A Distributed Memory Model of Semantic Priming

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An alternative to semantic network models of lexical knowledge representation and access is described, in which knowledge about a word is represented as a pattern of activation across a collection of processing units. In this distributed memory model, semantic priming effects arise naturally from the similarity of the patterns of activation that represent a related prime and target. Priming effects can be reduced by an intervening stimulus that modifies the pattern of activation before the target appears. This process is demonstrated empirically with a word naming task. An implemented version of the distributed memory model is used to simulate these results, and results from previous research in which participants overtly responded to the item that intervened between a prime and target are also simulated. Comparisons with semantic network and compound cue models of priming are discussed.

The exploration of issues regarding knowledge representation and retrieval has been guided by a number of fundamental, widely held principles. One of these important principles is the conception of knowledge as an interconnected network of nodes representing individual concepts. Another fundamental principle is the process of automatic spreading activation, which is assumed to enable access to knowledge in a network. When a concept's node becomes active, perhaps through encountering an instance of the concept in the environment, activation spreads to other related nodes making available information about the concept and preparing the system to identify related concepts should they, too, appear in the environment. Taken together, the network representation and spreading activation principles have formed the foundation for a powerful and important class of theories of knowledge representation and processing (e.g., Anderson, 1983; Collins & Loftus, 1975).

By applying the distinction between consciously controlled and automatic processes (e.g., Posner & Snyder, 1975), Neely (1977) developed a theory of semantic priming effects in which automatic spreading activation among related concepts plays a central role. Semantic priming is defined in this article as the facilitative effect of the presentation of a word on the identification or classification of a related word. Neely (1991; Neely & Keefe, 1989; Neely, Keefe, & Ross, 1989) has since expanded his theory to include processes of expectancy and semantic matching, as well as automatic spreading activation, to account for a wide range of priming effects. However, the principle of automatic spreading activation is an important component in many accounts of semantic priming phenomena (e.g., Balota, Black, & Cheney, 1992; Dagenbach, Horst, & Carr, 1990; McNamara, 1992a, 1992b, 1994; McNamara & Altarriba, 1988; Sereno & Rayner, 1992; Smith, MacLeod, Bain, & Hoppe, 1989; Yantis & Meyer, 1988).

Despite rather widespread application of the spreading activation principle, an alternative view of semantic priming has been developed that makes no appeal at all to this principle. According to compound cue theory, a prime and target may be combined or integrated during encoding, and the familiarity of this compound cue is determined by accessing long-term memory (Dosher & Rosedale, 1989; McKeon & Ratcliff, 1992; Ratcliff & McKeon, 1988; Whittlesea & Jacoby, 1990). The degree of familiarity of the compound cue is then used to make a decision about the target, as in a lexical decision task. In the case of related prime–target pairs, the compound cue is a relatively familiar one and a stronger match to existing long-term memory representations is obtained. It is assumed that there is an inverse relationship between strength of memory match and response latency, thereby generating a priming effect on response latency.

In addition to the spreading activation and compound cue models, a third view of semantic priming effects has emerged from recent work in connectionist modeling. Three models in particular have been advanced that make assumptions regarding knowledge representation and stimulus identification that are pertinent to the issue of semantic priming (Hinton & Shallice, 1991; Masson, 1989, 1991; N. E. Sharkey, 1989, 1990; A. J. C. Sharkey & N. E. Sharkey, 1992). A key feature of these models is the use of a distributed memory representation in which conceptual knowledge is captured in connection weights that link a set of processing units. This representational scheme is very different from the local representation typically assumed by spreading activation theories in which each concept is represented by a single node (local representation). The distributed nature of representation in these models also distinguishes them from other connectionist models of word identification and word production in which a local representation is used (e.g., Dell, 1986; McClelland & Rumelhart, 1981).

The distributed memory models also differ from the Seidenberg and McClelland (1989) distributed memory model of
word identification by the inclusion of an implemented module that represents word meaning. This module was not implemented in the Seidenberg and McClelland model, but it is crucial for simulating semantic context effects in word identification tasks. The basis for the simulation of semantic priming in the Hinton and Shallice (1991), Masson (1991), and N. E. Sharkey (1989, 1990) models is a process similar to spreading activation whereby activation in a processing unit is transmitted to neighboring units and is modulated by the connection weights that link the unit with its neighbors. As discussed below, however, connectionist models and certain spreading activation models make some different predictions with respect to priming effects.

In the connectionist models considered in this article, the activation or retrieval of a known concept entails establishing a specific pattern of activation across a set of processing units that represent various semantic features and that constitute a meaning module. In the simplest case, instantiation of the meaning of a word is driven by presentation of a visual stimulus that corresponds to the printed word. This activity can be described as a process of gradient descent in a multidimensional space in which basins of attraction correspond to known concepts. A hypothetical example of a three-dimensional space is shown in Figure 1. Each point on the surface corresponds to a particular pattern of activation across the processing units in a network. The local minimum residing at the bottom of each basin corresponds to a known concept. Presentation of a printed word causes a pattern somewhere in the appropriate basin of attraction to be instantiated, and further processing involves a gradient descent to the bottom of that basin.

The Hinton and Shallice (1991) model was developed primarily to explore patterns of acquired dyslexia and the relationship between orthographic and meaning modules, rather than semantic priming effects. The issue of semantic priming has more fully been developed in the N. E. Sharkey (1989, 1990; A. J. C. Sharkey & N. E. Sharkey, 1992) and the Masson (1989, 1991) models. These two models, although independently developed, are quite similar, and in the work reported here only the model described by Masson (1991; henceforth referred to as the distributed memory model) was used to formulate simulations of empirical results. Both models, however, use similar representational and processing principles and generate similar predictions.

In its initial formulation, the distributed memory model reproduced a number of fundamental latency results from word identification paradigms, such as a positively skewed response latency distribution, a negatively accelerated speed-accuracy trade-off function, cross-modal priming effects with ambiguous primes, and an interaction between strength of prime-target relatedness and stimulus onset asynchrony (SOA), in which strongly and weakly related primes influence target

Figure 1. A hypothetical space of activation patterns with basins containing local minima that represent learned patterns. Each point on the landscape represents a pattern of activation across an entire set of processing units. Movement over this space toward a local minimum constitutes settling on a learned pattern.
response latency at very short SOAs and reach their asymptotic effects at the same SOA value (see Masson, 1991, for details). Recently, Joordens and Besner (1992) have reported a result that poses a serious challenge for the original version of the model. Therefore, I begin by describing a modified version of the model that was designed to simulate performance on the word naming task and that was expected to reproduce the Joordens andBesner result. Next, a word identification paradigm that has played a significant role in the debate between spreading activation and compound cue theories is described. Two word naming experiments based on this paradigm are then presented, and simulations of those results and of the Joordens and Besner results are described. Finally, comparisons between the distributed memory model, spreading activation models, and the compound cue model are considered.

A Distributed Memory Model

The distributed memory model is a simple modification of a connectionist network known as a Hopfield net (Hopfield, 1982; Hopfield & Tank, 1986). The Hopfield net represents knowledge in connection weights that link processing units and it defines concepts as patterns of activation across those units. This type of network does not differentiate between groups of processing units (e.g., input, hidden, and output layers), as is done in many connectionist architectures (e.g., Rumelhart & McClelland, 1986). Instead, for each unit in the network, weighted connections are established with every other unit in the network. Moreover, units in a Hopfield net take on one of only two possible activation values (on or off).

Connection weights in a Hopfield net are established by a simple learning rule derived from Hebb (1949) that is used to encode a set of patterns. The learning of a pattern involves altering the connection weights between each pair of processing units as a function of the activation values taken on by the two units when the pattern is instantiated (equations for the learning rule and other aspects of the model are provided in the Appendix). This learning rule results in an increase to the connection weight when the two units take on the same value and decreases it when the two units have different values, thereby capturing the correlational patterns among units embodied by the entire set of learned patterns.

A major application of the Hopfield net is pattern completion. An entire learned pattern of activation can be recovered by first setting a subset of processing units to activation values consistent with the pattern and randomly assigning on or off states to the remaining units. Those units are then updated by computing the activation received by each unit. Updating continues until the entire pattern of activation stabilizes. In a procedure known as asynchronous updating (Hopfield, 1982), units are randomly sampled with replacement and incoming activation is computed. If sufficient activation is received by a unit, then it is turned on, otherwise it is turned off. This process can be visualized as starting the network near the rim of a basin of attraction on a surface such as that shown in Figure 1, then moving down the basin to its minimum, at which point the system comes to rest. The learned patterns correspond to the minima of basins of attraction, and pattern completion is achieved when one of these minima is reached. An error occurs if the model fails to reach the appropriate minimum. This can happen if the network begins at a random starting point that leads the network into a spurious local minimum that does not correspond to the target pattern. A disadvantage of Hopfield networks is that if too many patterns are learned, a large number of spurious local minima are created, making it likely that the network will fall into one of these traps and will fail to complete the pattern correctly. If the number of patterns is not too large, however, errors occur only rarely.

Word Identification

The distributed memory model was inspired by the pattern completion capability of the Hopfield net. In the initial version of the model (Masson, 1991), word identification consisted of (a) assigning appropriate activation values to a subset of processing units (perceptual units) representing visual perception of a word, and (b) updating the remaining units (conceptual units) to instantiate the pattern of activation corresponding to the word's meaning. An extension to that model is proposed in this article in which an additional set of processing units is designated. These units represent the phonological code associated with a word. Thus, the current version of the model consists of three processing modules, as shown in Figure 2, representing the orthographic, phonological, and meaning codes for a set of words. Each module contains a set of processing units, and the arrows indicate the flow of activation between modules. The model was designed to simulate word naming by taking orthographic input and generating a pattern of activation in the phonological module that represents the pronunciation of that word. Although all units in this model are connected to one another (both within and between modules), as in standard Hopfield nets, the configuration in Figure 2 reveals some key architectural assumptions and facilitates comparison with other models.

