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Masked Inhibitory Priming in English: Evidence for Lexical Inhibition

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Predictions derived from the interactive activation (IA) model were tested in 3 experiments using the masked priming technique in the lexical decision task. Experiment 1 showed a strong effect of prime lexicality: Classifications of target words were facilitated by orthographically related nonword primes (relative to unrelated nonword primes) but were inhibited by orthographically related word primes (relative to unrelated word primes). Experiment 2 confirmed IA's prediction that inhibitory priming effects are greater when the prime and target share a neighbor. Experiment 3 showed a minimal effect of target word neighborhood size (N) on inhibitory priming but a trend toward greater inhibition when nonword foils were high-N than when they were low-N. Simulations of 3 different versions of the IA model showed that the best fit to the data is produced when lexical inhibition is selective and when masking leads to reset of letter activities.

Keywords: masked priming, inhibition, interactive activation, lexical decision, visual word recognition

To retrieve the meaning of a visually encountered word, it is necessary for the reader to activate or access the corresponding mental representation of that word. This lexical access process requires the reader to select the correct lexical representation from a set of possible candidates (a set that is determined by the joint influence of bottom-up sensory and top-down contextual factors). But what is the mechanism underlying this lexical selection process? A major theoretical contender is the mechanism of lexical inhibition, whereby activated lexical representations mutually inhibit one another, ultimately enabling the best matching candidate to suppress words with similar forms. In this article, we present experimental evidence supporting this mechanism, as well as computational results that suggest constraints on the nature of lexical inhibition.

Inhibitory Masked Form Priming Effects

A key source of evidence for lexical inhibition is provided by inhibitory form priming effects in masked priming experiments. In the masked priming paradigm, a briefly presented (i.e., for no more than 60 ms) lowercase prime is immediately preceded by a forward mask and immediately followed by an uppercase target with all stimuli appearing in the same position on the screen. Participants are typically unable to report the identity of the prime and, generally, are not even aware of its existence. Thus, whatever impact it has is presumed to be a result of automatic, rather than strategic, processes.

In one of the first investigations of the issue, Forster and Davis (1984) reported that lexical decision latencies were facilitated when targets were preceded by formally related nonword primes (e.g., *bontrast–CONTRAST*). Nonword primes were also used in the majority of subsequent form priming lexical decision task (LDT) experiments, with the results typically replicating Forster and Davis's (1984) facilitory form priming effect (e.g., Forster, 1987; Forster, Davis, Schoknecht, & Carter, 1987; Forster, Mohan, & Hector, 2003; Forster, & Veres, 1998; Perea & Lupker, 2003b, 2004; Perea & Rosa, 2000; Sereno, 1991). However, these experiments are complemented by other form priming experiments that have used formally related word primes (e.g., *able–AXLE*). The latter experiments have typically shown inhibitory priming effects (e.g., Bijeljac-Babic, Biardeau, & Grainger, 1997; Brysbaert, Lange, & Van Wijnendaele, 2000; De Moor & Brysbaert, 2000; Drews & Zwitserlood, 1995; Grainger, Colé, & Segui, 1991; Grainger & Ferrand, 1994; Segui & Grainger, 1990). This evidence of a prime lexicality effect supports a general prediction of the lexical inhibition hypothesis. Related word primes should strongly activate lexical competitors of the target, increasing the effects of lexical inhibition, whereas related nonword primes should not have this effect because nonwords are, by definition, not lexically represented.

An Empirical Discrepancy

Although the majority of LDT experiments that have investigated the effect of related word primes have observed inhibitory priming effects, a conflicting set of results has been reported by

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Forster (1987) and Forster and Veres (1998). Forster (1987) reported a 38-ms facilitation effect for word targets primed by word primes. More recently, Forster and Veres (1998) reported a set of lexical decision experiments in which word primes produced either a null or a facilitory effect. Nonword primes, however, consistently produced facilitation. The experiments by Forster and Veres are also particularly relevant to testing the lexical inhibition hypothesis because the same set of targets were preceded by both word and nonword primes (using a counterbalanced design), thereby providing a critical test of the prime lexicality effect. The only other published masked priming experiment that included both word and nonword primes was a Dutch-language experiment reported by Drews and Zwitserlood (1995, Experiment 3B). This experiment obtained a small but significant inhibitory priming effect for formally related word primes (e.g., *kerst [Christmas]–KERS [cherry]*), but there was no facilitory effect for formally related nonword primes (e.g., *pilst–PIL*). Thus, no published study to date has succeeded in simultaneously showing facilitation from nonword primes and inhibition from word primes.

One potentially relevant factor that varies across the above experiments is the language in which the stimuli were presented. All of Forster's experiments used English stimuli, whereas virtually all of the experiments that have reported inhibitory priming effects were conducted in French, Dutch, or German (although Grainger & Ferrand, 1994, Experiment 3, found an inhibitory priming effect of 23 ms in an experiment with native English speakers, using English stimuli). This pattern raises the possibility that inhibitory priming effects from formally similar word primes are less likely to emerge in experiments using English stimuli than in experiments using French or Dutch stimuli. This might seem an unlikely explanation of the empirical discrepancy, were it not for the apparent language specificity of what is referred to as the *neighborhood frequency effect* in unprimed lexical decision experiments (e.g., Andrews, 1997).[1] In particular, research using English stimuli (e.g., Forster & Shen, 1996; Sears, Hino, & Lupker, 1995) has generally failed to find evidence of the inhibitory effects of higher frequency neighbors that have been obtained in experiments using French (e.g., Grainger & Jacobs, 1996), Spanish (e.g., Carreiras, Perea, & Grainger, 1997), and Dutch (e.g., Grainger, 1990). This pattern of results suggests that inhibitory processes may play a less important role in English than in other languages (e.g., perhaps because spelling–sound relationships are less consistent in English; see Andrews, 1997). However, before accepting this conclusion, one needs to consider other possible differences between the experiments that have and have not obtained inhibitory priming effects, as well as to verify the difficulty of obtaining inhibitory priming effects in English.

Forster and Veres (1998) argued that one important difference between their experiments and those that have obtained inhibitory form priming effects concerns the density of the target neighborhood: "in each of the aforementioned studies that failed to find facilitatory effects of a word prime, the word targets were generally four to five letters in length, which means that they were almost certainly located in high-density regions" (p. 505). In fact, a number of experiments have found that facilitory form priming effects (from nonword primes) are only obtained when the target's neighborhood density is very low (e.g., Forster et al., 1987; Perea & Rosa, 2000). This factor also provides a plausible explanation of the failure to obtain facilitory form priming from nonword primes in the above-mentioned experiment by Drews and Zwitserlood (1995), which used short targets (which presumably had high neighborhood densities). It is therefore conceivable that inhibitory form priming effects are restricted to high-density targets and that these effects will disappear (or even become facilitory) for low-density targets. This possibility was tested in the experiments reported below.

Another possibility, raised by the results of Forster and Veres (1998), is that the difficulty of the LDT plays a critical role in whether inhibitory priming effects are observed. When using nonword foils that did not bear any similarity to words, Forster and Veres found that word primes produced facilitation, as did Forster (1987). However, when using nonword foils that resemble words, the same word primes produced a null effect. In the same experiment, the same set of targets showed facilitory form priming when preceded by nonword neighbor primes; that is, there was a prime lexicality effect. This raises the prospect that, to obtain inhibitory form priming effects, it may be necessary to use nonword foils that are very wordlike. This possibility was tested in Experiment 3, in which the difficulty of the LDT was manipulated (as a between-subjects variable) by varying the neighborhood density of the nonword foils. Thus, the key empirical goals of the present work were to determine whether inhibitory form priming is found in English and whether it depends on target neighborhood size or the difficulty of the LDT.

The Interactive Activation Model

The most well-known example of a model that uses lexical inhibition to enable lexical selection is the interactive activation (IA) model (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). For over 20 years, this model has, arguably, been the most influential model in the word recognition literature. The model was originally proposed as an explanation of the word superiority effect and a number of related effects (Johnston & McClelland, 1973; McClelland & Johnston, 1977; Reicher, 1969; Wheeler, 1970) in perceptual identification tasks. More recently, it has formed the basis of models of performance in speeded response tasks as well, in particular, the LDT (in Grainger & Jacobs's, 1996, multiple read-out model [MROM]) and the naming task (in Coltheart, Rastle, Perry, Langdon, & Ziegler's, 2001, dual-route cascaded model). It is the model's performance in explaining LDT data that is the main focus of the present research.

Part of the IA model's attraction is that it is based on a fairly straightforward set of structures and processes. There are three levels of representation: a feature level, a letter level, and a word level. Inputs are presented to the model by fixing the activities of the feature-level units. The representational units at lower levels feed activation and inhibition to higher levels. So, for example, when the unit representing the letter "a" in the first letter position receives activation from the feature level, it in turn sends activation to all word-level units in which the word has an "a" in the first letter position and inhibition to all word-level units in which the

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[1] For present purposes, we define a word's *neighbors* as the set of words that can be formed by changing exactly one letter in the word (see Coltheart, Davelaar, Jonasson, & Besner, 1977). The *density* of a word's orthographic neighborhood refers to the number of neighbors of that word and is conventionally measured by a metric labeled N.

word does not have an "a" in the first letter position. In addition, there is lexical (i.e., intralevel) inhibition. So, for example, when the word *axle* is presented and the word-level unit for *axle* is activated, it sends inhibition to all other word-level units. This inhibition is crucially important for suppressing other word-level units that have received some activation from the letter-level units (e.g., *able*) and, hence, are competing with the word-level unit for *axle*. Thus, lexical inhibition allows the reader to identify the word as *axle* and not *able*.

Masked Priming Predictions From the IA Model

To analyze which factors were most important in producing masked form priming effects, according to the IA model, Davis (2003) conducted simulations in which every word target was preceded by each of its word neighbor primes (for a total of 7,004 trials, given the model's lexicon of 1,179 four-letter words) and by each of its possible nonword neighbor primes (for a total of 28,297 trials). At the beginning of each trial, the activity of all the nodes in the model was set to their resting levels, and the prime was input to the model for a fixed duration, causing activity to develop at the letter and word levels. The target was then input to the model, and the model was allowed to continue processing until the activity of one of the word nodes reached a specified response threshold. The results of these simulations give rise to the general predictions described in the following section.

