of hundreds of milliseconds, fragment completion (when successful) often occurs much more slowly, in many cases on the order of 5–10 s (Weldon, 1993). Hence, given this extended duration, fragment completion is in some ways a form of problem solving and thus relies heavily on processes that are not typically involved in normal word identification.

With this in mind, we modified the standard fragment completion task to make it more like reading and less like problem solving. In this new task, called *masked fragment completion,* subjects are given brief glimpses (e.g., 250 ms) of letter strings in which one of the letters has been replaced with a mask made of letter fragments. (See Fig. 1.) The position of the masked letter is such that at least three different letters can be substituted for the mask to form words (e.g., *#ark: bark, dark, hark, lark,*

FIG. 1. Examples of the stimuli used in the masked fragment completion task.

mark, and *park*), and subjects are led to believe that the mask covers a real letter. Under these conditions, subjects typically respond quickly and report having the sense that they are seeing intact words with one of the letters partially covered. Thus, the processes that underlie the performance of this task are reasonably similar to those involved in more typical reading situations.

EXPERIMENT 1

To the best of our knowledge, ours is the first study to make use of the masked fragment completion paradigm. Thus, one purpose of Experiment 1 was simply to establish that repetition priming occurs in this task. In addition, because repetition priming studies are sometimes "contaminated" by the influence of explicit memory processes, we sought some assurance that priming in the masked fragment completion task could be dissociated from explicit memory effects. One commonly used approach is to vary the study conditions in which the primes are initially processed. Typically, variations in the "depth" of processing at study have strong effects on measures of explicit memory (e.g., recall, old/new recognition) but little or no effect on the implicit memory processes that underlie repetition priming (see reviews by Brown & Mitchell, 1992, Challis & Brodbeck, 1992, and Roediger & McDermott, 1993).

To manipulate the depth of processing at study, subjects in Experiment 1 were asked to perform one of two study tasks. Subjects in the "deep" study condition rated the familiarity of a series of visually presented words, whereas subjects in the "shallow" condition counted the number of sounds in each word. After completing a filler task, each subject then performed the masked fragment completion task. Some of the fragments could be completed by a word presented during the study task, and the critical dependent measure was the proportion of such target completions actually generated. In the last phase of the experiment, subjects attempted to recall the words from the study list, thus providing a measure of explicit memory.

Method

Participants. The participants in this study were 64 University of Connecticut undergraduates who completed the experiment for course credit.

Materials. The stimuli included 64 target words ranging from three to five letters in length, listed in Appendix A. Each target word was chosen such that one of its letters could be replaced with at least three other letters that would still create legal words (e.g., *fire: fife, file, fine, five*). Generally, the target word was chosen to be the second or third most frequent (based on Kucera & Francis, 1967) of the words in the neighborhood defined by the position of the critical letter.

The stimuli were presented on a Macintosh Color Classic in 18-point extended Courier font. (Courier is a fixed width font, and thus letter spacing provided no cues about the identity of the masked letters.) In the masked fragment task the critical letter in each target word was removed and replaced by a mask. Two masks were used to reduce the effects of any biases associated with a particular mask. Each mask was constructed out of line and curve segments, so that when the mask was briefly presented it gave the appearance of covering a letter without strongly resembling any particular letter. (See Fig. 1.)

Design and procedure. Subjects were tested individually or in groups of two or three. At the beginning of the experiment each subject was seated in front of a computer in a quiet laboratory setting. The participants were told that they were participating in a study investigating vocabulary knowledge and its relation to reading and were then given the instructions for the study task. Subjects in the deep condition were told that they would see a series of words and that they were to judge the familiarity of each word on a seven-point scale. Subjects in the shallow condition were told to count the number of sounds in each word when it appeared on the screen. In both conditions, each stimulus was presented for 2 s, followed by a 2-s response interval. The stimuli presented during the study task included 32 of the 64 target words, along with 32 filler words. These words were presented in a different random order for each subject, with the constraint that the first 5 and last 5 words presented during the study task were fillers.

After the study task, all subjects performed a filler task in which they were given a list of fragmented famous names and asked to complete as many as possible in 4 min. Following the famous names task, instructions were given for the masked fragment completion task. The subjects were told that on each trial they would see a briefly presented word with scribbling over one of its letters and that they should attempt to identify the masked letter and respond by pressing the corresponding key on the computer keyboard.

The first three stimuli for the masked fragment task were fillers, which were then followed by all 64 target words (presented in a different random order for each subject). Each word fragment was presented for 250 ms and was presented 2 s after the preceding response. To counterbalance the items across conditions, the list of 64 target words was partitioned into two sublists of 32 words each, and each sublist provided the study items for half of the subjects in both the deep and shallow conditions. In addition, across subjects each word fragment was presented equally often with each of the two masks, and this factor was counterbalanced with the primed/unprimed and study task conditions. (We subsequently discovered that due to a programming error two of the critical fragments, one from each sublist, were not presented to all of the subjects. The data for these two items were discarded from all analyses.)

Finally, following the masked fragment completion task each subject was provided with paper and a pencil and asked to recall as many of the words as possible from the study task. Subjects were given as long as they liked to complete this task.

Results and Discussion

The proportion of target words generated during the masked fragment completion and recall tasks are presented in Table 1. Because there were no systematic differences in the results obtained with the different masks, the results are collapsed over this variable. Table 1 shows that a large priming effect was obtained: Targets that were presented during the study task were more likely to be produced as completions than targets that were not. This difference was significant by both subjects, $F1(1,62) = 78.95, p < .001, MS_e = 0.58$, and items, $F2(1,61) = 61.15, p < .001, MS_e = 1.11$. Moreover, neither the main effect of study task nor the interaction of study task and priming approached significance (all F's < 1). Thus, the levels-of-processing manipulation had no effect on priming in the masked fragment completion task. In contrast, it had a large effect on free recall. Target words presented during the familiarity task were recalled more often than target words presented during the phoneme-counting task, $F1(1,62) = 20.71, p < .001, MS_e = 0.08, F2(1,61) = 28.31, p < .001, MS_e = 0.17$.