Figure 2. Processing modules in the distributed memory model of word naming. Each module consists of a set of interconnected processing units, and arrows indicate flow of activation between and within modules.
The connections between modules shown in Figure 2 suggest that the model accepts the proposition that there are two routes that provide access to a word's meaning. One route provides direct access to meaning, and the other route uses phonological recoding as an intermediate step. The provision for both a direct and a phonologically mediated influence of orthography on meaning distinguishes this model from the model proposed by Van Orden, Pennington, and Stone (1990). In their view, the predominant means of accessing meaning is through phonology, although orthographic information would be consulted to resolve ambiguous cases such as homophones (e.g., read and reed). Recent findings by Jared and Seidenberg (1991), however, indicated that access to meaning can occur, at least for high-frequency words, without phonological mediation.

An alternative way of describing these routes is appropriate if the emphasis is on word naming. One route provides direct activation of phonological codes, and the other route passes through the meaning module. The distributed memory model's instantiation of two routes to word identification, however, is somewhat different from classic dual-route proposals (e.g., Coltheart, 1978; Forster & Chambers, 1973; Patterson & Morton, 1985). First, rather than constituting two independent routes, the two paths of activation in the distributed memory model converge on a single set of processing units so that their influence is combined. Thus, the model does not simulate a horse race (cf. Paap & Noel, 1991). Second, the meaning module does not contain information about how words are pronounced, so there is no direct "look-up" for word pronunciations. Although the model is not intended to provide a detailed account of the translation of an orthographic pattern into a phonological code, it is compatible with models that posit a single mechanism for this computation that is capable of handling regular and exception words (e.g., Brown, 1987; Plaut & McClelland, 1993; Seidenberg & McClelland, 1989).

The Role of the Meaning Module

The distributed memory model's architecture is very similar to the framework described by Seidenberg and McClelland (1989, Figure 1) with respect to proposed processing modules. In both cases, meaning, orthographic, and phonological modules are fully interconnected, although the Seidenberg and McClelland model includes hidden units between each pair of modules and a context module that are not present in the distributed memory model. The critical difference between these two models lies in the implementation of the proposed modules. Seidenberg and McClelland have not implemented the context and meaning modules in their simulations, and their model is therefore not appropriate for simulating semantic priming effects. The distributed memory model, however, was designed specifically for this purpose.

The distributed memory model can be compared with a number of other connectionist models of word identification. First, consider the McClelland and Rumelhart (1981) interactive activation model of word identification. The strength of that model lies in its ability to account for letter-word interactions. The model made no provision for semantic relationships between words, and connections between word nodes were inhibitory so semantic relatedness effects played no role in the model. The main purpose of the distributed memory model, on the other hand, was to explore the interaction between sequences of words and the effect of semantic relatedness between them. Second, Dell (1986) proposed a model of speech production that was used to simulate the articulation of a sequence of words. His primary interest, however, was in the interaction between parts of words (e.g., syllables and morphemes) and the factors that affect errors in combining components of words that compose a sequence. The distributed memory model is largely silent with respect to the encoding errors emphasized in Dell's model. As a simplifying assumption, in the simulations reported here it is assumed in the distributed memory model that orthographic patterns are always encoded correctly. Although the theory underlying Dell's model made provision for the influence of semantic relatedness on the activation of words, semantic factors were not implemented in the computational model used by Dell.

Simulation of Word Naming

To simulate word naming in the distributed memory model, visual presentation of a word involves loading the pattern of activation for that word into the orthographic units. While holding constant the pattern in the orthographic units, the units in the meaning and phonological modules are asynchronously updated. Asynchronous updating is biased so that the phonological units are sampled at a higher rate than the meaning units. This bias creates a degree of inertia in the meaning module, which is necessary for the model to account for some of the priming results considered below. From a theoretical perspective, the differential sampling rate means that the phonological module is activated relatively quickly and has an early influence on the meaning module. These features are consistent with evidence that phonological recoding of visually presented words occurs early during visual word recognition and contributes to meaning access (Perfetti & Bell, 1991; Perfetti, Bell, & Delaney, 1988; Van Orden, Johnston, & Hale, 1988; Van Orden et al., 1990).

Updating continues until the units in the phonological module settle into the pattern that matches the target word, enabling a naming response. When the phonological units completely match the pattern of activation associated with the target word, the units have achieved a stable state. That is, continued updating of the phonological units will produce no further changes in the pattern of activation. The number of updates required to achieve a stable pattern in the phonological module is taken as a measure of naming latency. An error is assumed to occur if the network fails to reach a stable pattern in the phonological module within some reasonable time limit. Failure to reach a stable pattern typically means that the network has reached a local minimum that does not correspond to the target pattern.

Some basic features of the distributed memory model's performance are revealed by examining the distribution of simulated naming latencies that the model produces. A simula-
tion of 100 participants performing 150 naming trials was conducted (details of the implementation of the model are provided in the Appendix). On each trial, processing continued until the phonological units stabilized, or until 500 cycles had been run. Less than 1% of the trials failed to stabilize within that limit. Naming latency, measured by number of updating cycles required to produce a stable pattern in the phonological units, was recorded for each trial. The distribution of these latencies, shown at the top of Figure 3, clearly displays the typical positive skew found in actual data (e.g., Ratcliff & Murdock, 1976). This feature of the distribution is a result of asynchronous updating of the meaning and phonological units. In this procedure, there are occasional trials in which the last few phonological units that must be updated fail to be sampled until many other units have been sampled multiple times, thereby producing rather long latencies.

Another way of examining the latency data is to consider the speed–accuracy trade-off function. The bottom of Figure 3 shows the cumulative proportion of trials on which the phonological units have settled into the correct pattern (thereby allowing a correct vocal response), as a function of cycles (processing time). The function follows the characteristic negatively accelerated curve evident in actual data (e.g., Dosher & Rosado, 1989).

The higher rate of sampling phonological units relative to meaning units during updating means that the phonological units usually will stabilize before the meaning units fully instantiate the meaning of the target. I replicated the simulation to illustrate the implications of the higher sampling rate among phonological units, but this time the activation of the target's phonological and meaning representation was measured on each update cycle. In the distributed memory model, activation is defined as the proportion of units in a module in which the states (on or off) match the target's pattern. At the start of a naming trial the phonological and meaning units are set to a random pattern, so the expected activation level for the target is .5 (on average, half of the units should be in the appropriate state—on or off). As updating progresses, the proportion of units in the appropriate state increases.

In this simulation, processing was terminated as soon as the phonological units stabilized. On a majority of trials the phonological units fully instantiated the target's phonological pattern within 200 updating cycles. Activation values for the target's phonological and meaning patterns achieved by the time the phonological units settled were frozen and included in computation of the mean activation values for each updating cycle beyond that point, up to the maximum of 500 cycles. Thus, the asymptotic activation value for the meaning units represents the mean activation at the point at which the phonological units reached full activation. Figure 4 shows the mean activation of the target's phonological and meaning patterns as a function of updating cycle. On average, by the time the phonological units had stabilized, the activation in the meaning units was approximately .72. If updating had been allowed to continue beyond the point at which the phonological units stabilized, activation in the meaning units would have continued to rise.

Figure 3. Frequency distribution of simulated word naming latencies (top) and simulated speed–accuracy trade-off function for word naming (bottom).

**Semantic Priming**

Simulation of semantic priming is grounded on the assumption that semantically related words have similar patterns of activation across the meaning units. Similarities in these patterns of activation arise because it is assumed that (a) a concept's meaning is constructed from the context in which the concept occurs and (b) concepts that frequently co-occur share many aspects of their contextually based meaning. The potential importance of co-occurrence has been noted by others as well (e.g., McKoon & Ratcliff, 1992; Spence & Owens, 1990), although there is some controversy with respect to whether the consequences of co-occurrence are semantic in nature (Shelton & Martin, 1992). By the view taken here, however, concepts such as *milk* and *cow* would have similar patterns of activation in the meaning units because of their co-occurrence in certain contexts. In contrast, *milk* and *bull* would not have very similar patterns because they rarely co-occur, despite the similarity between *bull* and *cow*.

Similarity in meaning is crucial in simulating priming effects because as the model begins to identify a prime, the meaning units move toward its pattern of activation. That pattern is similar to the pattern of activation of the upcoming related target. When the target is presented, after the appropriate prime–target SOA, its orthographic pattern replaces that of the prime and updating of the meaning and phonological units...
continues. At this point the pattern of activation in the meaning units is similar to that of the target and can help drive the phonological units to the target pattern more quickly. Taking the representational space of Figure 1 as an analogy, presentation of a target after a related prime is like jumping from one basin of attraction to a point part way down a nearby basin that corresponds to the target. In the case of an unrelated prime, the jump that is initiated by presentation of the target places the system near the rim of the target’s basin. The system has farther to travel (more updates are required) to reach stability in the phonological units when starting from this area.

**Intervening Stimulus Paradigm**

The distributed memory model, the compound cue model, and various spreading activation models make different predictions regarding the possible effect of placing an intervening stimulus between a prime and target. Of particular interest is the potential influence of the type of intervening stimulus on the priming effect obtained with related prime–target pairs. The models predict differential consequences of using a novel word, unrelated to either the prime or the target, as opposed to a neutral stimulus, such as a row of xs or a word that occurs in the intervening position on many trials (e.g., *ready* or *blank*). In all the models it is assumed that a frequently presented word to which no response is required (a neutral word) fails to engage the linguistic or attentional processing invoked by words that occur only rarely in an experimental session.

**Predictions of the Models**

In the distributed memory model, activation of word meaning takes place in a single collection of processing units. The effect of the intervening stimulus, if it is processed as a novel linguistic input, will be to push the meaning units toward an irrelevant pattern of activation. This change in the activation pattern among meaning units undermines the work done by the related prime in moving those units toward a pattern related to the target. The model, therefore, predicts that an intervening unrelated word will reduce or even eliminate priming effects, depending on the exposure duration of the prime and intervening item. All else being equal, as the exposure duration of the intervening stimulus increases, more of the work performed by the prime will be dismantled, and the priming effect will be correspondingly small.

On the other hand, if the intervening item is a neutral stimulus with no linguistic relevance (e.g., a row of xs), the orthographic module is assumed to take on a random pattern of activation (one not previously learned by the system) and will therefore not have a systematic influence on the pattern of activation in the meaning and phonological modules. These two modules will continue to update, influencing one another. The pattern of activation in the meaning and phonological modules will move closer to the stable state that corresponds to the prime, thereby establishing a robust priming effect on the upcoming target. Therefore, the distributed memory model makes the prediction that semantic priming should be stronger when the intervening stimulus is a neutral item than when it is an unrelated word. Whether any priming effect is obtained when an unrelated word intervenes between a prime and target should depend on the relative amounts of processing devoted to the prime and intervening items.