The most salient prediction of the IA model is the existence of a prime lexicality effect in masked form priming. In Davis's (2003) simulations of the model, related nonword primes had a mean facilitory priming effect of 14 processing cycles, whereas related word primes had a mean inhibitory priming effect of 42 processing cycles (both measured from an unprimed baseline). According to the IA model, facilitory masked form priming effects are due to preactivation of the target by the prime. For example, the prime *azle* will partially activate the word node *AXLE*, and hence lexical decision responses to the related prime trial *azle–AXLE* will be faster than to the unrelated prime trial *pody–AXLE*. More generally, however, form priming effects in the model are composed of a combination of facilitory and inhibitory priming components. The inhibitory component of form priming is due to the preactivation of the target's competitors. For example, the prime *azle* will partially activate the word node *ABLE*, which is a higher frequency competitor of the target *AXLE*. The magnitude of the inhibitory component differs markedly as a function of the lexicality of the prime. Thus, the word prime *able* will activate the competitor *ABLE* far more strongly than the nonword prime *azle*. By contrast, the facilitory component of form priming is roughly equivalent for related word and nonword primes (e.g., the level of preactivation of the target *AXLE* is not much smaller for the related word prime *able* than for the related nonword prime *azle*). It follows that responses to the target *AXLE* may be facilitated by nonword neighbor primes (*azle*) but inhibited by word neighbor primes (*able*). This prediction was tested in Experiment 1.

Davis's (2003) analysis of masked priming effects in the IA model found that, for word primes, far and away the most important factor in terms of predicted target latency (i.e., cycles to threshold) was the frequency relationship between the prime and target. The larger the frequency advantage of the prime over the target, the larger the predicted inhibition effect. This prediction was also tested in Experiment 1.

Another critical prediction of the IA model is the shared neighborhood effect. Davis's (2003) analysis of masked priming effects in the IA model noted that the magnitude of inhibitory priming effects is strongly influenced by whether the prime and the target share any neighbors. The reason that shared neighbors play a particularly important role in the competitive process is that their activation is supported by both the prime and the target. For example, in the trial *wait–BAIT*, the prime-only neighbor *WANT* is a less effective competitor than the shared neighbor *GAIT*, because its activation is only supported by the prime and not the target; similarly, the target-only neighbor *BAIL* is a less effective competitor than *GAIT*, because its activation is only supported by the target and not the prime. This leads to the prediction that "the inhibitory effect of priming is larger, on average, when the prime and target share a neighbor (e.g., *wait–BAIT*, where the shared neighbor is *GAIT*; PE = −57 cycles) than when they do not share any neighbors (e.g., *bail-BAIT*; PE = −38 cycles)" (Davis, 2003, p. 157). This prediction was tested in Experiment 2.

A separate issue concerns the effect of target neighborhood size (N) on inhibitory priming. As noted above, one reason for considering the influence of this factor is the possibility, raised by Forster and Veres (1998), that inhibitory form priming effects are more likely to be obtained for high-density targets than for low-density targets. The impact of shared neighbors in the IA model may suggest that a prediction of this result would follow from the model, given that targets with many neighbors are more likely to share neighbors with the prime. However, the actual prediction is more complex than this, due to the impact of neighbors of the target that are not neighbors of the prime (target-only neighbors). In unprimed identification, these neighbors have a (small) inhibitory influence on recognition of the target. When the target is preceded by a neighbor prime, however, target activation is enhanced much more than the activation of target-only neighbors. Hence, target-only neighbors become less effective competitors. Davis (2003) referred to this effect of priming as the *target neighbor suppression effect*. Increasing overall target N therefore has two counteracting effects: Increases in the number of shared neighbors increase the size of the inhibition effect, whereas increases in the number of target-only neighbors decrease the size of the inhibition effect. In simulations of the IA model, these two effects often tend to cancel each other out, resulting in a prediction of very little overall effect of target N on inhibitory priming. This prediction was tested in Experiment 3.

A final issue concerns the effect of the neighborhood size of the nonword foils in the LDT. This question is motivated primarily by Forster and Veres's (1998) finding of a prime lexicality effect that depended on the nature of the nonword foils. The manipulation of the difficulty of the nonword foils can be simulated by varying the setting of the model's activity threshold (μ) for responding "yes" in the LDT. The rationale for this is that very wordlike nonwords will lead to higher activities at the word level, and thus a more conservative criterion is required (i.e., a higher setting of μ). By contrast, when the nonwords are not especially wordlike a more liberal criterion (i.e., a lower setting of μ) can be used without increasing the likelihood of false alarms, thereby enabling more rapid responses. This analysis leads to the prediction that inhibitory priming effects should be stronger when the nonwords are more wordlike (this prediction is quantified in the simulations reported below).

Simulating Masked Priming in the IA Model: Pattern Masking and Letter Reset

To simulate masked priming with the IA model, it is necessary to make some assumptions about what happens during the course of a masked priming trial. A particularly important assumption concerns what happens when the target replaces the prime at the feature level. In McClelland and Rumelhart's (1981) simulations of the Reicher–Wheeler task, they assumed that a poststimulus pattern mask had the effect of automatically resetting letter-level activities (this assumption is critical for the model's explanation of word-superiority effect phenomena). This reset occurs because the pattern mask contains several features that are incompatible with the currently active letter (whatever that letter happens to be), and because feature-letter inhibition is very strong. In the masked priming paradigm, the prime stimulus is postmasked by the target. When the prime and target are unrelated, there will be extreme discrepancies between their letter features at each position. Even in the case of related primes and targets, there will typically be several different features at each position, because the prime and target are presented in different typecases. It therefore seems reasonable to generalize McClelland and Rumelhart's account of pattern masking by assuming that discrepancies between the letter features of the prime and the target will result in a rapid reset of letter-level activities when the target is presented. In practice, however, the letter features of the common letters of related primes and targets do not differ in simulations of the model, because the implementation of the model only includes uppercase letters (i.e., both the prime and the target must be presented to the model in uppercase). A more psychologically realistic model would contain abstract letter units that responded to both upper- and lowercase forms (e.g., Bowers, 2003).

In the simulations we report here, we opted to treat the issue of letter-level reset as an empirical question, by simulating two different versions of the model. In one version, we simulated the putative postmasking effect of the target by directly resetting letter-level (but not word-level) activities at the point of target onset. In the other version, there was no direct reset of letter-level activities. Instead, the target immediately overwrites the prime at the feature level, and the letter-level activities are modified through a combination of feedforward activation and inhibition. As we shall see, these two versions of the IA model make predictions that are quantitatively, and sometimes qualitatively, quite different from each other.

In summary, the experiments reported in the present article were motivated by both empirical and theoretical factors. A key empirical goal is to establish whether inhibitory form priming is found in English, given the failure of previous English-language experiments to observe such effects. To foreshadow our conclusions, our experiments show unambiguous evidence for the existence of inhibitory form priming effects in English. Thus, we also sought to explain the apparent empirical discrepancy between experiments that have and have not obtained inhibitory form priming. In particular, we explored whether inhibitory priming effects depend on target neighborhood size or the difficulty of the LDT or both. At the same time, we also sought to test theoretical predictions derived from the IA model, notably the existence of a prime lexicality effect, a relative prime–target frequency effect, and an effect of shared neighbors and target-only neighbors.

Experiment 1

Prime Lexicality

The primary issue in this experiment was the question of the impact of the lexicality of neighbor primes. As noted earlier, a key prediction of the IA model is that there should be a clear prime lexicality effect, because word neighbor primes will activate competitors of the target more strongly than nonword neighbor primes. At a broad level, there is already strong support for this prediction, in that many different experiments have repeatedly shown facilitory form priming for related nonword primes, whereas several experiments have shown inhibitory form priming for related word primes. However, it is essential to note that these experiments form disjoint sets—individual experiments have shown *either* facilitation *or* inhibition, but not both.

From a theoretical standpoint, it is quite important to demonstrate that both the facilitory and the inhibitory form priming effects can be obtained within the same experiment. The masked priming technique is, of course, supposed to prevent participants from strategically using the nature of the prime–target relationships when responding to the target. Thus, the assumption is that whatever effects emerge can unambiguously be attributed to the effects of automatic processes. Recent data (Bodner & Masson, 2001; Masson & Bodner, 2003), however, suggest that participants do have the ability not only to monitor the nature of the prime–target relationships when masked primes are used but also to strategically use that information in their response processes. Thus, one could propose that the differing patterns between Forster's (1987) and Forster and Veres's (1998) experiments and the experiments showing inhibitory priming were due to how participants strategically used the prime, with the existence of nonword primes causing the participants to engage in a processing strategy more likely to produce facilitation.

To date, the very few studies that have included both word and nonword primes within the same experiment have obtained all possible outcomes for word primes: inhibition (Drews & Zwitserlood, 1995), facilitation (Forster, 1987; Forster & Veres, Experiments 3 & 4, 1998), and null effects (Forster & Veres, Experiment 2, 1998). Of these, the one experiment that did show an inhibitory priming effect failed to show a facilitory form priming effect for related nonword primes. It is clear that further experimentation is warranted to address this issue. Furthermore, the absence of any sign of inhibitory priming effects in Forster's (1987) and Forster and Veres's (1998) experiments raises the question of whether such effects can be obtained at all in English. If the answer to this question is no, this result would (in combination with the discrepant findings concerning the neighborhood frequency effect in different languages) have significant implications for differences in the utilization of lexical inhibition in word recognition across different languages.