Two aspects of these results are of particular interest. First, as expected, repetition priming has a large influence on the performance of the masked fragment completion task. Second, because the levels of processing manipulation affected recall performance but not masked fragment completion, the priming effect in the latter task is unlikely to be due to contamination by explicit memory processes. Together, these findings suggest that the masked fragment completion task may be a useful tool for the study of repetition priming in general, and morphological priming in particular.

EXPERIMENT 2

The purpose of the next experiment was to investigate the effects of morphological prim-

TABLE 1

THE PROPORTION OF TARGET WORDS GENERATED IN THE MASKED FRAGMENT COMPLETION AND FREE RECALL TASKS IN EXPERIMENT 1

	Masked fragment completion		
Study task	Primed	Unprimed	Free recall
Familiarity (Deep)	.37	.27	.12
Phoneme counting (Shallow)	.34	.21	.04

ing on masked fragment completion. Accordingly, the relationship between the target words and the words presented during the study task was varied in a manner similar to that of several previous studies (e.g., Murrell & Morton, 1974; Napps & Fowler, 1987; Stolz & Feldman, 1995). Specifically, there were four study conditions defined by the relationships between the target words and the words presented during the study task. In the repeated condition, a given target word (e.g., *mark*) was itself presented during study task. In the morphologically related condition, an inflection or derivation of that target word (e.g., *marker*) was presented during the study task. In the formally related condition, the prime was a morphologically unrelated word that happened to contain the target word as its initial segment (e.g., *market*). Finally, in the unprimed condition none of the words presented during the study task were either morphologically or formally related to the target word.

In this design, the effect of morphological priming can be measured by comparing the target completion rate in the morphologically related condition with that in the unprimed (baseline) condition. In addition, this design also allows for an assessment of the relative magnitude of morphological and repetition priming and an appraisal of the degree to which morphological priming can be attributed to the formal similarity of the targets and their morphologcal primes.

Method

Participants. The participants in this study were 48 University of Connecticut undergraduates who completed the experiment for course credit.

Design and materials. The stimuli for this experiment included 60 word triplets (see Appendix B). Each triplet included a target word (e.g., *mark*), a morphologically related word (e.g., *marker*), and a morphologically and semantically unrelated word that was related to the target in spelling and pronunciation (e.g., *market*). Target words ranged in length from three to five letters, and as in Experiment 1, the critical letter position for each target was chosen so that it allowed for several possible completions (e.g., *mark, bark, dark, hark, lark, park*). The morphologically and formally related words were approximately matched in length and always included the entire target at the beginning of the word. In addition, the selection of the related words was constrained so that the segment corresponding to the target was always pronounced in the same way as the target itself (i.e., pairs like *bear–beard* were not allowed).

To counterbalance the stimuli across priming conditions, the 60 triplets were partitioned into four sublists of 15 triplets each. During the study task, each subject was presented with the target words from one of the sublists, the morphologically related words from a second sublist, and the formally related words from a third sublist. No words from the fourth sublist were presented during the study task—thus, the completion rates for the targets from this sublist provided a measure of baseline performance. The sublists were rotated through conditions such that each triplet was assigned to each priming condition equally often across subjects.

TABLE 2

THE PROPORTION OF TARGET COMPLETIONS AS A FUNCTION OF PRIMING CONDITION IN EXPERIMENT 2

Repeated	Morphologically related	Orthographically related	Unprimed
.45	.40	.32	.29

Procedure. The procedure was identical to that of the first experiment except for the following changes. First, more filler words were used—30 in the study task and 24 in the fragment completion task. Second, some of the items for the famous names filler task were changed and the stimuli were presented on the computer monitor. Finally, because the differential effects of the levels-of-processing manipulation on repetition priming and free recall in Experiment 1 suggest that any priming effects found in the masked fragment completion task are not the result of explicit memory processes, we simplified the design of the present experiment by having all subjects perform the same study task (familiarity ratings) and by eliminating the free recall task.

Results and Discussion

The proportion of target completions in each study condition is listed in Table 2. Analyses of variance revealed that the overall effect of study condition was significant by both subjects, $F1(3,47) = 16.01$, $p < .0001$, $MS_e = 0.26$, and items, $F2(3,58) = 19.78$, $p < .0001$, $MS_e = 0.32$. As expected, the completion rate varied systematically as a function of study condition and was highest in the repeated condition, with successively lower rates in the morphologically related, formally related, and unprimed conditions. The results of a series of planned comparisons are consistent with this characterization. Repeated words were more likely to be generated as completion than were words primed by morphological relatives, $t1(47) = 2.24$, $p < .05$, $t2(58) = 2.46$, $p < .05$. Similarly, morphological relatives were more effective primes than were formally similar (but morphologically unrelated) words, $t1(47) = 2.92$, $p < .01$, $t2(58) = 3.26$, $p < .01$. Finally, although there was a small numerical difference in the proportion of target responses in the formally similar and unprimed conditions, this difference was not statistically different, $t1(47) = 1.08$, $p = .28$, $t2(58) = 1.20$, $p = .23$.

Several conclusions can be drawn from these results. First, consistent with the findings of Experiment 1, repetition priming had a substantial effect on masked fragment completion. Second, target completions were primed by morphologically related words, although this effect was smaller than that of repetition priming. Third, and most important, the finding that the target completion rate in the morphologically related condition was significantly greater than that in the formally related condition indicates that morphological priming in the masked fragment completion task cannot be attributed solely to the formal similarity of morphologically related primes and targets. In this respect our results are in agreement with those obtained using the lexical decision task (Hanson & Wilkenfeld, 1985; Napps, 1989; Napps & Fowler, 1987; Stolz & Feldman, 1995).