The compound cue model developed by Ratcliff and McKoon (1988) makes a similar prediction. Given a sufficiently long presentation duration, an intervening unrelated word is assumed to “bump” the prime out of short-term memory and to take its place in the compound cue that includes the target. The resulting compound cue would be the same, regardless of the nature of the prime, so no priming effect would be obtained. A neural intervening stimulus is assumed not to be incorporated into compound cues, so in that case, the prime would form the compound cue with the target and a priming effect would result. By this account, the effect of inserting an unrelated word between the prime and target would be to eliminate the priming effect.

The compound cue model would predict a reduction, rather than elimination, of priming if it were assumed that bumping the prime from short-term memory occurred with some probability less than 1.0, or if three items were used to form the compound cue (McKoon & Ratcliff, 1992). In the latter case, the neutral-intervening stimulus might be excluded from the compound cue, and the target from the previous trial might be included. Thus, the compound cue would contain the earlier target, the prime, and the current target. If greater weight were given to the second item than to the first when computing the familiarity value of the compound cue, a priming effect ought to be observed. A smaller priming effect would be obtained if the intervening stimulus were an unrelated word because the prime would then occupy the first position in the cue set and would receive less weight in the familiarity computation.

A different prediction emerges from automatic spreading activation models as envisioned by Collins and Loftus (1975), Neely (1977), and Posner and Snyder (1975). In these models activation continues to spread after a concept ceases to be processed. Thus, even after a prime has been replaced by an intervening stimulus, its activated node will continue to spread activation to its related nodes. Consequently, priming should be unaffected by the presentation of an intervening stimulus. This prediction runs counter to the two possible outcomes predicted by the distributed memory and compound cue
models (priming is reduced or eliminated by an unrelated intervening word).

A variant of the spreading activation prediction is made by Anderson’s (1983) ACT* model (adaptive control of thought), in which it is assumed that the node representing a prime becomes a source of activation as a result of the visual presentation of the prime. As long as the prime is a source of activation, the node representing a related target will also be in a state of increased activation, producing a priming effect when the target is presented. Once the visual input representing the prime is terminated (e.g., by presenting an intervening stimulus), the prime will, after some delay, cease to be a source of activation. The length of this delay is a parameter in ACT* and its lower bound has been estimated as 400 ms (Anderson, 1983, p. 104). By this estimate, as long as the prime–target interstimulus interval is less than 400 ms, it is predicted that the intervening stimulus should have no effect on priming. If the delay parameter is reduced to a value that is less than the duration of the intervening stimulus, however, the ACT* model would predict a reduced priming effect.

Empirical Data

Experiments involving variants of the intervening stimulus paradigm have produced mixed results. In one version of the paradigm, a series of items is presented in a task such as lexical decision and participants respond to each item. The series is arranged so that some words are followed by either a related or an unrelated word. Members of these word pairs may occur consecutively (e.g., boy girl) or one or more unrelated items may intervene (e.g., boy chair girl), and the question is whether priming is obtained when the related words do not occur consecutively. Experiments with the lexical decision task have indicated that a priming effect is obtained when there is one intervening item (Davelaar & Coltheart, 1975; Meyer, Schvaneveldt, & Ruddy, 1972) and that this effect is not reliably less than the effect produced by consecutive targets (McNamara, 1992b). A priming effect with one intervening item has also been obtained in a recognition memory task (Ratcliff, Hockley, & McKoon, 1985) and in a naming task (Joordens & Besner, 1992). In contrast, other studies using the lexical decision task (Dannenbring & Briand, 1982; Gough, Alford, & Holley-Wilcox, 1981; A. J. Sharkey & N. E. Sharkey, 1992) and the phoneme monitoring task (Foss, 1982) have failed to obtain reliable priming effects when related targets were separated by one or more intervening items.

Some of the inconsistency regarding the effect of an intervening stimulus might be attributed to the use of the lexical decision task, which depends on postacquisition decision processes (Balota & Chumbley, 1984; Forster, 1981; Seidenberg, Waters, Sanders, & Langer, 1984). In that task there may be a tendency to compare a candidate interpretation of the target letter string with contextual information before making a response. A positive lexical decision can be made if this comparison yields evidence for similarity, otherwise a more careful check of perceptual information is necessary. If participants noticed instances in which two related targets were separated by one stimulus, they may have been encouraged to check a target against the item that occurred two positions earlier (see Ratcliff & McKoon, 1988, for a similar suggestion). Reliance on this strategy would reduce the effect of an intervening unrelated word and could account for the results obtained by McNamara (1992b) and Meyer et al. (1972).

An important limitation of the target series variant of the intervening stimulus paradigm is that in some of the reported studies (e.g., Joordens & Besner, 1992, Experiments 2 and 3) an item intervened between members of every critical pair, so priming in that condition could not be compared with a condition in which there was no intervening item. Moreover, even when such a condition has been included, the presence or absence of an intervening stimulus has been confounded with SOA between related target pairs. A reduction or absence of priming may therefore be due to decay rather than activity involving the intervening stimulus. Ratcliff and McKoon (1988) used a version of the paradigm that circumvents these problems. Targets on successive recognition memory trials were either related (through episodic study) or unrelated. Thus, the target on trial N–1 could prime the target on trial N. Each trial began with a briefly presented item that served as the intervening stimulus. On the trials of interest, the intervening item was either an unrelated word or a neutral stimulus (the word ready). When the SOA for the intervening stimulus and target was 300 ms, a priming effect was obtained with a neutral-intervening stimulus, but the effect was eliminated when the intervening item was an unrelated word. Ratcliff and McKoon (1994) have recently replicated this result by using a lexical decision task and a 350-ms SOA.

Although the Ratcliff and McKoon (1988, 1994) results support the compound cue model and are consistent with the distributed memory model, McNamara (1994) has failed to replicate the intervening item effect by using the lexical decision task and associatively related targets. It is somewhat difficult to interpret McNamara’s result, however, because the target-to-target priming effect was very small, regardless of the nature of the intervening item, and significant only when assessed across the entire set of experiments.

The small size of the priming effect in McNamara’s (1994) experiments suggests a possible explanation for the discrepancy with the Ratcliff and McKoon (1988, 1994) results. If the neutral intervening item used by McNamara (the word ready) were instead treated by participants as an unrelated word, a robust priming effect would not be expected under the compound cue model. Why then would the same stimulus be treated differently in these two studies? In the Ratcliff and McKoon (1988, 1994) experiments, 50% of the trials involved the neutral stimulus (also the word ready), whereas in the McNamara experiments the neutral stimulus appeared on as few as 21% of the trials and at most 26%. It could be that, because it did not occur frequently enough, participants in the McNamara experiments tended to treat the supposedly neutral stimulus as a normal word. It is important to note, however, that the compound cue model has no mechanism for discriminating between a word and a neutral stimulus. It appears that some learning mechanism is involved whereby over trials a frequently repeated stimulus comes to be treated

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1 I am grateful to Timothy McNamara for drawing to my attention this shortcoming of the compound cue model.
differently, but a full understanding of this learning mechanism currently is beyond our grasp.

Two factors, then, appear to have contributed to the inconsistency in the empirical results involving the intervening stimulus effect: (a) postaccess decision processes in the lexical decision task and (b) the status of the neutral intervening stimulus. In the experiments reported in this article, potential problems associated with these factors were minimized by adopting the word naming task and by using a neutral intervening stimulus that was not a word. It has been shown that the word naming task is not as strongly influenced as lexical decision by postaccess processes (Forster, 1981; Seidenberg et al., 1984). Moreover, although the distributed memory model can be extended to simulate the lexical decision task (e.g., Masson, 1994), the model was designed initially to account for latency data in the naming task. By using the naming task in my experiments, then, it was possible to test quantitative predictions of the model against the results of the experiments. Finally, the problem of how participants come to treat a designated neutral word differently from other words was sidestepped by using a nonlinguistic neutral stimulus (a row of xs). In the two experiments reported here, an intervening item consisting of either an unrelated word or the neutral stimulus was placed between a prime and a target. Prime–target pairs consisted of semantically related or unrelated words, and the task was to name the target. The crucial question was whether the nature of the intervening stimulus would influence the semantic priming effect.

Experiment 1

In Experiment 1 the prime and intervening stimulus were presented as two brief displays before the target. The exposure duration for the prime and intervening stimulus was set at 200 ms. The intervening stimulus was either a word unrelated to the prime or target or a neutral stimulus (a row of xs). On the appearance of the target word, participants were to name it. This procedure offers a number of important advantages over earlier versions of the intervening stimulus paradigm. Aside from the use of a naming task, which should reduce the involvement of postaccess processes, the design ensured that the SOA between prime and target was held constant across the two types of intervening stimulus. With the exception of McNamara (1994) and Ratcliff and McKoon (1988, 1994), earlier studies either measured priming only when an intervening word was used or they confounded presence of an intervening item and prime–target SOA.

Moreover, the use of very brief exposure durations for the prime and intervening items in Experiment 1 created a prime–target SOA of 400 ms, making it unlikely that strategic processing of these items would contribute to facilitation (Neely, 1977; Posner & Snyder, 1975; Ratcliff & McKoon, 1981). This precaution against strategic processing stands in contrast to the paradigm used by McNamara (1994) and Ratcliff and McKoon (1988), in which priming between targets on successive trials was measured. In the five experiments reported in those two articles, the SOA between successive targets, taking into account mean response latency on the first target, was at least 800 ms and over 3.5 s in two of the McNamara experiments. These long SOAs provided an opportunity for the development of strategic processing. By setting the prime–target SOA at only 400 ms in Experiment 1, the influence of an intervening unrelated word could be tested under conditions that minimized the contribution of strategic processes.