Relative Prime–Target Frequency

The other issue we sought to investigate in Experiment 1 was the effect of relative prime–target frequency. Our investigation of this factor was motivated by Davis's (2003) simulations, which showed that this factor is the most important predictor of the magnitude of inhibitory priming effects in the IA model. The larger the prime frequency advantage, the larger the predicted inhibition. There is already some support for this prediction. Segui and Grainger (1990) reported two masked priming experiments that showed significant effects of relative prime–target frequency. In the first, a 48-ms inhibitory effect was found when low-frequency targets were primed by high-frequency neighbor primes, whereas a statistically null (10-ms) facilitation effect was obtained when high-frequency words were primed by low-frequency neighbor primes. In the other experiment, target frequency was held constant, and prime frequency was varied. A 41-ms inhibition effect was obtained when medium-frequency words were primed by high-frequency neighbor primes, whereas a statistically null (12-ms) inhibition effect was obtained when medium-frequency words were primed by low-frequency neighbor primes.

In summary, Experiment 1 aimed to investigate the effects of prime lexicality and relative prime–target frequency and to establish whether inhibitory priming effects could reliably be obtained in English. The target words were primed by both word and nonword neighbors. On the basis of past research, the expectation is that nonword neighbors should produce facilitation, an expectation that is consistent with the predictions of the IA model. To maximize the chance of observing this effect (i.e., based on Forster et al.'s, 1987, density constraint), the word targets were low-N targets. We also conducted simulations of the IA model (with and without the letter-reset assumption) to directly compare the experimental results with theoretical predictions of the model.

Method

Participants. Thirty-two undergraduate students from the University of Western Ontario (London, Ontario, Canada) participated in this experiment for course credit. All had normal or corrected-to-normal vision.

Stimuli. Sixty-four pairs of words were selected. Half of the pairs involved four-letter words and the other half involved five-letter words. The words in each pair differed by exactly one letter (e.g., *AXLE–ABLE*). For each pair, one member was high in printed word frequency (Kucera & Francis, 1967, mean frequency = 365.5) and the other was of low frequency (Kucera & Francis mean frequency = 5.4). The neighborhood sizes, N, of the high- and low-frequency members of the pairs were 2.2 and 2.4, respectively. N values were obtained using Davis's (2005) N-Watch software. In one of the word prime related conditions, the high-frequency member of the pair primed the low-frequency member of the pair whereas in the other word prime related condition, the opposite was true.

To create the word prime unrelated conditions, we selected new primes for both the low- and high-frequency targets. For the low-frequency targets, the prime frequency and prime N matched that of the related high-frequency primes (Kucera & Francis, 1967, mean frequency = 370.7, N = 2.5). For the high-frequency targets, the prime frequency and prime N matched that of the low-frequency primes (Kucera & Francis, 1967, mean frequency = 7.8, N = 2.4).

To create the nonword prime related conditions, we primed each target, both low- and high-frequency, with a nonword differing from the target in one letter position (for the low-frequency targets, mean prime N = 2.2; for the high-frequency targets, mean prime N = 2.2). To create the nonword prime unrelated condition, each target, both low- and high-frequency, was primed by a nonword that was the same length as the target but did not match the target at any letter position (for the low-frequency targets, mean prime N = 2.5; for the high-frequency targets, mean prime N = 2.4). These nonwords were derived from the unrelated word primes for each target by changing one letter in that word.

Thirty-two nonword targets were also selected, 16 of which were four-letter nonwords and 16 of which were five-letter nonwords (N = 3.5). In the related condition, these nonwords were primed by either a word (Kucera & Francis, 1967, mean frequency = 24.4, N = 3.4) or a nonword (N = 3.6) that differed from the nonword target at one letter position. In the unrelated condition, these nonwords were primed by a word (Kucera & Francis, 1967, mean frequency = 20.0, N = 3.9) or a nonword (N = 3.3) that was the same length as the nonword target but differed from the target at all letter positions. A complete list of stimuli is contained in Appendix A.

For the word targets, it was necessary to create eight counterbalancing conditions. Each participant saw either the high-frequency or the low-frequency member of the word pair as a target, and each target was primed by one of four prime types. To accomplish the counterbalancing, we divided the word pairs into eight sets with equal numbers of four- and five-letter pairs in each group. For the first half of the participants, in four of those sets, the low-frequency word was designated as the target, and in the other four of those sets, the high-frequency word was designated as the target. Within each set of four target sets, the targets were primed by the other member of the pair, the selected unrelated prime word, the neighbor nonword, or the unrelated nonword. The assignment of primes to targets was rotated across four groups of participants. For the other half of the participants, the other member of each word pair was designated as the target. Once again, there were four prime types for each of the targets, with the assignment of primes to targets being rotated across four groups of participants.

There were only four counterbalancing conditions for the nonword targets. The nonwords were divided into four sets with equal numbers of four- and five-letter nonwords in each set. The targets in one of the sets were primed with related word primes, the targets in a second set were primed with related nonword primes, the targets in a third set were primed with unrelated word primes, and the targets in the fourth set were primed with unrelated nonword primes. The assignment of primes to targets was rotated across the eight groups of participants with each set of prime–nonword target pairs occurring for two of the groups.

Experimental procedure and equipment. Participants were tested individually in a quiet room. Each trial consisted of a sequence of three visual events. The first was a forward mask consisting of a row of five number signs (#####). This mask was presented for 500 ms. The mask was immediately followed by the prime in lowercase letters exposed for a duration of 57 ms. Finally, the target in uppercase letters replaced the mask and remained on the screen until the response. Each stimulus was centered in the viewing screen and, hence, occupied the same position as the preceding stimulus.

Stimuli were presented on a TTX Multiscan Monitor (Model No. 3435P). Presentation was controlled by an IBM-clone Trillium Computer Resources PC. Words appeared as white characters on a black background. Reaction times were measured from target onset until the participant's response. Participants were asked to classify the letter sequence presented in uppercase letters as a word or a nonword. No mention was made of the number of stimuli that would be presented on each trial. Participants indicated their decisions by pressing one of two response buttons. When the participant responded, the target disappeared from the screen. Each participant received a different pseudorandom ordering of items. Each participant also received 12 practice trials (involving the same manipulations as in the experimental trials) prior to the 96 experimental trials. The whole session lasted approximately 10 min.

Simulation procedure. Simulations were conducted using the procedures outlined in Davis (2003). At the beginning of each trial, the activities of all the nodes in the model were set to their resting levels, and the prime was input to the model (by fixing the activities of the feature nodes) for a duration of 50 cycles. The target was then input to the model, and the

Table 1

Latencies (in Milliseconds) and Error Rates (in Percentages) for Word and Nonword Targets as a Function of Prime Relatedness, Prime Type, and (for Word Targets) Frequency in Experiment 1

	Word targets					
	Low frequency		High frequency		Nonword targets	
Variable	Word prime	Nonword prime	Word prime	Nonword prime	Word prime	Nonword prime
Related	679 (8.7)	634 (5.6)	586 (2.4)	571 (1.8)	743 (6.2)	737 (6.2)
Unrelated	645 (5.6)	660 (4.6)	573 (1.9)	582 (0.9)	757 (6.6)	744 (7.0)
Effect	−34 (−3.1)	+26 (−1.0)	−13 (−0.5)	+11 (−0.9)	+14 (0.0)	+7 (+0.8)

Note. Error rates are in parentheses.

model was allowed to continue processing toward an equilibrium state. When the activity of a word node reached the level of the response criterion (set to .70), a unique identification was assumed to have been made. (Note that, unlike with the MROM [Grainger & Jacobs, 1996], local word unit activation provides the only basis for making "yes" responses.)

The model was tested on exactly the same stimuli as used in the experiment.[2] Models with different vocabularies were used for testing four-letter words (using the vocabulary of the original model) and five-letter words (which were not included in the original model), but an identical set of parameters was used for these two versions of the model. These parameters were identical to those used in the original IA simulations reported by McClelland and Rumelhart (1981), with one minor exception: The integration rate of the model was 10 times smaller than in McClelland and Rumelhart's simulations. This results in predictions with a finer temporal resolution but does not affect the qualitative behavior of the models for the stimuli tested here (the smaller integration rate does increase the stability of the model in certain exceptional situations, but these are not relevant to the present simulations). Thus, the prime duration of 50 cycles is equivalent to 5 cycles in the original model.

We tested two distinct variants of the model that differed only with respect to a single assumption regarding what happens to letter-level activities at the onset of the target. In the *letter-reset* version of the model, it was assumed that the onset of the target had the effect of resetting letter-level activities (the reasons for this assumption and its effects are discussed below). In the other version of the model that we tested (the *no-reset* model), the onset of the target was not associated with any reset of letter-level activities; instead, the letters of the target replaced the prime at the letter level by means of the strong feature-letter inhibitory signals.

Results and Discussion

Incorrect responses (3.7% of the data for word targets and 6.0% of the data for nonword targets) and latencies greater than 1,500 ms (0.2% of the data for word targets and 0.6% of the data for nonword targets) were counted as errors and excluded from the latency analysis. For the word data, three-way analyses of variance (ANOVAs) were conducted, both by subjects (F_1) and by items (F_2), with target frequency (high vs. low), prime type (word vs. nonword), and prime relatedness (related vs. unrelated) as variables. In the subject analysis, all variables were treated as within-subject variables. In the item analysis, prime type and prime relatedness were treated as within-item variables, whereas target frequency was treated as a between-item variable.[3] For the nonword data, two-way ANOVAs were conducted, both by subjects and by items, with prime type (word vs. nonword) and prime relatedness (related vs. unrelated) as variables. Both variables were within-subject variables in the subject ANOVA and within-item variables in the item ANOVA. Effects reported as significant were significant at the .05 level unless otherwise indicated. Mean latencies and error rates from the subject analysis are shown in Table 1.

Word latencies. The only significant main effect was the frequency effect, $F_1(1, 31) = 141.50$, $MSE = 2{,}638.76$; $F_2(1, 116) = 40.93$, $MSE = 18{,}350.65$. Participants responded to high-frequency targets faster than to low-frequency targets. The crucial Prime Type × Prime Relatedness interaction was also significant, $F_1(1, 31) = 14.99$, $MSE = 1{,}862.12$; $F_2(1, 120) = 10.41$, $MSE = 5{,}197.71$. This interaction was due to there being inhibition from word primes and facilitation from nonword primes. No other effects were significant (all Fs < 2.80). In particular, although there was some indication that the priming effects were larger for low-frequency targets, the Prime Type × Prime Relatedness × Frequency interaction was not significant in either analysis, $F_1(1, 31) = 1.67$, $MSE = 3{,}283.36$, $p < .25$; $F_2(1, 116) = 2.66$, $MSE = 5{,}197.71$, $p < .11$.