Finally, it should also be noted that although the effect of form-based similarity priming was not significant, *post hoc* analyses suggested that form-based priming may have had some effect, particularly for items with low baseline completion rates. Given that this pattern is consistent with other observations of form-based similarity priming (e.g., Feustel et al, 1983; Rueckl, 1990; Rueckl & Olds, 1993), it would be premature to conclude that form-based similarity priming had *no* effect in Experiment 2. Indeed, we see these results as suggesting that with appropriately selected items the masked fragment completion task may provide a relatively sensitive instrument for exploring such effects.

EXPERIMENT 3

The results of Experiment 2 revealed that masked fragment completion is influenced by morphological priming: Compared to the baseline condition, a fragment was more likely to be completed as a particular word if a morphological relative of that word had been presented during the study task. In Experiment 3 we asked whether this effect varies with the orthographic similarity of the morphologically related words. The target completions in this experiment were verbs with irregular past-tense forms. Half of these targets differ in spelling from their past-tense forms by a single letter (e.g., *make–made, sing–sang*), and the remaining targets differ from their inflections by at least two letters (e.g., *take–took, buy–bought*). Due to the small number of irregular English past-tense forms, the phonological similarity of the primes and targets was not perfectly controlled. Although the orthographically similar pairs tended to be more phonologically similar as well, both conditions included pairs that differed by a single phoneme (e.g., *come–came, take–took*) and others that differed by several (e.g., *lose–lost, buy–bought*).

As noted in the introduction, theoretical accounts of morphological priming differ in their expectations concerning the impact of formal similarity on morphological priming. Whereas the connectionist account predicts that more morphological priming should be found for more similar prime–target pairs, accounts predicated on the assumption that morphological relationships are explicitly represented in the lexicon do not. As also noted in the introduction, experiments that have addressed this issue using the lexical decision task have yielded an inconclusive pattern of results. Given that the fragment completion and lexical decision tasks may differ in their sensitivity to manipulations of orthographic similarity, we hoped that the results of Experiment 3 would help clarify this theoretically important issue.

Method

Participants. The participants in this study were 90 University of Connecticut undergraduates who completed the experiment for course credit.

Materials. The stimuli for this experiment included two lists of 27 verbs with irregular past-tense forms (see Appendix C). Words in the similar condition differed from their past-tense forms by either the subtraction (e.g., *bite–bit*) or substitution (e.g., *make–made*) of a single letter. Words in the dissimilar condition differed from their past-tense forms by at least two letters (e.g., *take–took*). A formal measure of similarity can be computed using a procedure developed by Napps (1989). In this procedure null characters are inserted (where necessary) so that the number of positions in which the prime and target have matching letters is maximized. The orthographic overlap is then given by dividing the number of matching letters by the number of letters in the longer of the two words. (See Napps, 1989, for further details.) Using this procedure, the average orthographic overlap in the similar and dissimilar conditions was .76 and .47, respectively. Target words in the similar and dissimilar conditions were closely matched on frequency and length. The average frequency of the targets in the similar and dissimilar conditions was 90.0 and 98.4 (Kucera & Francis, 1967), respectively, and the average length was 4.2 and 4.4 letters.

Design and procedure. For purposes of counterbalancing, the similar and dissimilar lists were each partitioned into three sublists. During the study task each subject was presented with the target items of one of the sublists from the similar and dissimilar conditions, along with the past-tense forms from a second sublist from each condition. Present- or past-tense forms from the third sublist were not presented during the study task, thus providing an unprimed baseline condition. Across subjects each item appeared equally often in the repeated, morphological, and unprimed conditions.

As in Experiment 2, each subject made familiarity judgments during the study phase. The study task was followed by a paper-and-pencil version of the famous names task, which was followed in turn by the masked fragment completion task. In addition to the critical items, 36 fillers were presented during the study task, and 18 fillers were presented during the completion task. In all other re-

TABLE 3

THE PROPORTION OF TARGET COMPLETIONS AS A FUNCTION OF PRIMING CONDITION IN EXPERIMENT 3

Stimulus type	Priming condition: Repeated	Morphologically related	Unprimed
Similar	.47	.44	.32
Dissimilar	.49	.38	.33

spects, the procedure of this experiment was identical to that of Experiment 2.

Results

The proportion of target completions in each condition is presented in Table 3. An analysis of variance revealed that the effect of study condition was significant by subjects, $F1(2,178) = 48.74$, $p < .0001$, $MS_e = 1.10$, and items, $F2(2,104) = 47.66, p < .0001, MS_e = 0.32$. As expected, more target completions were generated in the repeated condition than in the morphological condition, $t1(89) = 9.85$, $p < .0001$, $t2(52) = 9.74$, $p < .0001$, and more target completions were generated in the morphological condition than in the unprimed condition, $t1(89) = 5.48, p < .0001, t2(52) = 5.43$, $p < .0001$. Thus, performance in the fragment completion task was influenced by both identity and morphological priming.

The primary goal of this experiment was to investigate the effect of orthographic similarity on morphological priming. As predicted by the connectionist account, a significant interaction of similarity and study condition was obtained, $F1(2,178) = 3.45$, $p < .05$, $MS_e = 0.08$; $F2(2,104) = 3.77, p < .05, MS_e = 0.02$. Follow-up analyses pinpoint the basis for this interaction. Specifically, morphological priming (i.e., the difference between the morphological and baseline conditions) was stronger with similar prime–target pairs than with dissimilar pairs, $t1(89) = 2.12$, $p < .05$, $t2(52) = 2.12, p < .05$. In contrast, repetition priming (i.e., the difference between the repeated and baseline conditions) was statistically equivalent in the similar and dissimilar conditions (t's < 1).

Thus, as predicted by the connectionist account, orthographic similarity had an effect on morphological priming. Moreover, given the equivalent effects of repetition priming in the similar and dissimilar conditions, together with the fact that the baseline completion rates were nearly identical in both conditions, it is highly unlikely that the stronger effect of morphological priming in the similar condition arose because the target words in the similar and dissimilar conditions differed on some unintended dimension (e.g., because the words in the similar condition are, for some reason, more sensitive to priming in general). Rather, our results provide strong evidence that morphological priming varies in magnitude as a function of the orthographic similarity of the prime and target.