A further advantage of minimizing strategic processes is that predictions of the spreading activation, compound cue, and distributed memory models are much more clear under these conditions. The distributed memory model predicts a reduced priming effect in the case of an intervening unrelated word because the exposure durations for the prime and intervening stimulus are equal. The compound cue model was not intended to make predictions regarding the naming task, but if the tentative assumption is made that cue familiarity is directly related to the speed with which a pronunciation can be generated, a prediction can be made (see Humphreys, Wiles, & Bain, 1993, for a suggestion about how the compound cue model could be applied to naming). Specifically, the compound cue model predicts little or no priming when an unrelated word is the intervening stimulus because that item would be in view long enough to allow it to bump the prime from short-term memory and to enter into the compound cue with the target. Spreading activation models would predict that the type of intervening stimulus should have no effect on priming, although the ACT* model could account for reduced priming with an unrelated-word stimulus if its delay parameter were reduced to 200 ms or less.

Method

Participants. The participants were 40 undergraduate students at the University of Victoria whose native language was English.

Materials and design. A list of 120 associatively related word pairs was selected from various sources (Bousfield, Cohen, Whitmarsh, & Kincaid, 1961; Palermo & Jenkins, 1964; Postman & Keppe, 1970; Shapiro & Palermo, 1968). One member of each pair served as a target item and the other as its related prime. These words ranged in length from three to eight letters. The target words ranged in frequency from 6 to 1,772 per million (Kucera & Francis, 1967), with a mean of 183. The 120 pairs were randomly assigned to four lists of 30 pairs each. An unrelated prime was assigned to each target by randomly rearranging the primes within each list with the restriction that there be no obvious semantic relationship between the resulting prime–target pairs. An additional set of 120 words, from three to seven letters in length, was constructed to serve as unrelated intervening stimuli. One member of this list was randomly assigned to each prime–target pair with the constraint that there be no obvious semantic relationship with either member of the pair. Another list of 60 related word pairs was selected for use as filler items, and a list of four word pairs (two related and two unrelated) was selected for use as practice items.

The experiment was based on a 2 (prime: related vs. unrelated) × 2 (intervening stimulus: neutral vs. unrelated word) within-subject design. The neutral intervening stimulus was a row of eight lowercase xs. One list of 30 targets was assigned to each cell of the design, and this assignment was counterbalanced across the participants so that each list served equally often in each condition. On the 60 filler trials, the prime was always related to the target, and the intervening stimulus was always a row of xs. Thus, across all trials, the proportion of trials on which the prime was related to the target was 0.7, and the intervening stimulus was never related to the target.
Procedure. Instructions and stimuli were presented using an Apple II+ microcomputer equipped with two green monochrome monitors, a timing card that permitted millisecond accuracy, and a voice-operated relay. The participant viewed one monitor and the other monitor, turned away from the participant, was used to display the target item on each trial, which allowed the experimenter to check the accuracy of the participant's responses. Participants were tested individually and were instructed that their task was to read aloud as quickly as possible a series of capitalized words. They were told that each word would appear after the brief presentation of one or two other words. The instructions were followed by four practice trials and then by a randomly ordered presentation of 120 critical and 60 filler trials. Each trial began with a fixation point presented at the center of the monitor for 500 ms. The fixation point was erased and after a 500-ms delay a sequence of four stimuli was presented at the center of the monitor: a forward mask (a row of asterisks), a prime, an intervening stimulus, and a target. The first three stimuli each appeared for 200 ms, printed in lowercase letters, and the target was printed in uppercase letters. When the participant made a vocal response to the target a row of 10 asterisks was printed beneath the target. After a pause of 750 ms (during which time the experimenter entered a keyboard response in the case of a response error, including faulty triggering of the voice-operated relay), the monitor was erased and the next trial automatically began. After each set of 30 trials the participant was allowed to take a short break. At the end of the session the participant's average response latency for each condition was displayed on the monitor and the purpose of the experiment was explained.

Results

Data from the critical trials were analyzed by first removing trials on which response latencies were shorter than 150 ms or longer than 1,000 ms. This procedure eliminated 1.0% of the trials. Using the remaining data, I computed the mean latency and percentage of response errors in each condition for each participant. The mean latencies and error percentages taken across participants are shown in Table 1.

The latency data were analyzed in a two-factor analysis of variance (ANOVA), with prime and intervening stimulus as variables. The Type I error rate was set at .05 in this and all other analyses. There was a reliable 8-ms main effect of priming, with shorter latencies associated with related primes, \( F(1, 39) = 20.56, MSE = 122.6 \). Latencies were reliably longer when the intervening stimulus was an unrelated word (546 ms) rather than a neutral stimulus (524 ms), \( F(1, 39) = 142.36, MSE = 140.8 \). The interaction between prime and intervening stimulus was reliable, \( F(1, 39) = 9.42, MSE = 91.3 \), indicating that the priming effect was significantly reduced when an unrelated word was placed between the prime and target. Two planned comparisons tested for an effect of priming within each intervening stimulus condition. The priming effect was significant in the neutral condition, \( F(1, 39) = 28.93, p < .01, MSE = 109.3 \), but not in the unrelated-word condition, \( F(1, 39) = 2.08, p > .15, MSE = 104.5 \). A two-factor ANOVA applied to the error percentage data did not reveal any reliable effects.

Simulation of Results

The results of Experiment 1 were simulated by an implemented version of the distributed memory model based on the architecture shown in Figure 2. Details of the implementation are described in the Appendix, but an overview is provided here. A trial from Experiment 1 was simulated by loading the prime's pattern of activation into the orthographic units and setting all other units to a random pattern of activation. The prime either was related to the upcoming target item or was unrelated. To simulate the prime duration, I assumed that the approximately 200 update cycles needed to complete an item's phonological pattern of activation would correspond to the time needed to develop a pronunciation response in a naming task. Mean naming latencies range from about 400 to 600 ms, depending on the materials and how well participants anticipate the onset of targets (e.g., Joordens & Besner, 1992; Seidenberg, 1985; Waters & Seidenberg, 1985). The simulations were run under the assumption that the lower limit of this range, 400 ms obtained by Joordens and Besner, corresponds to 200 update cycles. At least part of the additional naming latency observed in other studies is ascribed to orienting to the target stimulus and to articulatory preparation and execution. Thus, a scale of 2 ms to 1 cycle was adopted in determining the number of update cycles for the prime and intervening stimulus. It should be noted that use of this scale is not intended as a plausible estimate of neural processing time. It is merely a convenient way of establishing a principled relationship between the model's processing time and real time. The scale would change if, for example, the model included a larger or smaller number of phonological nodes because it would then require more or less update cycles, on average, to converge on a stable pattern.

To simulate the 200-ms prime and intervening stimulus duration in Experiment 1, then, I used 100 update cycles for each stimulus. After the prime was processed for 100 cycles, the orthographic pattern was changed to represent the intervening stimulus. The intervening item was either a word unrelated to either the prime or the upcoming target or a neutral stimulus. In the case of an unrelated word, the learned orthographic pattern for that word was loaded into the orthographic units. When a neutral intervening stimulus was simulated, the orthographic units were set to an arbitrary random pattern. The rationale for using a random pattern was that the neutral stimulus (a row of xs in the actual experiment) was not a learned pattern, nor was it similar to any of the words learned by the network. After the orthographic pattern of the intervening stimulus was loaded into the orthographic units, the system was updated for a further 100 cycles. The orthographic pattern for the target was then loaded into the

<table>
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<th>Table 1</th>
<th>Mean Response Latencies (in Milliseconds), Standard Deviations, and Percentage Errors in Experiment 1</th>
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<tr>
<td></td>
<td>Intervening stimulus</td>
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<td></td>
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<td></td>
<td>Neutral</td>
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<td>Prime</td>
<td>M</td>
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<td>Related</td>
<td>517.6</td>
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<tr>
<td>Unrelated</td>
<td>530.2</td>
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orthographic units, and updating continued until the phonological units settled on the pattern of activation that matched the target item. Trials on which the model failed to complete the target phonological pattern within 500 update cycles were treated as errors and were not included in the computation of mean latency.

The mean number of update cycles needed to complete the target's phonological pattern in each priming condition, computed over 100 runs of the simulation, is shown in the top right of Figure 5. These results exclude 0.2% of the trials because of failure to reach the target phonological pattern within 500 cycles. The top left of Figure 5 presents the observed naming latencies from Experiment 1. It is clear that the model successfully replicated the interaction between prime and intervening stimulus, although it did not adequately capture the longer latency associated with the use of an unrelated word as the intervening stimulus. An ANOVA was applied to the stimulation results, treating each run as an independent participant. This analysis confirmed that there was a main effect of type of intervening stimulus, with more cycles required to settle when an unrelated word was the intervening stimulus, $F(1, 99) = 8.58, MSE = 36.9$. The main effect of priming was reliable, $F(1, 99) = 16.92, MSE = 63.8$, and there was a reliable interaction between prime and intervening stimulus, $F(1, 99) = 22.85, MSE = 39.5$. The simulated priming effects were 6.3 and 0.2 cycles for the neutral and unrelated-word conditions, respectively. When these priming values are doubled to take into account the 2:1 ratio of cycles to milliseconds, the resulting priming effects of 12.6 and 0.4 are comparable to the observed effects of 12.6 and 3.3 ms. As was true of the actual latency data, planned comparisons indicated that the priming effect was reliable only in the neutral intervening stimulus condition, $F(1, 99) = 28.40, MSE = 69.7$.

**Discussion**

An unexpected aspect of the results was the finding that response latencies generally were longer when an unrelated word was used as the intervening stimulus. Joordens and Besner (1992) have suggested that an increased response latency in the unrelated-word condition may be caused by a reduction in the relative response strength of the target as a result of the presence of an additional linguistic item. They further suggested that the reduced target response strength might be responsible for a reduced priming effect in the intervening stimulus paradigm. One difficulty with this idea is that it derives from Morton's (1999) proposal that relative response strength influences processing at a decision level and such a notion, although suited to a lexical decision task, is not convincing for the naming task. In addition, reduced target response strength might be expected to amplify the effect of context rather than reduce it because of the difficulty in generating a response. A similar effect is found when target identification is made difficult by degrading the visual stimulus (e.g., Becker & Killion, 1977; Besner & Smith, 1992).

An alternative possibility is that longer latencies associated with the unrelated-word condition reflect a difference in the relative frequency of occurrence of the two types of event (a word vs. a row of xs) that immediately preceded a target. Considering the filler and critical trials together, a word occurred just before a target on only half as many trials as a row of xs. By virtue of its more frequent occurrence, then, the row of xs may have come to be a more effective signal for the target's onset. This issue is addressed again in the discussion of Experiment 2.