Word errors. The only significant effect in both analyses was the main effect of frequency, $F_1(1, 31) = 20.31$, $MSE = 0.28$; $F_2(1, 116) = 10.39$, $MSE = 0.29$. Both the prime type effect, $F_1(1, 31) = 3.07$, $MSE = 0.18$, $p < .10$; $F_2(1, 116) = 1.90$, $MSE = 0.16$, $p < .20$, and the prime relatedness effect, $F_1(1, 31) = 1.19$, $MSE = 0.47$, *ns*; $F_2(1, 124) = 2.80$, $MSE = 0.11$, $p < .10$, were marginal in one analysis and nonsignificant in the other. No other effects approached significance (all Fs < 1.00).

Nonword latencies. Neither of the main effects nor the interaction approached significance in either analysis (all Fs < 1.90).

Nonword errors. Neither of the main effects nor the interaction approached significance in either analysis (all Fs < 1.00).

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[2] Six of the low-frequency words in Experiment 1 were not in the lexicon of this version of the IA model. Thus, predictions for those targets were unavailable. In addition, the predictions for their high-frequency mates were not generated because, as their low-frequency primes were not represented in the model's lexicon, they could not act as word primes. Given that 5 other stimuli were also removed because of high error rates (see Footnote 3), the predicted priming effects for Experiment 1 were therefore based on 53 of the 64 stimuli in each condition.

[3] For five of the low-frequency targets, *awry, nigh, aria, duly,* and *wren*, there were more than 50% errors. Thus, data for those five words and their matched high-frequency words (*away, high, area, duty,* and *when*) were not included in the analyses.

The key question in this experiment was whether there is a prime lexicality effect in masked form priming, as predicted by competitive network models such as the IA model. The results showed unequivocal evidence that there is indeed a prime lexicality effect: Related nonword primes facilitated lexical decisions to target words, whereas related word primes inhibited lexical decisions to the same targets. Although both of these results have been reported previously, this is the first experiment that has reported both effects within the same experiment. That is, although many previous experiments have obtained facilitory form priming effects using nonword primes, and several separate experiments have obtained inhibitory form priming effects using word primes, no previous experiment has demonstrated both of these effects simultaneously. The present demonstration that inhibition and facilitation effects can emerge in the same trial block effectively rules out explanations that appeal to strategic processing. Rather, it appears that both priming effects reflect the interactions that arise automatically within the lexical processing system. Furthermore, the results of Experiment 1 clearly demonstrate that it is possible to obtain inhibitory masked priming effects in English.

A second issue investigated in Experiment 1 was the influence of relative prime–target frequency on priming effects. The results showed a clear tendency for inhibitory priming effects to be stronger for low-frequency word targets preceded by high-frequency word neighbor primes than for the opposite pairing of primes and targets. This result is broadly consistent with the relative prime–target frequency effect observed by Segui and Grainger (1990). One slight difference is that Segui and Grainger observed (weak) facilitation for high-frequency primes paired with low-frequency targets, whereas we obtained (weak) inhibition for this condition. However, the priming effects for high-frequency targets did not attain significance in either experiment.

Simulation Results

Table 2 shows the results of the simulations for the no-reset and letter-reset versions of the model (as well as a third version of the model, which is discussed below). As can be seen, the no-reset model predicts a large prime lexicality effect: Related nonword primes produced very strong facilitation, whereas related word primes produced (on average) a negligible facilitory effect. Although the prediction of a prime lexicality effect is broadly in keeping with the results of the experiment, the nature of the observed effect is not captured by the model, which fails to predict the inhibitory priming effect for word primes. Furthermore, although the model predicts a relative prime–target frequency effect that is in the right direction and of a comparable magnitude to that in the data, it incorrectly predicts facilitation for high-frequency targets preceded by low-frequency primes and underestimates the inhibitory priming effect for low-frequency targets preceded by high-frequency primes.

The letter-reset version of the IA model is much more successful at capturing the main patterns in the data. It also predicts a large prime lexicality effect, but unlike the model without reset, it captures the qualitative nature of this effect, predicting facilitation for related nonword primes and inhibition for related word primes. This model also predicts a relative prime–target frequency effect, which is consistent with the trend shown in the data, that is, a relatively strong inhibitory priming effect for low-frequency targets preceded by high-frequency primes, compared with a much smaller inhibitory priming effect for high-frequency targets preceded by low-frequency primes. Finally, both models predict that target frequency has a negligible effect on the magnitude of the facilitory form priming produced by nonword primes. Although the experimental data showed a numerical difference (of 15 ms) between the form priming for high- and low-frequency targets, the corresponding interaction between target frequency and prime relatedness was not significant. Furthermore, it is worth noting that Sereno (1991) observed no difference in the magnitude of form priming effects for high- and low-frequency targets, in agreement with the prediction of this model.

Masking and Letter Reset

The reason that the no-reset model gives a poorer fit than the letter-reset model is not hard to discover. An important clue is provided by the fact that the no-reset model actually provides a relatively good fit to the data when priming effects are measured in relation to an unprimed baseline. For example, compared with an unprimed condition, the model predicts an inhibitory priming effect of 22 cycles for high-frequency targets preceded by low-frequency primes. This switches to a facilitory priming effect of 10

Table 2
Predicted Latencies and Priming Effects for Three Variants of the Interactive Activation (IA) Model in Simulations Manipulating Prime Lexicality, Relative Prime–Target Frequency, and Prime Relatedness

Prime lexicality/target frequency	IA (no reset)			IA (letter reset)			IA (selective inhibition)		
	Rel.	Unrel.	*PE*	Rel.	Unrel.	*PE*	Rel.	Unrel.	*PE*
Nonword prime									
LF target	141	215	+74	164	194	+30	165	190	+25
HF target	128	200	+72	147	179	+32	148	174	+26
M			+73			+31			+26
Word prime									
HF prime, LF target	223	218	−5	217	196	−21	218	190	−28
LF prime, HF target	194	204	+10	183	181	−2	183	174	−9
M			+3			−11			−18

Note. Rel. = related; Unrel. = unrelated; *PE* = priming effect; LF = low-frequency; HF = high-frequency.

cycles when priming is measured relative to an unrelated prime. It is clear, then, that the cause of this model's poor fit is that it predicts that unrelated primes produce considerable inhibition. For example, the model predicts that the unrelated prime *pony* would actually inhibit the target *ABLE* more than the related prime *axle*. As a result, when measured from an unrelated baseline, facilitation effects are overpredicted and inhibition effects are underpredicted.

This inhibitory effect of unrelated primes is due to "inertia" in the no-reset model. In this model, the target immediately overwrites the prime at the feature level, but it then takes some time for this new pattern of activation to feed forward to the letter level (partly due to top-down feedback from active word units to their constituent letters). That is, there is inertia in replacing the letter-level representation of the prime with a representation of the target. Thus, for some time following target onset, the target word node is inhibited by the (still active) letters of the prime (recall that active letter nodes send inhibitory signals to incompatible word nodes). For example, the reason the latency to respond to the target *ABLE* is 30 cycles slower following the unrelated prime *pony* compared with when the same target is presented without a prime is because there is a period following target onset during which the letters of the prime *pony* are still active and are inhibiting the target word node (e.g., a *P* in letter position 1 inhibits *AXLE*). By contrast, there is no inertia in the letter-reset model, in which the onset of the target is associated with a reset of the letter-level activities. Thus, it appears that (unless important aspects of the model are modified, such as its use of letter-word inhibition) the IA model requires the letter-reset assumption to explain masked form priming data. As noted earlier, we believe that the reset assumption is most consistent with the original spirit of McClelland and Rumelhart's (1981) model. In the General Discussion we consider some independent justifications for this assumption.

Homogeneous Inhibition vs. Selective Inhibition

The main reason that the letter-reset model provides a better account of the data than the no-reset model is that the reset of letter-level activities reduces the inhibitory effect of unrelated primes on target recognition. However, the reset assumption is not sufficient to completely eliminate this inhibitory effect. An additional factor underlying the inhibitory effect of unrelated primes is word-level inhibition. In the IA model, the lateral inhibitory signal to each word node is simply the total word-level activity minus the activity of the recipient word node. Thus, if the *DOOR* word node is active, it will add to the total word-level activity and will thereby inhibit all other word nodes, including unrelated word nodes like *AXLE*. In this respect, lateral inhibition is homogeneous. As a consequence, identification of the target *AXLE* is slower following the unrelated prime *DOOR* compared with when the same target is unprimed. This additional inhibitory impact of unrelated primes contributes to the letter-reset model's underestimation of inhibitory priming from related primes.

To investigate this issue further, we tested a modified version of the IA model that involved a change in the nature of lateral inhibition at the word level. In this modified model, lateral inhibition is nonhomogeneous and selective: Only word nodes that code orthographically overlapping words send inhibitory signals to each other. We implemented this in a relatively simple manner, counting two words as orthographically overlapping if they shared at least one letter in the same position. For example, *AXLE* receives inhibitory signals from word nodes like *ABLE, ARID,* and *EXIT* but not from word nodes like *DOOR* and *EMIT*. This selective inhibition assumption is a simplification of the continuous form of lateral inhibition used in Davis's (1999) SOLAR model, which is another competitive network model of visual word recognition. The introduction of selective inhibition greatly reduces the word-level inhibitory component of unrelated word primes; for example, priming the target *AXLE* with the unrelated word *DOOR* produces negligible word-level inhibition of the target. It is also worth noting that the selective inhibition assumption has no impact on the identification of unprimed targets, because words that do not share at least one letter with the target are never activated in the unprimed situation (i.e., it is only in the priming paradigm that a word node completely unrelated to the target could be activated). The modified IA model, which we refer to as the *selective inhibition model*, also assumes that the onset of the target is associated with letter-level reset. The combination of letter reset and selective inhibition virtually eliminates the inhibitory effect of unrelated primes (i.e., the recognition latencies for targets preceded by unrelated primes are very similar to the unprimed latencies).