EXPERIMENT 4

As noted in the introduction, the effect of orthographic similarity on morphological priming was a focus of several previous studies (Fowler et al., 1985; Napps, 1989; Stanners et al., 1979; Stolz & Feldman, 1995). Although the numerical trend in each of these studies is consistent with the findings of our Experiment 3, our experiment is the first to yield a statistically significant effect of orthographic similarity on long-term morphological priming. Thus, we felt it was important to replicate this result and show that it is not peculiar to the specific procedure and stimulus set used in Experiment 3.

Experiment 4 was designed with this in mind. As in the previous experiment, subjects made familiarity judgments about words that were either target completions on a subsequent fragment completion task or were irregular past-tense inflections of those targets. However, several modifications of the methodology of Experiment 3 were made to help establish the generality of our findings across changes in stimuli and procedure. First, we used a relatively common form of the fragment completion task rather than masked fragment completion. In the masked fragment completion task used in Experiments 1–3, a single letter was replaced by a pattern mask, and the stimulus was presented for 250 ms. In contrast, in Experiment 4 several letters were removed from each fragment, the missing letters were indicated by an underscored blank space (e.g., _l_ph_n_), and the fragments remained visible until a solution was found. Although we noted several concerns about the standard version of the fragment completion task in the introduction, we felt that, given its frequent usage, it would be valuable to determine whether the standard fragment completion task yields results similar to those of the masked fragment completion task.

A second change from Experiment 3 involved the composition of the stimulus set. Ideally, an entirely new set of stimuli might have been used. However, given the constraints on stimulus construction (including the relatively small number of irregular inflections and the requirement that each fragment could be completed by only one of the target words), we found that some overlap in stimuli between Experiments 3 and 4 was unavoidable. Thus, 20 of the 60 pairs of targets and irregular past-tense inflections used in Experiment 4 were not used in Experiment 3, and 17 of the 54 pairs used in Experiment 3 were not used in the present experiment.

A third change from the design of Experiment 3 also arose from the requirement that each fragment could be completed by only one of the target words. Specifically, because the number of solutions for a given fragment increases with the number of missing letters, we found it necessary to manipulate orthographic similarity between subjects in order to construct a reasonably sized stimulus set. In Experiment 3 similarity was a within-subject variable.

Method

Participants. The participants in this study were 90 University of Connecticut undergraduates who completed the experiment for course credit.

Materials. The stimuli for this experiment included two lists of 30 verbs with irregular past-tense forms (see Appendix D). Of these 60 verbs, 40 served as targets in Experiment 3. As in Experiment 3, words in the similar condition differed from their past-tense forms by either the subtraction (e.g., *bite–bit*) or substitution (e.g., *make–made*) of a single letter, and words in the dissimilar condition differed from their past-tense forms by at least two letters (e.g., *take–took*). The average orthographic overlap (using the measure developed by Napps, 1989) was .77 in the similar condition and .58 in the dissimilar condition. The average frequency of the targets in the similar and dissimilar conditions was 106.7 and 113.1 (Kucera & Francis, 1967), respectively, and the average length was 4.47 and 4.57 letters.

For each target word, a fragment was formed by replacing all but two of the letters with an underscored blank space. The fragments were constructed with the constraints that (a) the past-tense form of the target word was not a legal solution; (b) the fragment could not be completed by any of the other present or past-tense forms in the same (i.e., similar or dissimilar) list; and (c) each fragment had at least two solutions.

Design and procedure. As in Experiment 3, study condition (i.e., repeated, morphological, or baseline) was manipulated within subjects. Unlike Experiment 3, however, similarity was a between-subjects variable. For purposes of counterbalancing, the similar and dissimilar lists were each partitioned into three sublists. During the study task, subjects in the similar condition were presented with the target items of one of the sublists of similar pairs, along with the past-tense forms from a second sublist of similar pairs. Present- or past-tense forms from the third sublist were not presented during the study task, thus providing an unprimed baseline condition. The same procedure was followed for subjects in the dissimilar condition. Across subjects each item appeared equally often in the repeated, morphological, and unprimed conditions.

Paper-and-pencil versions of the familiarity and fragment completion tasks were used so that subjects could be run in groups of 5–

10. At the beginning of the experiment the subjects were told that they were participating in a study investigating vocabulary knowledge and its relation to reading and were then given booklets containing the instructions and materials for each task. The stimuli for the familiarity task included 32 words (10 words in the repeated condition, 10 in the morphological condition, and 12 fillers) arranged in three columns on a single sheet of paper. The stimuli were randomly ordered with the constraint that the first 4 and last 4 words were fillers.

After rating the familiarity of each word on a 1–7 scale, the subjects were then given the instructions for the fragment completion task. They were told that they would perform a sort of crossword puzzle task involving word fragments, that there were several solutions to each fragment, and that they should respond with the first legal solution that came to mind. Performance was untimed, but the subjects were told that if they could not think of an answer within about 10 s, they should go on to the next fragment. The stimuli for this task included 39 fragments (the 30 test fragments and 9 fillers) arranged in three columns on a single sheet of paper. The fragments were randomly ordered with the constraint that the first 3 fragments were fillers, and two such random orders were used.

Results

The results for Experiment 4 are presented in Table 4. Overall, this pattern of results closely resembles that of Experiment 3. As in Experiment 3, the main effect of study condition was significant by both subjects, $F1(2,176) = 21.25, p < .0001, MS_e = 0.32$, and items, $F2(2,116) = 22.28, p < .0001, MS_e = 0.24$. Performance in the fragment completion task again reflected the influence of both repetition and morphological priming: More target completions were generated in the repeated condition than in the morphological condition, $t1(89) = 6.51, p < .0001, t2(52) = 6.66, p < .0001$, and more target completions were generated in the morphological condition than in the unprimed condition, $t1(89) = 2.91, p < .005, t2(52) = 2.94, p < .005$.