The crucial result in Experiment 1, however, was the interaction between prime and intervening stimulus, which replicated the pattern obtained by Ratcliff and McKoon (1988). Priming was significantly reduced, and apparently eliminated, by using an intervening word stimulus rather than a neutral stimulus. Before discussing the implications of this outcome for models of semantic priming, the possible role of strategic factors should be considered. First, one could examine the possible role of expectancies that participants might develop as a result of the appearance of related word pairs (Keefe & Neely, 1990; Neely, 1991). The arrangement of critical and filler trials in Experiment 1 was such that, across the entire session, the proportion of trials on which the prime was related to the target was .67, whereas the intervening stimulus was never related to the target. If participants were to develop and apply expectancies in this experiment, they ought to ignore the intervening stimulus and produce a robust.
priming effect across both types of stimulus, as predicted by spreading activation models. The results indicate that this did not happen.

By using a related prime and the neutral intervening stimulus on every filler trial, however, a situation was created in which the nature of the intervening stimulus was somewhat predictive of the relationship between the prime and target. Specifically, considering both filler and critical trials, the probability that the prime and target were related was .5 when the intervening stimulus was an unrelated word, but this probability was .75 when the neutral stimulus intervened. It might be argued that priming was greater in the neutral condition because the occurrence of the neutral stimulus was a reliable indication that the prime was related to the target and that participants capitalized on this cue. In support of this view, Keefe and Neely (1990) found that semantic priming in the naming task was greater when a larger proportion of trials involved related primes.

There are a number of reasons, however, to question this account. First, the Keefe and Neely (1990) result was based on the proportion of related prime–target pairs, not on the predictive validity of a third stimulus. Second, the SOA in their study was 1,000 ms, ample time for strategic processes to be engaged, whereas the SOA in this experiment was only 400 ms. Third, the relatedness effect in their study was found only with high-dominance category exemplars but not with low-dominance exemplars, again indicating a strategic effect that is unlikely to develop within the 200-ms period that was available after the onset of the predictive cue (the neutral intervening stimulus).

By assuming that the priming effects observed in Experiment 1 were not the product of strategic processes, then, the interaction between prime and intervening stimulus is consistent with the prediction of the distributed memory and compound cue models. Moreover, the distributed memory model provided a good fit to the interaction effect. However, the interaction is problematic for simple spreading activation models (Collins & Loftus, 1975; Neely, 1977), which predict that the priming effect would not be influenced by the nature of the intervening prime.

Anderson's ACT* model of spreading activation could accommodate this interaction by assuming that the length of time a source node can stay active in this paradigm is at most 200 ms, unless activation is maintained by attentional processes such as assigning the model's goal element to maintain attention on the prime. A further necessary assumption is that when the intervening stimulus is an unrelated word, it draws attention from the prime. A neutral intervening stimulus would not be assumed to have this effect. A problem with this proposal, however, is that Joordens and Besner (1992) obtained a reliable priming effect in a naming task when two related targets were separated by an unrelated target that had to be named. This requirement made the interstimulus interval between related targets at least 400 ms. The priming effect obtained in that study indicates that the delay before decay of activation in the naming task is 400 ms or greater. Therefore, either the delay parameter would have to vary across these experiments (200 ms in Experiment 1, and 400 ms in the Joordens and Besner experiments) or the influence of an intervening unrelated word on maintenance of attention to the preceding word would have to vary (an interfering effect in Experiment 1, but no effect in the Joordens and Besner experiments). If it is assumed that the task used in Experiment 1 is more attentionally demanding than the continuous naming task used by Joordens and Besner, then it might be argued that delay of decay is reduced, interference with attentional maintenance is increased by tasks with higher attentional demands, or both.

Experiment 2

The results of Experiment 1 clearly indicate that an irrelevant intervening word presented for the same duration as a preceding prime can eliminate the prime's influence on the subsequent target. This result is predicted by the distributed memory model because the intervening word moves the network away from the favorable pattern of activation established by the prime. The model also predicts, however, that the influence of the intervening word should depend on the amount of processing devoted to it, relative to the amount of processing spent on the prime. In particular, when the amount of processing applied to the intervening word is less than that applied to the prime, less damage will be done to the pattern created by the prime.

This prediction was tested in Experiment 2 with a variant of the paradigm used by Ratcliff and McKoon (1988, 1994) and McNamara (1994). In that paradigm, priming between targets on consecutive trials was measured. The intervening stimulus was a briefly presented item that preceded the target on each trial. In the experiment reported here, I used a naming task in an effort to minimize the role played by postaccess decision processes and to permit the distributed memory model to make quantitative predictions. Once again, the neutral intervening stimulus was a component of the cue, so concern about whether a neutral word stimulus would truly be neutral need not arise. Trials were designated as pairs, with the target of the first trial in a pair serving as the functional prime for the target on the next trial. The relatedness of the targets in each pair was varied. On each trial, the target was preceded by a 300-ms presentation of an intervening stimulus to which no response was required. The intervening stimulus on the first member of each pair of trials was a related word, an unrelated word, or a neutral stimulus (a component of the cue). For the second member of each pair of trials, the intervening stimulus was either an unrelated word or the neutral stimulus. The requirement of naming a target (the functional prime for the subsequent target) was expected to induce more processing than the 300-ms exposure to the intervening item.

The distributed memory model's qualitative prediction for Experiment 2 was that an unrelated intervening word should reduce but perhaps not eliminate the amount of priming observed between consecutive targets. The compound cue model, if extended to the naming task (cf. Humphreys et al., 1993), predicts an interaction like the one found in Experiment 1. In fact, Experiment 2 was virtually a replication of the Ratcliff and McKoon (1988, 1994) experiments but with a naming rather than a recognition memory or a lexical decision task. If one assumes that with a probability somewhat less than
1.0 the intervening word replaces the target from the previous trial as part of the compound cue on the current trial, a reduced but perhaps reliable priming effect would be expected relative to when a neutral intervening stimulus is used.

Simple spreading activation models would continue to predict that the nature of the intervening stimulus would have no effect. The ACT* model, however, would make a different prediction, depending on the delay of decay parameter and the involvement of attention. The interstimulus interval between successive targets in Experiment 2 was 550 ms, consisting of a 250-ms intertrial interval (including the warning signal at the start of the trial) and a 300-ms duration for the intervening stimulus. If the delay of decay parameter is assumed to be less than 550 ms, activation from the first target would have decayed by the time the second target appeared. Thus, no priming effect would be expected in any condition. Alternatively, if the delay parameter is longer than 550 ms, equal priming should be obtained regardless of the type of intervening prime. Finally, reduced priming in the case of an unrelated intervening word would be predicted under the following set of assumptions: (a) the delay parameter is less than 550 ms, (b) the first target in a related pair remains active because of attentional processes, and (c) attention is shifted away from the first target by the intervening word, but not by a neutral stimulus.

Method

Participants. The participants were 60 undergraduate students drawn from the same population as in Experiment 1.

Design. Two independent variables were manipulated within subject: relationship between targets on a pair of consecutive trials (related vs. unrelated), and the type of prime on the second member of the pair of trials (neutral vs. unrelated word). These two variables were analogous to the prime and intervening stimulus variables, respectively, in Experiment 1. The first trial in each pair are referred to as the preceding trial, and the second trial in each pair are called the critical trial. The target on the preceding trial was the functional prime for the target on the critical trial, and the prime on the critical trial was the functional intervening stimulus. On each trial, the prime was presented for 300 ms and no response was required. There were 120 pairs of trials in all. On half of the pairs (n = 60), the targets were related and on the other half they were unrelated. Within each of these two types of pairs, the prime on half of the critical trials (n = 30) was an unrelated-word prime and on the other half it was the neutral stimulus. In each of these sets of 30 trials, the prime on the preceding trial was a related word (n = 20), an unrelated word (n = 5), or a neutral stimulus (n = 5).

Materials. The 120 prime-target pairs from Experiment 1 were used to construct a list of 120 pairs of related targets. This list was then used to create a list of 120 pairs of unrelated targets by reassigning the first members of the pairs. Reassignment was done within each of four blocks of 30 trial pairs that were defined for purposes of counterbalancing. Each participant was tested with two blocks of 30 trial pairs taken from each of these two lists. Blocks were selected so that 120 unique critical-trial targets were involved. For two of these blocks, one taken from each list, the prime on each critical trial was a neutral stimulus consisting of a row of four xs. For the other two blocks the prime was an unrelated word, selected so that it was unrelated to either target of the trial pair. With the exception of a few substitutions, this word had served as the intervening stimulus for the critical target in Experiment 1.

An additional set of 120 pairs of words was selected to serve as primes for the preceding trial. One member of each pair was related to the preceding-trial target, and the other member was unrelated to it. All items that served as primes were between three and eight letters in length. For each block of 30 trial pairs, 20 of the preceding trials used the related prime, 5 used the unrelated prime, and 5 used the neutral prime. Type of prime on the preceding trial was not a factor of interest in the design, so assignment of prime type for these trials was done randomly within each block of 30 trials. Six other target words, two with each type of prime (related, unrelated, and neutral), were selected to serve as practice items.

Assignment of blocks of trials pairs to participants was counterbalanced so that each critical-trial target was tested equally often in each of the four conditions of the experiment. An example of one critical target indicating how it appeared in each of the four conditions is shown in Table 2.

Across the entire set of 120 preceding and 120 critical trials, there were 80 trials with each prime type (related, unrelated, and neutral). Thus, the proportion of all trials on which the prime was related to the target was .33. With respect to the relationship between targets on successive trials, related targets were used for half of the trial pairs, but the target on a critical trial was never related to the target on the first trial of the next pair. Considering all trial-to-trial transitions (between as well as within trial pairs), then, the proportion of successive target pairs that were related was .25. The nature of the prime on a critical trial (the intervening stimulus) was not predictive of the relationship between the target on that trial and the preceding-trial target. On critical trials each type of prime was followed equally often by a target that was related or unrelated to the preceding-trial target. Nor was the prime on the preceding trial predictive of this relationship. The only predictive value of the primes was that a related prime, which only occurred on preceding trials, perfectly predicted that the target on that trial would be unrelated to the target on the previous trial (a critical trial). This correlation was not thought to be consequential, however, because it could only affect response latencies on preceding trials.