The results for the selective inhibition model are shown in the final three columns of Table 2. As can be seen, the predicted latencies for related prime trials are very similar to those for the letter-reset model, whereas the latencies for trials involving unrelated primes are slightly faster: This reflects the reduced inhibition from unrelated word primes. As a consequence, facilitory form priming effects are slightly smaller in this model, and inhibitory priming effects are slightly larger. This results in a better quantitative fit to the data than the letter-reset model.

In summary, Experiment 1 showed that inhibitory masked form priming from related word primes can be found in English and that this effect can be found within the same experiment as a facilitory form priming effect from related nonword primes, thereby confirming the prime lexicality effect predicted by the IA model. Furthermore, the results provided support for another key prediction of the model, namely the relative prime–target frequency effect. Finally, the results of the model simulations showed a fairly poor fit to the data for an IA model without the letter-reset assumption, but a good qualitative fit for an IA model that assumes that letter activities are reset when the target is presented; this suggests constraints on how to simulate masked priming in the IA model. An even better fit was provided by a model which combined the letter-reset assumption with the assumption that lexical inhibition is selective (in contrast to the homogeneous inhibition assumed in the original IA model). Thus, in addition to providing support for the general assumption of lexical inhibition, the results of Experiment 1 may also provide evidence regarding the nature of lexical inhibition.

Experiment 2

As noted in the introduction, a critical prediction of the IA model is that the magnitude of form priming effects should be strongly influenced by the presence of shared neighbors of the prime and target. A detailed discussion of shared neighborhood effects in the IA model can be found in Davis (2003). For example, the model predicts that the magnitude of facilitory form priming effects should be greater for nonword primes and word targets that do not share any neighbors (e.g., *sant–SALT*) than for primes and targets that do share neighbors (e.g., *saln–SALT*, which share the neighbor *sale*), because, in the latter case, the shared neighbor will be activated by the prime and then will continue to inhibit the target after it is presented. Support for this prediction has been obtained in Dutch (Van Heuven, Dijkstra, Grainger, & Schriefers, 2001) and, more recently, in English (Lupker, Perry, & Davis, 2005). The model also makes a similar prediction about shared neighbors for partial word primes (e.g., that facilitory priming should be greater for *sa#t–SALT* than for *sal#–SALT*), and empirical support for this prediction has also been obtained (Grainger & Jacobs, 1993; Hinton, Liversedge, & Underwood, 1998; Lupker et al., 2005). However, the IA model's prediction that inhibitory priming effects should be greater for primes and targets that share neighbors has yet to be investigated empirically. The aim of the present experiment was to test this prediction.

Two sets of target words were selected in which the N sizes were small (3.5) and equal. For one set, higher frequency neighbor primes were selected such that the prime and the target had no shared neighbors (e.g., *heard–BEARD*). In the other set, the higher frequency prime and target shared one neighbor with a frequency higher than that of the target (e.g., *short–SNORT*, in which the prime and target share the neighbor *sport*). In the *no-shared neighbor* condition, all the target's neighbors (other than the prime) are target-only neighbors. These target-only neighbors should be (relatively) suppressed by the presentation of a prime that is not one of their neighbors, such that they have little impact on recognition of the target. In this condition, the only lexical competitor that should exert an inhibitory influence on the target is the prime word itself. In the *one-shared neighbor* condition, by contrast, there are two lexical competitors that exert a strong inhibitory influence on the target: the prime word and the shared neighbor. Thus, it is expected that inhibitory priming should be stronger in the one-shared neighbor condition than in the no-shared neighbor condition.

Method

Participants. Fifty undergraduate students from the University of Western Ontario participated in this experiment for monetary payment. All had normal or corrected-to-normal vision.

Stimuli. To create the no-shared neighbor condition, we selected 24 low-frequency, small neighborhood targets (Kucera & Francis, 1967, mean target frequency = 8.0, average N = 3.5; all N values were obtained from the N-Watch program; Davis, 2005) and high-frequency neighbor primes (Kucera & Francis, 1967, mean frequency = 98.9) such that they had no shared neighbors. To create the one-shared neighbor condition, we selected 24 low-frequency, small neighborhood targets (Kucera & Francis, 1967, mean target frequency = 8.0, average N = 3.5) and high-frequency neighbor primes (Kucera & Francis, 1967, mean frequency = 105.1) sharing exactly one neighbor.

A set of 48 nonwords were created by selecting 48 words and changing one letter to produce a nonword (average N = 4.1). Those words served as related primes for each nonword. All the words and nonwords were five letters long. The complete set of stimuli is contained in Appendix B.

Each set of words and the set of nonwords were divided into two subsets. Half of the participants saw the targets in one subset preceded by their related prime and the targets in the other subset preceded by an unrelated prime. The unrelated trials were constructed by repairing the primes and targets from the stimuli in a subset. For the other half of the participants, the targets in the other subsets appeared with related primes. The targets in the first subset appeared with unrelated primes.

Procedures and equipment. The experimental and simulation procedures and equipment were identical to those of Experiment 1.

Results and Discussion

Incorrect responses (7.8% of the data for word targets and 11.3% of the data for nonword targets) and reaction times greater than 1,500 ms (1.8% of the data for word targets and 4.1% of the data for nonword targets) were excluded from the latency analysis. For the word data, two-way ANOVAs were conducted, both by subject (F_1) and by items (F_2), with number of shared neighbors (zero vs. one) and prime relatedness (related vs. unrelated) as variables. In the subject analysis, both variables were treated as within-subject variables. In the item analysis, prime relatedness was treated as a within-item variable, whereas number of shared neighbors was treated as a between-item variable.[4] For the nonword data, one-way ANOVAs were conducted, both by subject and by items, with prime relatedness (related vs. unrelated) as the only variable. Prime relatedness was a within-subject variable in the subject ANOVA and a within-item variable in the item ANOVA. Effects reported as significant were significant at the .05 level unless otherwise indicated. Mean latencies and error rates from the subject analysis are shown in Table 3.

Word latencies. The prime relatedness main effect was significant in both analyses, $F_1(1, 49) = 9.01$, $MSE = 2{,}601.40$; $F_2(1, 42) = 4.59$, $MSE = 2{,}415.25$. Once again, higher frequency related primes produced inhibition. The main effect of number of shared neighbors was significant as a within-subject variable in the subject analysis, $F_1(1, 49) = 29.04$, $MSE = 1{,}584.24$, and marginal as a between-item variable in the item analysis, $F_2(1, 42) = 3.04$, $MSE = 6{,}059.27$, $p < .10$. Targets in the one-shared neighbor condition were responded to 30 ms more rapidly than targets in the no-shared neighbor condition. Most important, the Prime Relatedness × Number of Shared Neighbors interaction was significant in the subject analysis, $F_1(1, 49) = 4.09$, $MSE = 2{,}362.17$, but not in the item analysis, $F_2(1, 42) = .97$, $MSE = 2{,}415.25$, *ns*. Simple main effects tests revealed that the inhibition effect was significant in the one-shared neighbor condition, $t_1(49) = 3.58$ and $t_2(21) = 2.56$, but not in the no-shared neighbor condition, $t_1(49) = 0.78$ and $t_2(21) = 0.75$.

Word errors. The prime relatedness main effect was significant in the subject analysis, $F_1(1, 49) = 4.94$, $MSE = 57.16$, and marginal in the item analysis, $F_2(1, 42) = 3.90$, $MSE = 36.19$. Participants were more accurate with unrelated primes than with related primes. The number of shared neighbors main effect was significant as a within-subject variable in the subject analysis, $F_1(1, 49) = 8.83$, $MSE = 84.87$, but not as a between-item variable in the item analysis, $F_2(1, 42) = 2.60$, $MSE = 137.63$, $p > .10$. Participants were more accurate in the one-shared neighbor condition. The interaction failed to approach significance in either analysis (both Fs $< .11$).

Nonword latencies. The prime relatedness main effect did not approach significance in either analysis (both Fs $< .10$).

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[4] For four of the targets, *triad, brash, graft,* and *greet*, there were more than 30% errors. Thus, data from those words were not included in the analysis.

Table 3

Latencies (in Milliseconds) and Error Rates (in Percentages) for Word and Nonword Targets as a Function of Prime Relatedness, and (for Word Targets) Number of Shared Neighbors in Experiment 2

	Word targets		
	No shared neighbors	One shared neighbor	Nonword targets
Related	736 (13.0)	720 (8.8)	826 (14.4)
Unrelated	729 (8.2)	685 (6.5)	826 (16.5)
Effect	−7 (−4.8)	−35 (−2.3)	0 (+2.1)

Note. Error rates are in parentheses.

Nonword errors. Although there were slightly more errors in the unrelated condition, this difference was not significant in either analysis, $F_1(1, 49) = 2.14$, $MSE = 101.50$; $F_2(1, 42) = 2.06$, $MSE = 86.45$.

The main question in Experiment 2 was whether there would be a larger inhibition effect in the one-shared neighbor condition than in the no-shared neighbor condition. The answer is clearly yes, with a significant 35-ms effect in the former condition and a nonsignificant 7-ms effect in the latter. This supports the claim that the inhibitory processes acting on the target are weaker in the no-shared neighbor condition than in the one-shared neighbor condition. In the one-shared neighbor condition, the target must compete with not only the prime but also the shared neighbor. As a result, the overall inhibitory process is stronger, producing a larger inhibition effect. Thus, the present results would appear to provide nice evidence for the existence of inhibitory processes like those outlined in the IA model. This conclusion is further supported by the results of the IA simulations.

Simulation Results

As before, we compared three versions of the IA model: the no-reset model, the letter-reset model, and the selective inhibition model. The results of the simulations are presented in Table 4. All three models predicted a shared neighbor effect, with stronger inhibitory priming for primes and targets that share a neighbor than for primes and targets that do not share any neighbors. This is in accord with the results of the experiment. However, the no-reset model once again underestimated the extent of inhibitory priming, predicting facilitation in the no-shared neighbor condition and predicting inhibition that was weaker than obtained in the shared neighbor condition. This underestimation of inhibitory priming is due to the relatively large inhibitory effect of unrelated primes.