TABLE 4

THE PROPORTION OF TARGET COMPLETIONS AS A FUNCTION OF PRIMING CONDITION IN EXPERIMENT 4

	Priming condition		
Stimulus type	Repeated	Morphologically related	Unprimed
Similar	.30	.28	.19
Dissimilar	.31	.19	.18

The critical question addressed by Experiment 4 is whether morphological priming varies as a function of prime–target similarity. The main effect of similarity was marginally significant by subjects, $F1(1,88) = 3.54, p < .07, MS_e = 0.06$, but not by items ($F2 < 1$). More important, however, the interaction of similarity and study condition was again significant by both subjects, $F1(2,176) = 3.76, p < .05, MS_e = 0.06$, and items, $F2(2,116) = 3.89, p < .05, MS_e = 0.04$. As in Experiment 3, the basis for this interaction is clear. More morphological priming was obtained with similar prime–target pairs than with dissimilar primes and targets, $t1(88) = 2.13, p < .05, t2(58) = 2.36, p < .05$, whereas equivalent levels of repetition priming were found in the similar and dissimilar conditions (t's < 1). Together, the results of Experiments 3 and 4 provide strong evidence that morphological priming varies in magnitude as a function of the orthographic similarity of the target words and their morphologically related primes.

GENERAL DISCUSSION

The results of the experiments reported above reveal several important characteristics of long-term morphological priming. First, morphological priming is a robust effect that influences performance on a variety of tasks, including both masked and standard fragment completion. Second, morphological priming cannot be attributed solely to the formal similarity of morphologically related words: When matched in formal similarity, morphological relatives are better primes than are morphologically unrelated words. Third, even though formal similarity does not provide a sufficient basis for morphological priming, it does influence the magnitude of the priming effect. Specifically, in Experiments 3 and 4 the degree to which an irregular inflection primed its root form depended on the orthographic similarity of these forms.

These results have important implications for theoretical accounts of long-term morphological priming. For the most part, morphological priming effects have been taken to mean that morphological structure is explicitly represented in the lexicon, either in the form of morphemic access units that play a mediating role in the retrieval of lexical entries (Taft & Forster, 1975) or else in the form of interconnections among those entries (Feldman & Fowler, 1987; Lukatela et al., 1980; Stanners et al., 1979). One interesting aspect of these accounts is that they provide a ready explanation for certain gradations in the magnitude of morphological priming. For example, Stanners et al. (1979) found that a root form was primed more strongly by a regular inflection than by either an irregular inflection or a derivation. They argued that this pattern was attributable to differences in the manner in which different sorts of morphological relationships are represented in the lexicon. Specifically, they proposed that a root form and its regular inflections are identified via a common access unit, whereas irregular inflections and derivations are represented by separate (but interconnected) lexical entries.

The Stanners et al. (1979) account provides a framework for explaining behavioral differences that can be linked to different categories of morphological relationships. But whereas such accounts can readily explain between-category effects, it is less obvious how they might address within-category effects such as the influence of orthographic similarity on morphological priming found in Experiments 3 and 4. Put another way, for models that assume that the lexicon is organized around morphological principles, behavioral equivalence classes are defined along morphological lines. Systematic differences within such classes appear to demand an additional (or alternative) set of principles.

One possibility is suggested by the recent development of "dual-route" models of the role of morphology in reading (e.g., Caramazza, Laudanna, & Romani, 1988; Frauenfelder & Schreuder, 1992; Schreuder & Bayaan, 1995). According to such models, word identification involves a horse race between two processes that operate in parallel. Words can be identified either by a decompositional process, in which representations of the morphological constituents of a word serve as access units, or via a direct route, in which whole-word representations serve as the access units. A number of factors have been identified as potential determinants of which process wins the horse race (Chialant & Caramazza, 1995; Frauenfelder & Schreuder, 1992; Schreuder & Bayaan, 1995), including both characteristics of a word's internal structure (e.g., the presence of pseudoaffixes) as well as statistical variables (e.g., stem and whole-word frequency).

Perhaps a dual-route model could provide an account for the influence of orthographic similarity on long-term morphological priming observed in Experiments 3 and 4. For example, a dual-route model could account for our results by assuming both that morphological priming facilitates the decompositional process but not the direct process and that the likelihood that an irregular inflection is identified via the decompositional route depends on its similarity to its root form. Note, however, that the very spelling and sound changes that make an inflection irregular are also problematic for the kinds of parsing strategies that might be used to decompose a word into its morphological constituents (Chialant & Caramazza, 1995; Taft & Forster, 1975). Thus, one might expect dual-route models to hold that irregular inflections are always identified via the direct route, regardless of their similarity to their root forms. In addition, the assumption that morphological priming does not facilitate the direct process is inconsistent with at least some versions of the dual-process approach. For example, Caramazza et al.'s (1988) Augmented Addressed Model (AAM) assumes that the primary role of the decompositional route is to process unfamiliar words (e.g., *greenify*) and that familiar words are typically identified via the direct route. Thus, to account for the robust effects of long-term morphological priming on the identification of familiar words, the AAM would need to assume that priming influences the operation of the direct route, in contrast to the account suggested above.

An alternative account of our results is provided by the connectionist model described in the introduction. A distinguishing feature of this account is its rejection of the claim that morphology is explicitly represented in the lexicon. Instead, morphological effects are attributed to the influence of morphological regularities on the structure of the lexical network's weight matrix and, hence, on its activation dynamics. Specifically, because the frequency of a word's morphological constituents are necessarily higher than that of the word itself, the features that comprise these constituents tend to be relatively highly correlated. These intercorrelations have both within- and between-layer effects on the activation dynamics. The within-layer effects occur because, at each level, features corresponding to a morpheme act (by virtue of their intercorrelations) as stable subpatterns that can be established quickly and that anchor the activation dynamics (see McRae, de Sa, & Seidenberg, 1995, and Seidenberg, 1987, for discussion of related ideas). In a similar manner, the intercorrelations among the features of a morpheme at different levels also play an influential role in shaping the network's activation trajectory. In particular, because morphological relationships are virtually the only source of structure in the mappings between (orthographic and phonological) form and meaning, morphological regularities play an especially important role in establishing resonance between the semantic layer and the orthographic and phonological layers.