Procedure. Instructions and stimuli were presented using the same equipment as in Experiment 1. Participants were tested individually and were instructed that their task was to read aloud as quickly as possible a series of capitalized words. They were told that each word would appear following the brief presentation of some other material. The instructions were followed by six practice trials and then by a randomly ordered presentation of 120 pairs of preceding and critical trials, in which pair members occurred consecutively. The stream of events, however, gave the appearance of 240 distinct trials. Each trial consisted of a sequence of three stimuli presented at the center of the monitor. The first stimulus was a fixation cross that appeared for 200 ms. It was replaced by a prime in lowercase letters that was visible for 300 ms. Finally, the target appeared in uppercase letters and remained

<table>
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<tr>
<th>Target relatedness and critical trial prime*</th>
<th>Preceding</th>
<th>Critical</th>
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<tbody>
<tr>
<td>Related-neutral</td>
<td>XXXX-LIBRARY</td>
<td>XXXX-BOOK</td>
</tr>
<tr>
<td>Unrelated-neutral</td>
<td>XXXX-MINUTE</td>
<td>XXXX-BOOK</td>
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<tr>
<td>Related-unrelated</td>
<td>XXXX-LIBRARY</td>
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<tr>
<td>Unrelated-unrelated</td>
<td>XXXX-MINUTE</td>
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Note. The prime on the preceding trial is the neutral stimulus in this example, but in the experiment it also could have been a related or an unrelated word. Each pair of targets was seen in only one condition by a particular participant.

*\( n = 30 \) for each condition.
on the monitor until the participant responded. When a response was detected, the monitor was erased and after a 50-ms pause the next trial began. The experimenter viewed a monitor that displayed the trial number and the target and made a written record of trial numbers on which response errors (including faulty triggering of the voice-operated relay) occurred. After each set of 20 trials the participant was allowed to take a short break. At the end of this session the participants’ average response latency for each condition was displayed on the monitor and the purpose of the experiment was explained.

**Results**

Data from the critical trials were included in the analysis only if two conditions were met: (a) the response on the preceding trial was normal (correct and latency within 150 to 1,000 ms) and (b) the response latency on the critical trial was within 150 to 1,000 ms. The first criterion eliminated 2.9% of the critical trials (1.4% due to errors and 1.5% due to out-of-bounds latencies), and the second criterion eliminated a further 0.7% of the trials. The percentage of errors and the mean latency for correct responses on eligible critical trials were then computed for each participant as a function of condition. The mean latencies and error percentages taken across participants are shown in Table 3.

The latency data were analyzed in a two-factor ANOVA with preceding target (related vs. unrelated) and critical-trial prime (neutral vs. unrelated word) as variables. There was a reliable 7-ms effect of preceding target, indicating that related preceding targets reduced naming latencies, $F(1, 59) = 16.76, MSE = 167.2$. Latencies were reliably shorter when the prime on the critical trial was an unrelated word (503 ms) rather than a neutral stimulus (510 ms), $F(1, 59) = 14.32, MSE = 199.5$. The pattern of means fit the expected interaction between preceding target and critical-trial prime, but the interaction was not significant, $F(1, 59) = 2.28, p < .10, MSE = 141.0$. As in Experiment 1, two planned comparisons tested for an effect of preceding target within each critical-trial prime condition. The preceding target effect was significant in the neutral condition, $F(1, 59) = 16.92, p < .01, MSE = 148.5$, and was marginally reliable in the unrelated-word condition, $F(1, 59) = 3.83, p < .06, MSE = 159.7$. With a Type I error rate of .01, the power of the test of the priming effect in the unrelated-word condition to detect a priming effect as large as the effect observed in the neutral condition was approximately .90. Although the interaction between preceding target and critical-trial prime was not reliable, there is good evidence from the power analysis of simple effects that the priming effect in the unrelated-word condition is not as large as in the neutral condition. There were no significant effects in an ANOVA that was applied to the error percentage data.

**Simulation of Results**

The results of Experiment 2 were simulated in the same way as those of Experiment 1, with two exceptions dictated by differences in the experimental procedures. First, the prime was actually the target on the preceding trial, so rather than presenting the prime for a fixed number of cycles, the model was run until the prime’s phonological pattern was established. Second, the duration of the intervening stimulus in Experiment 2 was 300 ms, so in the simulation that item was processed for 150 cycles (in keeping with the 2:1 ratio of real time and processing cycles) before the target was presented.

On 0.4% of the trials the model failed to settle on either the preceding target’s or the critical target’s phonological pattern within 500 cycles. These trials were excluded from the means. The results of the simulation of Experiment 2 are shown in the middle section on the right side of Figure 5. An ANOVA indicated that the simulated results did not yield an effect of critical-trial prime, but there was a reliable effect of type of preceding target, $F(1, 99) = 35.77, MSE = 105.6$, with shorter latencies associated with related targets. There was also a reliable interaction between preceding target and critical-trial prime, $F(1, 99) = 39.71, MSE = 53.5$. The interaction is stronger than that observed in the actual latency data, shown in the left side of Figure 5. The discrepancy was due primarily to the large simulated effect of preceding target in the neutral-prime condition. Converting the simulated priming effects (10.7 and 1.5 cycles) to milliseconds estimates yields effects of 21.4 and 3.0 for the neutral and unrelated-word conditions, respectively, as compared with the observed effects of 9.2 and 4.5 ms. The outcome of planned comparisons matched those obtained with the observed data. The priming effect was reliable in the neutral-prime condition, $F(1, 99) = 48.26, MSE = 119.9$, and marginally reliable in the unrelated-word prime condition, $F(1, 99) = 3.01, p < .09, MSE = 39.3$.

**Discussion**

The main effect of critical-trial prime in the observed data was the reverse of the intervening stimulus effect observed in Experiment 1. In the successive target procedure of Experiment 2, the neutral prime led to slower naming responses than did the unrelated-word prime. This result is consistent with findings obtained by Keeve and Neely (1990) and Borowsky and Besner (1993) by using a neutral prime that had no linguistic relevance (a row of asterisks or xs). Differences in response latencies to subsequent targets may not, however, stem from the linguistic relevance of the preceding event. For instance, West and Stanovich (1982) used a neutral sentence prime (they said it was the) that led to longer naming latencies for a subsequent target word than did novel unrelated sentences.

An alternative explanation of the critical-trial prime effect is based on the relative frequency with which a repeated neutral stimulus occurs. In Experiment 2, the neutral stimulus appeared as a prime only half as frequently as word primes.
similar situation held in the Keefe and Neely (1990) and Borowsky and Besner (1993) experiments. In Experiment 1, the relative frequency of neutral and unrelated-word intervening stimuli was the reverse of that in Experiment 2, and the effect of type of intervening stimulus also was opposite to that of Experiment 2. Finally, in the Ratcliff and McKoon (1988) study, the neutral prime occurred as frequently as all other prime words combined. In that study, there was no reliable difference between prime types when the preceding target was unrelated to the current target. Thus, prime types that occur with higher relative frequency appear to encourage shorter response latencies, perhaps by serving as a better warning of the target's onset.

In any case, the longer latency in the neutral-prime condition is not consistent with the response strength proposal described in the discussion of Experiment 1. Despite the longer naming latency in the neutral-prime condition of Experiment 2, the pattern of the interaction between target relatedness and prime, although not statistically significant, was the same as the pattern obtained in Experiment 1. If elevated naming latencies in the unrelated-word intervening stimulus condition were responsible for the interaction in Experiment 1, then the pattern of this interaction should have been reversed in Experiment 2.

A clear target-to-target priming effect was observed in Experiment 2, replicating Ratcliff and McKoon (1988, 1994). This result contrasts with the weak target-to-target priming effect reported by McNamara (1994). As in McNamara's study, associatively related pairs were used in Experiment 2, so the reason for the discrepancy would appear to be due to differences in procedure rather than in materials. It is not yet clear exactly which aspect of the procedure is responsible, although the use of different criterion tasks (lexical decision vs. naming) may have been a factor. It is also possible, as discussed above, that the relatively infrequent appearance of what McNamara took to be a neutral priming stimulus (the word ready) may have led participants in his experiments to treat that item as a regular word. If so, target-to-target priming would be reduced regardless of the nature of the intervening stimulus.

The target-to-target priming effect obtained in Experiment 2 does not appear to be the product of strategic processes such as expectancy. Because the relatedness proportion was higher for the critical-trial prime than for successive targets (.33 vs. .25), participants should have relied more on the prime than on the previous target when forming expectancies. If they had done this, a more powerful interaction should have been obtained in Experiment 2 than in Experiment 1, in which the relatedness proportion for the intervening stimulus was zero. Instead, however, the interaction was not reliable in Experiment 2.

The lack of a reliable interaction in Experiment 2 contrasts with the effects obtained by Ratcliff and McKoon (1988, 1994), who used very similar procedures with a recognition memory task and a lexical decision task. One reason for the small size of the interaction in Experiment 2 was the fact that there was a marginally significant target relatedness effect in the unrelated-word prime condition. This outcome suggests that in naming, as compared with recognition memory and lexical decision tasks, the influence of an earlier target has a greater chance of surviving an intervening stimulus.

It would be inappropriate, however, to place great emphasis on the fact that the interaction was not reliable in Experiment 2 because the pattern of means was the same as in Experiment 1. Moreover, the power analysis of simple effects in Experiment 2 revealed that there was ample power for the test of target-to-target priming in the unrelated-word condition to reveal a highly reliable effect if the true priming effect size were as large as in the neutral condition. The failure of the priming effect in the unrelated-word condition to reach significance is at least modest evidence in support of the conclusion that the true priming effect in that condition is not as large as in the neutral condition.

The results of Experiment 2 do not seriously embarrass any of the models considered in this article. The lack of a reliable interaction is to be expected under spreading activation models, although the similarity across Experiments 1 and 2 in the pattern of means and the implications of the power analysis of simple effects in Experiment 2 is troublesome. The ACT\(^*\) model, however, could account for the results by assuming that attention was maintained on the preceding target in the neutral-prime condition. A very weak priming effect in the unrelated-word prime condition could be explained by assuming (a) that attention was not maintained on the preceding target once an unrelated-word prime appeared and (b) that the delay of activation decay is in the region of 300 ms (the duration of the prime). If the delay were substantially shorter than 300 ms, a reliable interaction like that in Experiment 1 would have been found. This account is problematic because it is not clear why participants would maintain attention to a stimulus to which a response already has been made.