The letter-reset model produced a better fit, predicting moderately strong inhibition in the shared neighbor condition but negligible priming in the no-shared neighbor condition. However, this simulation also underestimates the extent of inhibitory priming. That is, although the reaction time data showed only a nonsignificant trend toward inhibition in the no-shared neighbor condition, the error data from this condition showed a robust inhibition effect.

The selective inhibition model once again produced the best fit to the data, with modest inhibition in the no-shared neighbor condition and somewhat stronger inhibition in the shared neighbor condition. This analysis provides further support for the idea that lateral inhibition is modulated by orthographic overlap, in contrast to the homogeneous inhibition in the original IA model.

Experiment 3

The results of Experiments 1 and 2 do, of course, stand in clear contrast to those of Forster and Veres (1998). Why is it that we were able to find inhibitory effects but they were not? In the introduction, we noted three factors that could potentially explain the difference between the experiments that have obtained inhibitory priming effects and the experiments reported by Forster (1987; Forster & Veres, 1998). The first of these concerned cross-linguistic differences: Forster's experiments used English-language stimuli, whereas all but one of the experiments that have obtained inhibitory priming effects used languages other than English. However, our results show that robust inhibitory priming can be obtained in English, and hence that the use of English-language stimuli cannot be the relevant explanatory factor.

A second possible explanatory factor is the nature of the nonword foils used. When the foils were quite distinct from words (their Experiments 3 and 4), Forster and Veres (1998) reported that word primes actually produced facilitation. More important, in their Experiment 2, when the nonword foils did resemble words, which is the standard situation in the lexical decision literature, there was only a null effect. Thus, a reasonable hypothesis is that the size of the inhibition effect is strongly affected by the nature of the nonword foils (i.e., by the difficulty of the word–nonword discrimination). We tested this hypothesis in Experiment 3. Nonword N was manipulated as a between-subjects variable. The question of interest was whether the inhibitory effect would be greater with large-N nonword foils than with small-N nonword foils. As noted in the introduction, this is the prediction that follows from the IA model when differences in nonword difficulty are simulated by varying the model's response threshold.

Table 4

Predicted Latencies and Priming Effects for Three Variants of the Interactive Activation (IA) Model in Simulations Manipulating Shared Neighborhood of Prime and Target

	IA (no reset)			IA (letter reset)			IA (selective inhibition)		
Shared neighborhood (N)	Rel.	Unrel.	*PE*	Rel.	Unrel.	*PE*	Rel.	Unrel.	*PE*
No-shared N	191	210	+19	187	189	+2	188	181	−7
Shared N	223	212	−11	207	191	−16	207	184	−23

Note. Rel. = related; Unrel. = unrelated; *PE* = priming effect.

A third factor that could explain the difference between the experiments that have obtained inhibitory priming effects and the experiments reported by Forster (1987; Forster & Veres, 1998) is the neighborhood density of the word targets. Previous investigations of masked form priming effects have suggested that these effects are dependent on the number of neighbors of the target—the so-called neighborhood density constraint (Forster et al., 1987). These observations have been based on facilitory form priming effects with nonword primes, and the question of how neighborhood density modulates inhibitory form priming effects has not previously been investigated. What is apparent, though, is that Forster (1987; Forster & Veres, 1998) used very low-N targets, whereas Grainger and Ferrand (1994) and Bijeljac-Babic et al. (1997) used targets that, on average, had much denser neighborhoods. The results of Experiment 1 indicate that relatively small N targets can produce inhibition. The question remains, however, as to whether large N targets would show larger inhibition effects.

The manipulation of target N also enables a test of the IA model. In view of the effect of shared neighbors in the IA model, one might expect that the model would predict a larger inhibitory effect as target N increases, given that targets with many neighbors are more likely to share neighbors with the prime. However, as noted earlier, the actual prediction is more complex than this, owing to the opposite influence of neighbors of the target that are not neighbors of the prime (target-only neighbors). That is, increasing overall target N has two counteracting effects: Increases in the number of shared neighbors increase the size of the inhibition effect, whereas increases in the number of target-only neighbors decrease the size of the inhibition effect, due to the target neighbor suppression effect (Davis, 2003). Overall, then, the IA model predicts relatively little effect of target N on inhibitory priming. This prediction was quantified in the simulations reported below, and the empirical prediction was tested in Experiment 3, in which word N was manipulated as a within-subject variable.

Method

Participants. Sixty-eight undergraduate students from the University of Western Ontario participated in this experiment for course credit. All had normal or corrected-to-normal vision.

Stimuli. With six exceptions (the five targets that had unacceptably high error rates in Experiment 1 and the target *ALTO*), the low-N targets and primes were the four-letter stimuli used in Experiment 1 (Kucera & Francis, 1967, mean target frequency = 5.0, mean related prime frequency = 467.9, mean unrelated prime frequency = 513.9; target N = 2.8, related prime N = 3.0, unrelated prime N = 2.9; N values were obtained from the N-Watch program [Davis, 2005]). In addition, 32 pairs involving high-N targets were selected (Kucera & Francis, 1967, mean target frequency = 6.8, mean related prime frequency = 329.0, target N = 13.1, related prime N = 12.1). Unrelated primes for these words were selected to match the related primes in frequency (Kucera & Francis, 1967, mean frequency = 294.4) and N (N = 10.7).

Two sets of 32 four-letter nonword targets were also selected. One set contained nonwords with large neighborhoods (N = 13.2). The other set contained nonwords with small neighborhoods (N = 2.8). Two word primes were selected for each nonword target. One was a neighbor in the Coltheart et al. (1977) sense, the other differed at all four letter positions. For the large neighborhood nonword targets, the Kucera and Francis (1967) mean related prime frequency was 68.9 (N = 11.2) and the mean unrelated prime frequency was 62.4 (N = 11.3). For the small neighborhood targets, the Kucera and Francis (1967) mean related prime frequency was 68.8 (N = 4.9) and the mean unrelated prime frequency was 67.8 (N = 6.0). The complete set of stimuli is contained in Appendix C.

For the word targets, it was necessary to create two counterbalancing conditions. Both the low-N and high-N targets were divided into two sets of size 16. Half of the participants (Group 1) saw the targets in the first sets preceded by related word primes and the targets in the second sets preceded by unrelated word primes. For the other half of the participants (Group 2), the assignment of target sets to primes was reversed. In addition, half of the participants in each group were presented with low-N nonwords whereas the other half was presented with high-N nonwords. Hence, nonword N was a between-subjects variable.

Procedures and equipment. The experimental and simulation procedures and equipment were identical to those of Experiment 1. Variations in the difficulty of the word–nonword discrimination were simulated by varying the model's response threshold μ. Four different values for μ were simulated: .55, .60, .65, and .70.

Results and Discussion

Incorrect responses (5.5% of the data for word targets and 10.6% of the data for nonword targets) and reaction times greater than 1,500 ms (0.1% of the data for word targets and 1.2% of the data for nonword targets) were excluded from the latency analysis. There were also two trials in which a latency of 0 was recorded. Because of a programming error, the final six stimulus pairs in the stimulus set for each participant were not presented. These were all unrelated nonword trials. Thus, the word–nonword ratio for this experiment was 64:26, and the nonword analysis is based on only 20 targets in each neighborhood size condition.

For the word data, three-way ANOVAs were conducted, both by subject and by items, with target N (high vs. low), prime relatedness (related vs. unrelated), and nonword N (high vs. low) as variables. In the subject analysis, target N and prime relatedness were treated as within-subject variables, whereas nonword N was treated as a between-subjects variable. In the item analysis, nonword N and prime relationship were treated as within-item variables, whereas target N was treated as a between-item variable.[5] For the nonword data, two-way ANOVAs were conducted, both by subject and by items, with target N (high vs. low) and prime relatedness (related vs. unrelated) as variables. Target N was both a between-subjects and between-item variable. Prime relatedness was both a within-subject and within-item variable. Effects reported as significant were significant at the .05 level. Mean latencies and error rates from the subject analysis are presented in Table 5.

Word latencies. The prime relatedness variable was significant in both analyses, $F_1(1, 66) = 23.40$, $MSE = 1{,}240.83$; $F_2(1, 59) = 15.19$, $MSE = 2{,}197.40$. Latencies were longer following a related prime than following an unrelated prime. Target N was significant, as a within-subject variable, in the subject analysis and was marginal, as a between-item variable, in the item analysis, $F_1(1, 66) = 15.53$, $MSE = 2{,}373.93$; $F_2(1, 59) = 2.98$, $MSE = 15{,}059.32$, $p < .10$. As is often the case (Andrews, 1989, 1992, 1997; Sears et al., 1995), latencies were shorter for high-N words. Nonword N was not significant, as a between-subjects variable, in the subject analysis; however, it was significant, as a within-item variable, in the item analysis, $F_1(1, 66) = 1.71$, $MSE = 39{,}474.83$; $F_2(1, 62) =$

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[5] For three of the targets, *defy, fret,* and *seep*, there were more than 30% errors. Thus, data from those words were not included in the analysis.

Table 5

Latencies (in Milliseconds) and Error Rates (in Percentages) for Word and Nonword Targets as a Function of Nonword N, Prime Relatedness, and (for Word Targets) Word N in Experiment 3

Variable	High-N words	Low-N words
	Word targets with high-N nonwords	
Related	659 (5.5)	684 (8.5)
Unrelated	638 (5.0)	647 (6.2)
Effect	−21 (−0.5)	−37 (−2.3)
	Word targets with low-N nonwords	
	High-N words	Low-N words
Related	615 (3.5)	649 (7.3)
Unrelated	607 (2.3)	632 (6.0)
Inhibition	−8 (−1.2)	−17 (−1.3)
	Nonword targets	
	High-N nonwords	Low-N nonwords
Related	784 (11.2)	737 (12.1)
Unrelated	786 (13.8)	713 (10.3)
Inhibition	+2 (+2.6)	−24 (−1.8)

Note. Error rates are in parentheses.