By this account, long-term morphological priming is simply one manifestation of the learning process by which these intercorrelations structure the weight matrix. When a word is processed, the connections among its features are strengthened, deepening its basin of attraction and thus facilitating its subsequent identification. To the degree that other words share these features, their basins of attraction will also be strengthened. Because morphological relatives are typically similar in both form and meaning, the transfer of learning between morphologically related words is especially pronounced.

This relationship between similarity and morphological priming can be seen in the results of the experiments reported above. For example, in Experiments 3 and 4 the degree to which an irregular inflection primed its root form depended on the orthographic similarity of these two forms—the more similar the words, the greater the priming. By our account, this pattern is the result of similarity-based gradations in the transfer of learning. Specifically, we assume that after a prime is identified, the weight matrix is modified to strengthen its attractor. To the extent that another word is spelled in the same way, its attractor will also be strengthened by the weight changes made within the orthographic layer. In this respect, our account parallels Seidenberg's (1987, 1989) claim that the effects of morphological structure in word identification tasks are best understood in terms of how the weights within the orthographic layer are structured by *orthographic redundancy* (i.e., statistical regularities in the co-occurrence of letter patterns). It should be noted, however, that whereas Seidenberg's proposal emphasizes the orthographic similarity of morphologically related words, in our account their semantic similarity plays an equally important role.

Results like those of Experiment 2 suggest that orthographic similarity alone cannot provide the basis for a complete account of all facets of morphological priming. In that experiment we found that target words were primed more effectively by morphological relatives than by morphologically unrelated control words. (See Feldman & Moskovijevic, 1987, Hanson & Wilkenfeld, 1985, Napps, 1989, Napps & Fowler, 1987, Stolz & Feldman, 1995, for similar findings.) By our account, because the related and unrelated prime–target pairs were matched in terms of formal similarity, the weight changes made within the orthographic (and phonological) layers had equivalent effects in both conditions. In contrast, because only the morphologically related primes and targets were similar in meaning, the weight changes made within the semantic layer (and in the pathways between that layer and the orthographic and phonological layers) benefited morphologically related targets but not unrelated targets. (Indeed, weight changes on these connections might have had a negative effect when the prime and target are semantically unrelated, which would help explain why form-based similarity priming had so little effect in Experiment 2.[3])

Although the results of Experiment 2 are consistent with our claim that morphological priming depends on semantic (as well as formal) similarity, it should be noted that semantic relatedness and morphological relatedness covaried in that experiment. Thus, a critical test for this aspect of our account is whether semantic similarity modulates morphological priming when the morphological relationship is held constant (in a manner similar to the test for an orthographic similarity effect in Experiments 3 and 4). Research into this question is currently under way. It is worth noting, however, that the results of a study by Weldon (1991, Experiment 4) provide encouragement for our view. Subjects in Weldon's experiment studied target words (e.g., *black, opera*) presented as components of compound words and phrases in which the meaning of the target in isolation was either preserved (e.g., *blackbird, Italian opera*) or not (e.g., *blackmail, soap opera*). Consistent with the connectionist account, the effect of priming on fragment completion was greater when the prime preserved the meaning of the target than when it did not.[4]

Thus, the empirical evidence supports our claim that morphological effects arise because morphologically related words are similar in both form and meaning. Note, however, that we are not claiming that morphological priming is simply the sum of two independent priming effects, one based on similarity of form and the other based on similarity of meaning. Characterizing our account in this way ignores the fact that, because the pattern of activation in each layer influences, and is in turn influenced by, the patterns of activation in the other layers, changing the weights within each layer will have synergistic, rather than independent, effects on the activation dynamics. Moreover, because morphologically related words are similar in both form and meaning, weight changes made on the connections between the semantic layer and the orthographic and phonological layers will also support morphological priming. In contrast, weight changes on these connections will not result in positive transfer between words that are similar in either form or meaning but not both.

The results of several recent studies support our claim that repetition effects reflect, in part, the influence of weight changes on connections to and from semantic-layer nodes. For example, Rueckl (1990) found that although thrice-presented words showed more priming than words presented only once, neither pseudoword repetition priming nor form-based similarity priming benefited from additional presentations of the primes. According to our account, this pattern of results can be attributed to the differential effect of learning on the connections between the semantic layer and the orthographic and phonological layers. Weight changes made on these connections

[3] We thank Ken McRae for pointing this out.

[4] Although semantic similarity affected priming in the fragment completion task, it had no effect on tachistoscopic identification. Weldon (1991) took her results to mean that performance in the fragment completion task relies more on semantic-level processes than does performance in the identification task. If so, this could have implications for our account of morphological priming. However, at present the degree to which tachistoscopic identification draws on semantic-level processes remains unclear (cf. Balota, Ferraro, & Connor, 1991; Jacoby, 1983; Masson & MacLeod, 1992; Weldon, 1991, 1993).

enhance word repetition priming but do not contribute to either pseudoword repetition priming (because pseudowords have no meaning) or form-based similarity priming (because formally similar words are semantically unrelated). Consistent with this account, Rueckl and Olds (1993) found that when pseudowords were made more meaningful (by pairing them with definitions during the priming task), pseudoword priming, like word priming, increased as a function of the number of repetitions.

The influence of learning on connections to and from the semantic layer can also be seen in the results of a study by Rueckl and Dror (1994). Subjects in this study were taught a set of pseudoword–definition pairings over a 5-week period. For some of the subjects, the pairings were constructed so that similarly spelled pseudowords were assigned similar meanings (e.g., *durch–dog, hurch–cat*). For other subjects, the same set of pseudowords and definitions comprised the training set, but the pairings of pseudowords and definitions were constructed so that no such regularities existed (e.g., *durch–dog, hurch–shirt*). The results revealed that the structured pairings were easier to learn, and, in addition, that the pseudowords in this condition were more accurately identified in a tachistoscopic identification task. According to our account, the advantage of the systematic pairings reflects the manner in which these pairings structure the connections between the formal and semantic layers and, hence, influence the activation dynamics that underlie word (and pseudoword) identification. Similarly, because morphology creates systematic pairings of form and meaning, morphological structure influences the identification process in the same way.