If applied to the naming task used in Experiment 2, the compound cue model (cf. Humphreys et al., 1993) would predict an interaction like that in Experiment 1, with no target-to-target priming when an unrelated word was used as the critical-trial prime. Although a weak priming effect was found in that condition, this outcome could be explained if one were to assume that the unrelated-word prime replaced the preceding target as part of the compound cue with some probability less than 1.0 or that the compound cue contained three rather than just two items (McKoon & Ratcliff, 1992). If three items were combined in the cue, the previous target would be included in the compound cue at least on some trials. It is not clear why this should occur in Experiment 2 but not in Experiment 1 nor in the recognition memory and lexical decision tasks used by Ratcliff and McKoon (1988, 1994).

The distributed memory model accounted for the data in Experiment 2 rather well, except that it yielded a larger interaction than was observed in the actual data. Specifically, target-to-target priming in the model was too large when the neutral stimulus was used as the critical-trial prime. It is possible that the smaller observed priming effect came about

\(^2\) A power analysis indicated that if the interaction effect obtained in Experiment 2 were an accurate estimate of the size of the true interaction effect, a sample size of over 180 would be needed for the test of the interaction to have power equal to about 80.
because participants, after naming a target, did not continue processing it. In the simulation, however, processing cycles continued throughout the presentation of the neutral prime, magnifying the priming effect produced by the preceding target.

**Primming Effects With a Named Intervening Stimulus**

The version of the distributed memory model used in this article was the result of a modification of the model originally proposed by Masson (1991). The modification was prompted by results reported by Joordens and Besner (1992, Experiment 2). They obtained a priming effect in a continuous naming task in which participants named a series of targets. Related and unrelated target pairs were separated by an intervening unrelated word that also had to be named. By implementing a phonological module that was sampled at a higher rate than the meaning module, it was expected that a small priming effect could be found in the model, even when the intervening unrelated word was named. The pattern of activation in the meaning units created by a prime should not completely be changed by a subsequently named word. Enough of the pattern in the meaning module should be preserved so that when the critical target is presented there is some overlap between its meaning and the pattern already established in the meaning units.

This account was tested by running a simulation of the Joordens and Besner (1992) study with the same parameters as those applied in the simulation of Experiments 1 and 2. Each critical target was preceded by two other targets: an unrelated word that served as the intervening stimulus and, before that, a related or an unrelated word that served as the prime. To simulate the priming effect obtained by Joordens and Besner, the model was run just as the earlier simulations, except that both the prime and intervening stimulus were presented until their phonological patterns stabilized (representing a naming response). The bottom of Figure 5 shows the results obtained by Joordens and Besner (1992, Experiment 2) and the results of the simulation, excluding the 0.6% of trials on which the model failed to identify within 500 cycles one of the three items in a sequence. The priming effect of 4.2 ms reported by Joordens and Besner was closely approximated by the model's priming effect (1.5 cycles, or 3.0 ms), which, like the Joordens and Besner result, was significant by a directional test, t(99) = 1.82, SE_{dem} = 0.84. The model was successful at producing a small priming effect because the meaning module does not completely stabilize when a word is named. This feature of the model enables the preservation of part of the pattern of activation created by an earlier word, which is crucial in generating a priming effect under the circumstances of naming an intervening word.

**General Discussion**

The two naming experiments described in this article provide evidence that an intervening word may disrupt the facilitative effect of a related prime. In Experiment 1, when the prime and intervening stimulus were present for equally brief durations, there was a reliable interaction between prime and intervening stimulus and a lack of significant priming when an unrelated word was the intervening item. In Experiment 2 a naming response was made to the prime, and the intervening stimulus was presented for a brief duration. Under these conditions, the Prime × Intervening Stimulus interaction followed the same pattern as in Experiment 1, although it was not reliable, and a weak priming effect was found when the intervening item was an unrelated word. A third relevant finding, reported by Joordens and Besner (1992), is that a priming effect can be obtained in the naming task even when a naming response is made to both the prime and the intervening stimulus. This pattern of results has a number of implications for models of semantic priming and underlying assumptions about knowledge representation. Spreading activation and compound cue models are considered in turn, particularly in relation to the distributed memory model. Finally, limitations of the distributed memory model are considered.

**Spreading Activation With Local Representation**

Two of the most fully developed models of spreading activation, Collins and Loftus (1975) and Anderson (1983), assume a local representation of concepts in which each concept is represented by a single node in a network. The automatic spread of activation in such a network is incompatible with the disruptive effect found in Experiments 1 and 2 in this article. Anderson's ACT* model can account for such results if it is assumed that activation of a prime decays after a short interval once visual input terminates, unless it is maintained by attention to the prime. By allowing the delay parameter to vary across paradigms and maintenance of attention to vary across intervening stimulus conditions, the ACT* model is capable of accounting for any of the possible outcomes of the intervening stimulus paradigm—no effect of an unrelated intervening word, a reduced priming effect, and elimination of priming. The delay of decay parameter could be varied across the two experiments to explain the results of Experiments 1 and 2, and in Experiment 2, attention could be assumed to be maintained on a target to which a response has already been made. Alternatively, the decay parameter could be held constant and it could be assumed that the maintenance of attention on the prime (Experiment 1) or preceding target (Experiment 2) was affected by the nature of the intervening stimulus. This application of ACT* is rather complex in comparison with the Collins and Loftus (1975) model of automatic spreading activation, and it will be challenging to develop principles that can account for changes in the delay parameter and allocation of attention.

Joordens and Besner (1992) suggested that disruption of priming by an intervening stimulus is not a critical result for local representation models because (a) the notion of automatic spreading activation as embodied in models such as those of Collins and Loftus (1975), Anderson (1983), and Neely (1991) are not widely held and (b) there are other variants of this class of model that assume inhibitory connections between word nodes, and these models should account for the obtained results (Martindale, 1981; McClelland & Rumelhart, 1981; McLeod & Walley, 1989; Walley & Weiden, 1973). With respect to the importance of the concept of
automaticity in spreading activation, it should be noted that the lack of disruption by a small number of intervening items is a component of a number of current theories of semantic priming (e.g., McNamara, 1992a, 1992b, 1994) and is essential to modular theories of language processing in which intralexical priming is assumed to be responsible for sentence context effects in word identification (Seidenberg & Tanenhaus, 1986; Tanenhaus & Lucas, 1987). According to modular theory, words occurring early in a sentence prime related words that appear later, despite intervening words.

With respect to other local representation models, the McClelland and Rumelhart model contains only inhibitory connections between word nodes and is not capable of simulating facilitative priming effects. The other models cited are variants of an approach developed by Konorski (1967) involving lateral inhibition between nodes that was intended to protect the encoding of an input from interference by subsequent inputs. In this scheme, then, lateral inhibition works to suppress the effects of an intervening stimulus rather than to reduce the activation generated by the prime (e.g., Waletty & Weiden, 1973). Even if this mechanism were to be reversed, general inhibition created by an intervening word would be expected to increase response latency but not necessarily reduce priming and it might even enhance priming as do other factors that slow word identification, such as stimulus degradation and poor reading skill (Becker & Killon, 1977; Besner & Smith, 1992; Perfetti & Roth, 1981).

The finding that an intervening stimulus can disrupt priming is fundamentally important to local representation models. I know of no currently implemented model of this type that can accommodate the effect, except for ACT* under the constellations of assumptions discussed above. The instantiation of facilitative and inhibitory connections between nodes might yield a local representation system capable of generating the intervening stimulus effect, but it is not yet clear whether this solution will prove adequate. Moreover, a model of this kind may turn out to be isomorphic with distributed memory models.

There is a prediction, however, that is a natural consequence of the classic local representation system and that seems incompatible with distributed representations as applied here. This prediction involves the depth of spreading activation in a local network and the claim that activation can spread from one concept to another, even though the two concepts are not directly related, as long as there is a mediating concept linked to both (e.g., lion can prime stripes through the chain lion-tiger-stripe). Evidence for mediated priming has not always been found (de Groot, 1983) but has been obtained when care is taken to avoid postacess processes in identification tasks (Balota & Lorch, 1986; McNamara & Altarriba, 1988). More recently, McNamara (1992b) has found small but reliable mediated priming in which the chain is four items long (e.g., mane-lion-tiger-stripe).

I have not been able to simulate mediated priming using the distributed memory model, except under the assumption that mediated items are semantically related. Although free association tasks suggest that mediated pairs are not associatively related, it is possible that some degree of semantic similarity or association exists (McKoon & Ratcliffe, 1992). As McNamara (1992b) pointed out, however, this hypothesis is difficult to test in the absence of a theory of semantic representation. Nevertheless, there is currently evidence in favor of this view. Fischler (1977) and Seidenberg et al. (1984) have shown that semantically related word pairs can produce about as much priming as associatively related pairs. Fischler also found that semantic similarity is a better predictor of the magnitude of the priming effect for associatively related words than is the degree of associative strength. Thus, mediated priming may actually be a product of a modest amount of semantic similarity.

**Compound Cue Models**

Compound cue models such as that proposed by Ratcliff and McKoon (1988) can be implemented with either a localist or a distributed memory representation scheme. Therefore, compound cue models are not intended to address the question of representational format. Rather, they constitute an alternative conception of the processing operations involved in contextually regulated word identification tasks. These models are compatible with the results of Experiment 1, assuming they can be extended to the naming task as suggested by Humphreys et al. (1993). The outcome of Experiment 1 closely replicated the effects of an intervening unrelated word that Ratcliff and McKoon (1988, 1994) obtained using recognition memory and lexical decision tasks. Furthermore, if it is assumed that a compound cue can include two items that preceded the target, the model can also account for the results obtained by Joordens and Besner (1992). One can only speculate, however, about the reason for the number of elements in the compound cue to vary across experiments. The results of Experiment 2 are slightly problematic for the compound cue model because a weak priming effect was obtained when an unrelated intervening word was used. This weak effect implies that an unrelated intervening word usurps a prime's position in the compound cue with some probability less than 1.0. By varying this probability, one can account for any of the possible outcomes of the intervening stimulus paradigm. The disadvantage of this approach is that a principled basis for varying the parameter is required.