37.85, *MSE* = 1,828.85. Word latencies were faster with the low-N nonword foils. The only other variable that approached significance was the Prime Relatedness × Nonword N interaction, $F_1(1, 66) = 3.66$, *MSE* = 1,240.83, $p = .06$; $F_2(1, 59) = 1.09$, *MSE* = 2,461.40. This interaction was due to the inhibition effects being larger in the high-N nonword condition.

Word errors. The prime relatedness variable was marginal in the subject analysis and significant in the item analysis, $F_1(1, 66) = 3.80$, *MSE* = 0.76, $p < .06$; $F_2(1, 59) = 5.07$, *MSE* = 0.64. The error rate was higher on related trials. Target N was significant in both analyses, $F_1(1, 66) = 17.98$, *MSE* = 0.74; $F_2(1, 59) = 4.22$, *MSE* = 3.95. The error rate was higher for low-N words. Nonword N was not significant, as a between-subjects variable, in the subject analysis; however, it was marginal, as a within-item variable, in the item analysis, $F_1(1, 66) = 1.56$, *MSE* = 2.42; $F_2(1, 62) = 3.20$, *MSE* = 1.29, $p < .10$. The error rate was slightly higher with high-N nonword foils. None of the interactions approached significance (all *F*s < 1.65).

Nonword latencies. The only significant effect was the (nonword) target N effect, $F_1(1, 66) = 5.59$, *MSE* = 21,105.83; $F_2(1, 38) = 17.17$, *MSE* = 4,553.71. Neither the prime relatedness effect nor the interaction approached significance in either analysis (all *F*s < 2.26).

Nonword errors. Neither of the main effects nor the interaction approached significance in either analysis (all *F*s < 1.74).

Experiment 3 provides further confirmation that high-frequency word primes produce inhibitory effects for low-frequency word targets in English. There was also some evidence that priming effects vary as a function of nonword N. The difference in the inhibition effects for the high-N and low-N nonword conditions was 17 ms (29 ms to 12 ms), a difference that was marginal in the subject analysis but not in the item analysis.

Although the effect of nonword N is relatively small, the present results are at least consistent with the possibility that if we had used nonword foils having as low an N value as Forster and Veres (1998; i.e., 1.04, as opposed to 2.8 in the present experiment), we might indeed have been able to eliminate the inhibition effect entirely. That is, reductions in nonword N could, at least partly, explain why Forster and Veres obtained a null effect in their Experiment 2. What needs to be kept in mind, of course, is that reductions in effect sizes (and overall latencies) as the word–nonword discrimination gets easier are fairly standard results in the speeded response literature (e.g., Stone & Van Orden, 1993). Thus, even if the effect can be made to go away if the task is made easy enough, this fact would not seem to have any important implications for conclusions about lexical processing.

The results of this experiment showed very little evidence of an effect of target N on inhibitory priming: There was only a nonsignificant 13-ms difference (27 ms for low-N targets vs. 14 ms for high-N targets) in the size of the inhibition effects in spite of the fact that the difference in N between our high- and low-N targets was more than 10 (13.2 to 2.8). Thus, it seems unlikely that any major discrepancies between prior results can be explained in terms of target N.

Simulation Results

The results of the simulations are presented in Table 6. For all three models, mean latency decreased markedly with decreases in mu. This corresponds to the decreases in participants' latencies with decreases in the neighborhood density of the nonword foils. Decreases in μ are also associated with reduced inhibitory priming. This is because the activation of lexical competitors greatly slows the time that it takes for the target to reach high levels of activity (by contrast, the effects of inhibition are much weaker earlier in processing). This impact of varying the response threshold on the predicted inhibition effects accords with the empirical effect of varying the difficulty of the word–nonword discrimination.

The no-reset model predicts that inhibitory priming effects should be much greater for high-N target words than for low-N targets; this prediction is clearly at odds with the data. By contrast, both the letter-reset and the selective inhibition models predict a very weak effect of target word N on inhibitory priming effects, with slightly more inhibition for high-N target words than for low-N targets. This is generally compatible with the experimental data, which showed no significant effect of target N on the size of the inhibition effects. Nevertheless, the small trends in the data and in the predictions do go in opposite directions, such that inhibitory priming was greater for low-N targets in the former and for high-N targets in the latter. The trend in the experimental data may reflect participants' use of a more sophisticated strategy for making lexical decisions than we assumed here. Previous accounts of Forster et al.'s (1987) target density constraint in masked form priming have considered the possibility that the smaller facilitory priming effects for high-N targets may reflect the use of overall word-level activity to make lexical decisions (e.g., Davis, 2003; Perea & Rosa, 2000). A similar argument may apply to inhibitory form priming effects. Lexical inhibition does affect the time that it takes for the target to reach a local activity threshold, but, typically, it would not affect the time taken to reach a global activity threshold (e.g., one based on total word-level activity). Therefore,

Table 6

Predicted Latencies and Priming Effects for Three Variants of the Interactive Activation (IA) Model in Simulations Manipulating Neighborhood Density of the Word Targets and the Response Threshold μ

μ and Target N	IA (no reset)			IA (letter reset)			IA (selective inhibition)		
	Rel.	Unrel.	*PE*	Rel.	Unrel.	*PE*	Rel.	Unrel.	*PE*
μ = .70									
Low N	279	229	−50	257	208	−49	256	204	−52
High N	298	226	−72	257	205	−52	257	201	−56
μ = .65									
Low N	216	200	−16	202	178	−24	202	172	−30
High N	239	199	−40	206	178	−28	206	173	−33
μ = .60									
Low N	179	181	+2	172	159	−13	172	152	−20
High N	205	182	−23	178	160	−18	178	155	−22
μ = .55									
Low N	154	167	+13	151	145	−6	151	137	−14
High N	182	168	−14	158	147	−11	158	141	−17

Note. Rel. = related; Unrel. = unrelated; *PE* = priming effect.

if high-N targets can be responded to on the basis of overall lexical activity, their responses would be less affected by inhibition. As a result, inhibitory priming effects would be smaller for high-N target words than for low-N target words.

Some support for this interpretation can be found by examining the effect of target N for trials with unrelated primes. When the nonwords were high-N, the target N effect was only 9 ms (31% of the mean inhibitory priming effect for this nonword condition), but when the nonwords were low-N (and hence a large neighborhood density was a somewhat reliable indicator that the stimulus was a word), the target N effect was 25 ms (200% of the inhibitory priming effect for this nonword condition). This suggests that participants in the low-N nonword condition may sometimes have responded to high-N targets on the basis of the target's global similarity to English words rather than on the basis of a lexical identification.

General Discussion

The key empirical question addressed in the present research was whether it is possible to obtain inhibitory masked priming effects from formally similar primes in English. The answer provided in all three experiments is yes. When word targets are primed by masked, higher frequency neighbor primes, target latencies are prolonged. Like other recent findings (Bowers, Davis, & Hanley, 2005), this pattern of results strongly supports the role of lexical inhibition in lexical selection.

Each of the experiments assessed different factors that, according to the IA model, should determine the magnitude of inhibitory priming. The model predicts that the frequency relationship between the prime and target is a key determinant of whether inhibition will be obtained: The larger the frequency advantage that the prime has over the target, the stronger the likelihood of obtaining inhibition. This prediction was confirmed in Experiment 1. The model also predicts that nonword primes, which do not have lexical representations, should produce facilitation, a prediction that was also confirmed in Experiment 1. Finally, Experiment 1 is informative from another perspective. The existence of facilitation from nonword primes and inhibition from word primes in the same experiment indicates that neither phenomenon is a result of using a particular processing strategy. Rather, both phenomena seem to be the result of the automatic interactions within the lexical system.

Experiment 2 was designed to test another prediction of the IA model concerning the impact of shared neighborhood of the prime and target. A contrast was made between two groups of low-N targets, one in which the prime and target had no shared neighbors and one in which the prime and target had one shared neighbor. The latter condition was predicted to result in strong inhibitory priming, because the presence of a shared neighbor means that there are two strong competitors of the target. By contrast, in the no-shared neighbor condition, according to the model, the only strong competitor of the target is the prime, with target-only neighbors playing a relatively small role in the competitive process. The results were in agreement with this prediction: The one-shared neighbor condition produced a larger inhibition effect than the no-shared neighbor condition.

In Experiment 3, the issue was the neighborhood sizes of both the targets and the nonword foils. Increasing nonword N slowed responses and increased the size of the inhibition effect from 12 to 29 ms. Given the previous literature on the impact of making the word–nonword discrimination more difficult (e.g., Stone & Van Orden, 1993), a result of this sort was not unexpected. Within the IA model this effect can be explained by assuming that the difficulty of the word–nonword discrimination affects the setting of the activity threshold for responding "yes" in the LDT. The more wordlike the nonword foils, the more conservative the criterion should be (resulting in a higher response threshold), which leads to longer latencies and larger effects, including inhibitory priming effects.

Increasing target N also had a fairly small, nonsignificant impact on the size of the inhibition effect (a decrease from 27 to 14 ms). This result is broadly consistent with the predictions of the versions of the IA model with letter reset, according to which target N should have very little effect on the magnitude of inhibitory priming. However, it is possible that the trend in the data toward weaker inhibition for targets with more neighbors reflects a genuine (albeit weak) effect, which might be significant in a more powerful experiment. This effect is in the opposite direction to the weak effect of target N predicted in the model. As noted above, one possible explanation for why the data showed a smaller priming effect for high-N targets is that participants actually use a more complex lexical decision mechanism than the one we used in the present simulations.

Assessing the Fit of the Three Versions of the IA Model

At a qualitative level, both the letter-reset and the selective inhibition versions of the IA model did a good job of accounting for the present data. Although it is possible that variations in the parameters of the models would produce an even better fit, our goal in the present research was to explore the key characteristics of the IA model rather than to engage in precise model fitting. To this end, we retained all of the parameters of the original IA simulations reported by McClelland and Rumelhart (1981), varying only a time-scaling factor. Comparisons across the three models that we tested therefore allow us to assess assumptions regarding type of lexical inhibition (homogeneous or selective) and letter reset due to masking, which are the only factors that vary across these models.