In sum, then, what is important about morphologically related words is not simply that they are similar in form and similar in meaning but, rather, that they are similar in *both* form and meaning. Because morphological relationships impart structure to the otherwise arbitrary mapping between form and meaning, morphology has a unique and important influence on the dynamics of the lexical system.

Morphological Priming and Theories of Implicit Memory

We conclude with a discussion of the implications of morphological priming for theories of implicit memory. It is noteworthy that whereas repetition priming has figured prominently (although rather independently) in the study of both memory and word identification, research on morphological priming has been confined almost exclusively to the latter. We believe that this is somewhat unfortunate and that morphological priming has important implications for theories concerned with repetition priming as a memory phenomenon.

Schacter (1987; also see Roediger & McDermott, 1993) identified three classes of memory theories that have been used to explain repetition priming: the *activation, processing,* and *multiple memory systems* accounts. Of these three, activation theories (e.g., Dorfman, 1994; Graf & Mandler, 1984; Mandler, 1980; Morton, 1979) are most closely linked to models of word identification and, hence, most accounts of morphological priming (e.g., Feldman, 1994; Fowler et al., 1985; Murrell & Morton, 1974; Stanners et al., 1979) are activation accounts . These accounts hold that long-term priming is due to the temporary activation of a preexisting lexical (or morphemic) representation that automatically occurs whenever a word (or morpheme) is identified. In recent years, activation theories have been criticized for their inability to accommodate certain findings, such as the relatively lengthy persistence of priming effects (Jacoby & Dallas, 1981; Sloman, Hayman, Ohta, Law, & Tulving, 1988), priming effects involving unfamiliar pseudowords (Feustel et al., 1983; Rueckl, 1990; Rueckl & Olds, 1993), and form-based similarity priming (Feustel et al., 1983; Rueckl, 1990; Rueckl & Olds, 1993). (See Rueckl, 1990, 1995b, and Tenpenny, 1995, for reviews of these arguments, and Dorfman, 1994, for a forceful defense of the activation approach.) The results of Experiments 3 and 4 raise yet another problem for the activation approach. As noted earlier, it is difficult to see how an activation theory could explain the finding that morphological priming varies in magnitude with the orthographic similarity of the prime and target. Perhaps one approach would be to claim that the orthographic similarity effect observed in our experiments is a form-based phenomenon that occurs independently of, but in conjunction with, a morphological effect. To this end, it is worth noting that activation accounts make exactly the wrong prediction about form-based effects; namely, these accounts predict that the identification of a word should be *inhibited* (rather than facilitated) by the priming of an orthographically similar word (Rueckl, 1995b).

Compared with activation theories, neither processing theories nor multiple memory system theories provide an account of repetition priming that is closely tied to a detailed model of visual word identification. For example, according to processing theories (Jacoby, 1983; Roediger & Blaxton, 1987; Weldon, 1991), the identification of a word is accomplished through the retrieval of memory traces for previous processing episodes. Each trace contains a record of the processes conducted during the corresponding episode, and repetition priming occurs to the extent that processes conducted during the priming event match the processes that are carried out during the test event. Unfortunately, the nature of these processes is rarely discussed at the level of detail required to address issues related to, for example, morphological effects in word identification.

One avenue toward a processing account of morphological priming is suggested by Hintzman's (1986) MINERVA model of schema abstraction. This model illustrates how a variety of phenomena related to categorization (e.g., prototypicality effects, the classification of unfamiliar exemplars) can arise from the retrieval of a large number of episodic memory traces. By analogy, given appropriate assumptions about the characteristics of the memory traces that are retrieved in the course of identifying a word, it may be possible to show how effects of morphological structure emerge from the retrieval of these traces. Presumably, an important issue to be addressed by this account would be the same one discussed in connection with the network model; specifically, the degree to which morphological effects involve the representation of form, meaning, or both.

The third class of memory theories to be considered here are multiple memory systems accounts (e.g., Squire & Cohen, 1984; Schacter, 1992; Tulving, 1983). These accounts propose that a number of neurally and functionally distinct memory systems underlie human behavior and that different systems may be responsible for manifestations of memory on different tasks. At a broad level, the structural assumptions of certain systems theories can be aligned with the architectural assumptions of models of word identification. For example, Schacter (1992) has proposed that repetition priming reflects the operation of a presemantic "perceptual representation system." This system includes subsystems that "process and represent information about the form and structure, but not the meaning and other associative properties, of words and objects" (Schacter, 1992, p. 245) and includes different subsystems for the representation of visual and auditory word forms. This distinction between the visual and auditory word form subsystems closely resembles the distinction between the orthographic and phonological lexicons made in the literature on word identification (cf. Coltheart, Curtis, Atkins, & Haller, 1993; Morton, 1979; Seidenberg & McClelland, 1989) and, indeed, much of the evidence he uses to support this distinction is drawn from this literature.

Although Schacter's (1992) version of the multiple memory systems account resembles models of word identification in this respect, a detailed explication of the representations and processes employed by each subsystem has not yet been developed. Thus, as is also the case for processing theories, the characteristics of morphological priming neither support nor refute current systems accounts. Instead, morphological priming provides a set of constraints against which the development of the systems approach can be measured and highlights some of the issues that future work must address. For example, although memory systems are typically characterized as operating independently of one another, our account of morphological priming suggests that it reflects synergies that arise in the interaction of formal and semantic (or, in the terminology of memory theories, perceptual and conceptual) subsystems. Incorporating such interactions in systems accounts may have far-reaching consequences.