A difficulty with using compound cue theory to explain priming in word identification tasks is that a degree of circularity is involved. For an item to be encoded into short-term memory to form part of the compound cue, it must be identified to the extent that a representational code is built from visual input. The encoded representation may then be included in a probe that interacts with long-term memory, giving rise to varying degrees of familiarity. In the compound cue model the question of how the representational code is generated and whether that process can be primed remains unanswered. A possible resolution of this problem is that semantic priming effects across naming, lexical decision, and recognition memory tasks might be accounted for by a combination of (a) some version of spreading activation (e.g., as in the distributed memory model) that influences word identification and encoding into short-term memory and (b) long-term memory retrieval by a compound cue in short-term memory that influences binary decision tasks.
Distributed Memory Model

As the simulations of my experiments and the Joordens and Besner (1992) result indicate, the distributed memory model provides a principled account of the influence of an intervening stimulus on semantic priming. It is encouraging that the distributed memory model was able to account for the pattern of priming effects across these studies with no changes in parameters, except for those dictated by specific features of the experiments such as stimulus duration. Other results that have been problematic for spreading activation theories based on local representations are accounted for in a natural way by the distributed memory model (see Masson, 1991). This model differs from both the classic view of spreading activation and the compound cue model. Although activation spreads among processing units in the distributed memory model, the critical feature of this model is the distributed nature of knowledge. Instantiation of knowledge is assumed to take place in a shared representational space so that successive stimulus events of the same type (e.g., words) influence the same set of processing units, regardless of their degree of relatedness. It is this rich interaction that produces the intervening stimulus effect.

The distributed memory model account of priming effects differs from the compound cue model in that it is based on altered states of long-term memory representations induced by a priming stimulus before the target appears, rather than access of an unaltered long-term memory by a compound cue. Instead of viewing these two models as alternative explanations of priming effects, however, I see substantial merit in the proposal that the distributed memory and compound cue models account for different components of semantic priming phenomena, as suggested above. For example, there are aspects of priming paradigms, especially postaccess processes, for which the distributed memory model has no account but that fall within the purview of compound cue theory.

Limitations. The most serious limitation of the current version of the distributed memory model is that it operates with a very small vocabulary. As discussed in the Appendix, all of the simulations presented in this article were based on a learned vocabulary consisting of three pairs of semantically related items. The size of the vocabulary is limited by the Hebbian learning rule that is used to encode patterns into the Hopfield net. As more items are learned the network becomes less likely to recover any one of those patterns given a partial pattern as a starting point (Hopfield, 1982). Other learning and encoding schemes are under consideration to overcome this limitation. A version that has shown promise in preliminary work is one that involves sparse coding and a modified Hebbian learning rule (e.g., McRae, de Sa, & Seidenberg, 1993).

The learning rule used by McRae et al. (1993) also appears useful in overcoming another problem with the version of Hebbian learning used here. The standard Hebbian learning rule permits weights to grow without bound so that as more words are learned or if some words are presented with greater frequency during the learning phase, the system will become incapable of recovering some patterns, particularly the less frequent ones. Therefore, simulating a wide range of word frequency values will also depend on implementation of a more robust learning rule. Moving to a different learning rule, however, will not affect the interaction between processing modules that has been demonstrated by the current version of the model. It is very likely that the effects simulated here would be replicated with a new version of the model that incorporates a different learning rule and a much larger vocabulary.

The process of semantic priming that is simulated in the current version of the distributed memory model is limited to lexical processes that contribute to the pronunciation task. An important next step in developing the model will be to provide an account of the lexical decision task and the various postaccess processes that appear to be invoked by this task. Many of the components for this venture already are in place, embodied in the model's three processing modules. The interesting question is how these modules interact to produce lexical decisions. For example, a lexical decision might be based on the familiarity a stimulus invokes in each of the processing modules, where familiarity is measured using the energy function described in the Appendix. Learned patterns have deeper local minima than other patterns, so this metric is a plausible basis for decision making (Masson, 1994).

The model also lacks any provision for attentional or strategic factors that play an important role in word identification tasks. For example, the model was unable to capture the main effect of intervening stimulus and its change across Experiments 1 and 2. Moreover, the distributed memory model shares with the compound cue and spreading activation models the lack of a learning mechanism that would account for the development of "neutrality" associated with a frequently presented prime word (e.g., ready). In the experiments reported in this article, that problem was circumvented by using a nonlinguistic stimulus as a neutral intervening item. A full account of results obtained when a "neutral" word was used, however, will require postulation of a process by which a frequently presented word loses its ability to capture attention, initiate the usual word identification processes, or to be combined as part of a compound cue.

The distributed memory model also has no mechanism to account for the influence of variables such as proportion of related primes, proportion and type of nonwords, and expectancy. Effects involving proportion of certain stimulus types in the lexical decision task might be reproduced by adjusting the relative contribution to lexical decisions of the different processing modules. Other effects might require that the model be joined with semantic matching and expectancy processes hypothesized by Neely and Keefe (1989), replacing the version of spreading activation currently assumed in their three-process theory.

Conclusion. The distributed memory model described in this article is only one instantiation of an entire class of connectionist models that could be called on to model priming effects (see also, Hinton & Shallice, 1991; Plaut & McClelland, 1993; N. E. Sharkey, 1989). A number of other models in this class will generate similar predictions. The value of the model presented here, however, lies in its simplicity and the natural way that it accounts for word identification and priming phenomena. Although connectionist models are distinguished from other classes of models (such as spreading activation and compound cue models) by fundamentally different assump-
tions about process and representation, the similarity in the predictions made by these different classes of models is striking. Nevertheless, the intervening stimulus effect reported here poses something of a problem for versions of spreading activation theory that apply local representation schemes. Further assumptions might be invoked to enable these models to accommodate the effect, but pending such a development there is reason to question the adequacy of local representations. Moreover, the account of priming effects rendered by the distributed memory model is sufficiently plausible to suggest that this approach may serve as a very useful guide in the study of context effects in word identification.

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Appendix

Implementation of the Distributed Memory Model

**Learning and Pattern Completion**

Concepts are represented in the distributed memory model as a pattern of activation across a set of processing units, each of which can take on one or two values: +1 or −1. Connection weights between units are modified to encode a new item into memory. The learning rule used to make these changes is based on one derived from Hebb (1949), in which the change in the connection weight between any pair of units is defined as $\Delta w_{ij} = n_i n_j$, where $w_{ij}$ represents the connection weight between units $i$ and $j$, and $n_i$ and $n_j$ represent the activation values (+1 or -1) taken on by those units when the pattern is instantiated.

When performing a pattern completion task using asynchronous updating, a subset of the units are set to a pattern of activation that corresponds to the target concept. These units are “clamped” in the sense that they are not updated, but remain in their starting states. The other, unclamped, units are set to a random pattern or are in a state produced by earlier processing activity. The unclamped units are randomly sampled with replacement, and incoming activation is computed as

$$a_i = \sum_{(rj)} w_{ij} r_j,$$

where $a_i$ represents the amount of activation directed to unit $i$. The activation function that transforms received activation into an activation value is just a threshold function: if $a_i > 0$ then $n_i = 1$, else $n_i = -1$. From a quantitative perspective, the updating procedure is a form of gradient descent that minimizes an energy function, $E$, defined as

$$E = \frac{1}{2} \sum_{(rj)} w_{ij} n_i n_j.$$

When a minimum is reached, the system stabilizes in the sense that the activation values of all units are consistent with the activation received from other units (e.g., if $a_i > 0$). Further updating of the units will not result in any changes in activation values.

**Simulation of Empirical Results**

The implemented model consisted of 250 processing units, divided into three modules as shown in Figure 2: orthographic (130 units), phonological (40 units), and meaning (80 units). The numbers of units assigned to the modules were chosen to meet a number of constraints. First, a large number of units were assigned to the orthographic module because the pattern of activation in these units, representing visual input, is clamped while the system attempts to complete the rest of the pattern. If too few units are used the system will often fail to complete the correct pattern. Second, a majority of the remaining units were assigned to the meaning module so that these units would have a strong influence on processing in the phonological module. Use of too few units in the meaning module makes it very difficult to detect a semantic priming effect.

Both of these constraints (a large number of orthographic units and more meaning than phonological units) could be removed if the connection strengths between modules were ampliﬁed. For example, fewer orthographic units are needed if the connection weights between those units and units in other modules, as established by the Hebbian learning rule, are multiplied by a constant greater than 1. This adjustment increases the influence of the orthographic units on the activation of other units. The influence of meaning units on phonological units could similarly be increased. In the simulations reported here, however, no such weight adjustments were used.

Word identiﬁcation was initiated by loading a pattern of activation into the orthographic units to simulate visual presentation of the word. This pattern was clamped, so activation coming into the orthographic module from the other two modules was not relevant in these simulations. This version of the model did not simulate the build up of orthographic information, but assumed that it was fully available instantaneously. Only the meaning and phonological units were sampled in the updating process that led to a naming response. The sampling of these two sets of units was biased so that the probability of sampling from the phonological module on any given update cycle was .75.

To simulate a single participant in an experiment, the model learned a simple vocabulary of three pairs of semantically related items using the learning rule described above, with all weights initially set to zero. Then a series of naming trials was simulated with learning turned off. This procedure was replicated 100 times with an independently selected set of items to simulate a sample of 100 participants. A large number of participants were simulated so that a stable picture of the model’s performance would emerge.

Each item in the vocabulary was defined by a random pattern of activation across the 250 processing units. Related pairs were created by adopting the constraint that for both members of a pair the pattern of activation in the meaning units was quite similar. In the model, the similarity of the meaning unit patterns of related words is directly related to the size of the priming effect. For the simulations reported here, related word pairs were constructed so that exactly 54 of the 80 meaning units had the same value in the words’ respective patterns of activation. This degree of similarity was selected so that the simulations would produce priming effects similar in magnitude to those obtained in the observed data.

In each replication, one member of each of the three pairs of items served as a target 50 times in each word naming condition that was
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simulated. A replication, therefore, produced 150 naming trials in each condition. Repeated presentation of targets was not a problem because no learning was in effect during identification trials and it allowed more stable estimates of the model's performance. The mean number of update cycles required to establish the target pattern of activation in the phonological units was computed for each condition, and the mean across all replications was the model's simulated naming latency for the experiment.

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