We conclude this section with two points. First, our discussion of the implications of morphological priming for theories of memory is not intended as an attack on those theories. Although our results are problematic for activation accounts, they are not necessarily inconsistent with either processing or systems theories. Given that the intended scope of these theories is far broader than the range of phenomena related to word identification and that breadth comes at the expense of detail, the fact that current versions of these theories do not provide explicit accounts of morphological priming is not unreasonable. However, we believe that an important test of these theories is whether their fundamental premises can be successfully instantiated in more detailed models of specific processing domains, and we suggest that word identification provides a particularly appropriate domain for such an endeavor.

Our final point is that connectionist models have intriguing points of commonality with both multiple memory systems and processing accounts. As noted previously, connectionist models employ architectural assumptions similar (in certain respects) to those of systems theories. Similarly, in attributing priming effects to the laying down of new memory traces (McClelland & Rumelhart, 1985; Rueckl, 1990) and in emphasizing the behavioral implications of differences in task demands (Becker et al., 1993; McRae et al., 1995), connectionist models strongly resemble processing accounts. We suggest that connectionist models are not necessarily competitors of these accounts; rather, connectionism offers a framework in which the fundamental assertions of these theories can be instantiated in computationally explicit models of specific processing domains.

Appendix A

The Stimuli from Experiment 1

babe	fare	junk	rice
bean	fight	lift	rush
bike	fire	line	seek
bit	fix	lip	shade
boom	foil	lose	shore
brain	gain	meat	spot
breed	game	mile	stake
bump	gap	mock	task
buy	graze	moon	tire
claw	hall	move	tore
code	hate	must	vine
crown	haze	oath	wary
die	held	pat	water
dive	hold	pine	wave
drank	hope	plush	wound
fade	jail	pose	zest

Note. Underlined letters were removed for the masked fragment completion task.

Appendix B

The Stimuli from Experiment 2

art	artist	article
band	banded	bandage
bat	batted	battery
bill	billing	billion
bit	bitten	bitter
blank	blanked	blanket
boar	boars	board
brow	brows	brown
buck	bucked	bucket
bud	budded	budget
cape	capes	caper
car	cars	card
cent	cents	center
chap	chapped	chapter
clam	clammy	clamor
cop	cops	copy
drag	dragged	dragon
elect	elected	electric
fan	fanned	fancy
fee	fees	feed
gull	gulls	gully
hat	hats	hatch
jack	jacked	jacket
kid	kidded	kidney
law	laws	lawn

APPENDIX B—*Continued*

let	letting	letter
mark	marker	market
mat	mats	match
mess	messed	message
musk	musky	musket
need	needed	needle
pad	padded	paddle
pain	pains	paint
pig	piggish	pigment
pill	pills	pillow
plan	plans	plant
plum	plums	plumb
prop	propped	proper
pun	punned	punish
rap	raps	rapid
rave	raved	raven
rib	ribbed	ribbon
rob	robber	robin
rug	rugs	rugby
sand	sandy	sandal
scan	scanner	scandal
sea	seas	seat
sill	sills	silly
skim	skims	skimp
slum	slummed	slumber
sneak	sneaked	sneaker
spin	spinning	spinach
star	stars	start
stew	stewing	steward
stub	stubbed	stubborn
sum	summed	summer
sweat	sweated	sweater
tail	tailed	tailor
wall	walled	wallow
wind	windy	window

Note. The first word in each triplet is the target, the second word is the morphologically related prime, and the third word is the formally related prime. Underlined letters were removed for the masked fragment completion task.

APPENDIX C

The Target Words and Morphologically Related Primes from Experiment 3

Similar		Dissimilar	
bite	bit	bear	bore
blow	blew	break	broke
burn	burnt	buy	bought
come	came	catch	caught
deal	dealt	creep	crept
dive	dove	eat	ate
drink	drank	feel	felt
fall	fell	fly	flew
grow	grew	leave	left
hang	hung	lie	lay
hold	held	light	lit
lead	led	seek	sought
leap	leapt	sell	sold
lose	lost	shake	shook
mean	meant	slay	slew
meet	met	sleep	slept
rise	rose	steal	stole
send	sent	strike	struck
slide	slid	swear	swore
spend	spent	sweep	swept
spit	spat	take	took
stick	stuck	teach	taught
swim	swam	tear	tore
swing	swung	think	thought
throw	threw	wear	wore
win	won	weep	wept
write	wrote	wind	wound

Note. Underlined letters were removed for the masked fragment completion task.

APPENDIX D

The Target Words, Morphologically Related Primes, and Test Fragments from Experiment 4

	Similar			Dissimilar	
awake	awoke	_wa__	bear	bore	b_a_
become	became	___om_	break	broke	b_e__
begin	begun	__gi_	buy	bought	_uy
bite	bit	__te	catch	caught	__t_h
blow	blew	b_o_	creep	crept	c__e_
choose	chose	c__o__	eat	ate	_at
cling	clung	c_i__	feel	felt	__el
come	came	co__	fight	fought	fi___
dive	dove	di__	find	found	fi__
draw	draw	d_a_	fly	flew	f_y
drive	drove	__iv_	freeze	froze	__ee__
fall	fell	fa__	grind	ground	__i_d
give	gave	gi__	keep	kept	k_e_
grow	grew	_ro_	kneel	knelt	___el
hold	held	ho__	leave	left	l___e
lead	led	__ad	mistake	mistook	____ak_
lose	lost	l__e	seek	sought	__ek
meet	met	m_e_	sell	sold	s__l
rise	rose	_is_	shake	shook	s__k_
run	ran	ru_	slay	slew	s__y
shoot	shot	___ot	sleep	slept	_l_e_
shrink	shrunk	_h_i__	stand	stood	__an_
slide	slid	___de	strike	struck	s__i__
speed	sped	_p_e_	swear	swore	_we__
spit	spat	_pi_	take	took	__ke
stick	stuck	__ic_	teach	taught	__a_h
swim	swam	_wi_	tell	told	te__
throw	threw	t__o_	think	thought	_hi__
win	won	wi_	wear	wore	w_a_
write	wrote	w_i__	weep	wept	w_e_

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(Received August 17, 1995)
(Revision received June 14, 1996)