A quantitative measure of the relative goodness of fit of the three models was obtained by computing likelihood ratios, based on the observed and predicted priming effects for the 10 conditions tested across all three experiments (e.g., Glover & Dixon, 2004).[6] This analysis indicated that the observed data were 5.9 times more likely given the letter-reset model than given the no-reset model, thereby providing strong support for the letter-reset assumption (the only factor that differs between these models). The likelihood ratios also showed that the observed data were 1.6 times more likely given the selective inhibition model than given the letter-reset model. Other things being equal, then, selective inhibition is to be preferred to homogeneous inhibition. These two assumptions of letter reset and selective inhibition are now discussed in more detail.

Masking and Letter Reset

The above results appear to provide strong support for the hypothesis that letter-level activities should be reset when simulating the effects of a posttarget mask in the IA model. However, this conclusion need not generalize to other models. For example, Davis (1999) noted several reasons for dropping the assumption of letter-word inhibition. If letter-word inhibition was dropped, the main reason for resetting letter-level activities in the present simulations would be eliminated (because, without letter-word inhibition, inertia at the letter level during the prime–target transition will not lead to inhibition of targets that are unrelated to the prime).

There are, however, a number of independent considerations that also lend support to the letter-reset hypothesis. From an adaptive standpoint, it would clearly be useful for the word recognition system to use a dynamic letter-reset mechanism so as to prevent old inputs from interfering with the recognition of new visual inputs (e.g., when the eyes land on a new word, as in normal reading). From an empirical standpoint, the absence of letter priming effects in letter identification and letter decision tasks (e.g., Arguin & Bub, 1995; Bowers, Vigliocco, & Haan, 1998; Jacobs, Grainger, & Ferrand, 1995) suggests that letter-level activation is not maintained when new inputs are encountered. Bowers et al. (1998) suggested that the absence of priming for letter pairs that are identical in meaning but visually dissimilar (i.e., different case letter pairs like *r* and *R*) could be due to

> the short-lasting activation of abstract letter codes following the presentation of the prime, which is due either to a fast decay rate of letter activation or to an active suppression of this activation when new letter information (the target) arrives. In both cases, the prior encoding of the prime would not facilitate the processing of the target because the letter activation would be at baseline levels again when the target was encoded. (p. 1718)

This account is consistent with the assumption that the onset of the target results in the reset of letter-level activities.

A further issue that is raised in the present context is whether masking is critical for the inhibitory priming effects we observed. The most obvious difference between masked and unmasked priming—that participants are aware of the prime in the latter case but not the former—is irrelevant to models like IA, which have no mechanism for distinguishing between conscious and nonconscious processing. The present data do not address this issue, but the results of other LDT experiments do show inhibitory priming effects from unmasked orthographically related word primes (e.g., Colombo, 1986; Lupker & Colombo, 1994; Segui & Grainger, 1990). These experiments have, however, also provided evidence for a dissociation between masked and unmasked priming. Specifically, the relative prime–target frequency effect that is obtained in masked priming appears to be inverted in unmasked priming, that is, high-frequency targets are inhibited by low-frequency related word primes, but low-frequency targets are not inhibited by high-frequency related word primes. It has been suggested that this pattern occurs because successful (conscious) identification of a (prime) word leads to suppression of that word's higher frequency competitors (Colombo, 1986; Segui & Grainger, 1990). However, it is worth noting that a recent series of unmasked priming experiments conducted by Burt (2006, unpublished) failed to replicate the inverted relative prime–target frequency effect in English. It is clear that this is an area in which further research is required, both to clarify the effects and to determine whether models like IA need to posit an additional mechanism that occurs following identification.

Is Lexical Inhibition Homogeneous or Selective?

Although lexical inhibition is a central component of the IA model, it is not essential that it should work in exactly the way that it does in the original model. It is interesting to note that the TRACE model of speech perception (McClelland & Elman, 1986) uses an architecture and equations that are very similar to those used in the IA model, but replaces the homogeneous inhibition of the original IA model with a continuous form of selective inhibi-

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[6] The response threshold mu was set at .70 for all conditions except the simulations of the low-N nonword foil conditions, in which μ was set to .60.

tion. The above comparison of the letter-reset and selective inhibition versions of the IA model suggests that, other things being equal, a model with selective inhibition should be preferred to one with homogeneous inhibition. It is important to note that these two versions of the models behave identically for unprimed targets and virtually identically for targets preceded by related primes. The key difference between them concerns behavior for targets preceded by unrelated primes. That is, does a prime like *door* inhibit an unrelated target like *AXLE*? More broadly, does inhibition punish both related and unrelated words? The greater predictive power of the selective inhibition model suggests that the answer to these questions is no. The general conclusion seems to be that lexical inhibition is modulated by formal similarity.

Other Theoretical Frameworks

It is also important to consider how well the present data might be modeled within other theoretical frameworks. It would clearly be of interest to know, for example, whether parallel distributed processing models (e.g., Plaut, McClelland, Seidenberg, & Paterson, 1996) could accommodate the present findings. At present, the answer to this question would appear to be no. Current instantiations of these models do not possess a satisfactory mechanism for making lexical decisions (Borowsky & Besner, 2006; Coltheart, 2004). Nor is it clear how the masked priming paradigm could be simulated within these models. Finally, it is unclear why form-related primes should have an inhibitory effect, compared with unrelated primes, within this framework.

A theoretical framework that has often been applied to explaining lexical decision data in the masked form priming paradigm is Forster's (1987, 1999; Forster & Davis, 1984; Forster et al., 2003) bin model. According to this model, lexical access involves a rapid serial search of an area of the lexicon most likely to contain the lexical representation of the presented word. Lexical units that provide close matches to the orthographic properties of the input are flagged for further analysis (verification). The verification process begins as soon as a close match has been found. Priming effects emerge because, while awaiting verification, those units that are flagged are "opened." Thus, once the verification process reaches them, their processing is more rapid.

As conceptualized, this type of account would immediately run into problems explaining the present data for two major reasons. First, although it has a mechanism for explaining facilitation effects, it has no obvious mechanism for explaining inhibition effects. Second, when the prime is masked, there is no obvious way to distinguish between the effects of word and nonword primes. In the present version of the model, neither leads to the successful verification of the prime. Instead, both leave a number of lexical units open and ready for verification. Modifications to the model are therefore required if the present data are to be explained. Whether a modified search model could accommodate the results of the present experiments remains an open question.

Reconciling the Apparent Empirical Discrepancies

One thing to note is that Forster's (1987, 1999) original account was never designed to explain inhibition effects because in none of those papers was inhibition reported. In fact, as noted, both Forster (1987) and Forster and Veres (1998) reported facilitation from word primes that, of course, raises the question of why they obtained facilitation rather than null effects or inhibition. Although the answer is not yet entirely clear, a number of factors are likely to have contributed to this result.

The present work has shown that the inhibitory influences of a formally related word prime are maximized when (a) the prime word is of higher frequency than the target word, (b) the prime also activates other competitors that are shared neighbors of the target, and (c) the target must attain a high level of activity before a response is made (i.e., the response threshold is set high). In general, these conditions were not met in Forster and Veres's (1998) experiments. About 45% of the primes were lower in frequency than their targets (and, in many cases, prime frequency was very close to 0, such that many of the primes would have seemed like nonwords to the participants). For an additional approximately 30% of the pairs, the prime frequency was essentially the same as the target frequency. Furthermore, only a couple of the primes and targets used by Forster and Veres shared any neighbors. Finally, Forster and Veres's experiments used nonword foils with very low-N values; in the experiments in which they produced facilitation, the nonword foils had N values of 0, enabling participants to set their response thresholds at a relatively low level. Thus, at the very least, the conditions most likely to produce inhibition were not close to being met.

However, another important factor underlying the facilitation observed by Forster and Veres (1998) may have been the length of their stimuli. As noted, a masked neighbor prime has both facilitory and inhibitory influences on target recognition. According to the IA model, a key determinant of the facilitory influence of a prime is the extent of its overlap with the target. The experiments reported here used four- and five-letter words, so that the related primes shared either three out of four letters with the target, or four out of five letters. In Forster and Veres's experiments, however, the targets were eight or nine letters long, so that the related primes shared either seven out of eight letters with the target, or eight out of nine letters. This increased overlap greatly increases the facilitory boost of the prime on the target; for example, in the model, the net letter-word input to the target word node is three times as large for primes that share eight out of nine letters as for primes that share three out of four letters. Even in the simulations we reported here, there was a clear difference between four- and five-letter stimuli, which explains why inhibitory priming effects were larger in the simulation of Experiment 3 (which used only four-letter words) than in the simulations of Experiment 1 (which used a combination of four- and five-letter words) or Experiment 2 (which used only five-letter words).

To investigate this explanation further, we set up a selective inhibition version of the IA model with a vocabulary of 5,447 eight-letter words and tested this model on the 39 eight-letter stimuli used by Forster and Veres (1998). The simulation showed that related primes had mean facilitory priming effects (relative to unrelated primes) of 21 cycles for word primes and 27 cycles for nonword primes. Thus, exactly the same model that predicts a qualitative prime lexicality effect for four- and five-letter words (i.e., inhibition for related word primes and facilitation for related nonword primes) predicts facilitation from both word and nonword primes in the case of eight-letter words, with only a small prime lexicality effect (the latter effect becomes negligible as the response threshold decreases, in line with Forster and Veres's finding that the prime lexicality effect disappears when the word–nonword discrimination is made easier). This analysis appears to provide a plausible resolution of the apparent discrepancy between the inhibitory priming effects that we observed and the facilitation observed by Forster and Veres.

It is interesting to note that previously published experiments have observed differences in the magnitude of form priming as a function of stimulus length. When the prime was an orthographically similar nonword, Forster et al. (1987) reported that longer target words tended to show facilitation, whereas shorter target words tended to show null effects. Although Forster et al. went on to suggest that this pattern reflected differences in target neighborhood density, it may be that the initial result was (at least in part) a genuine length effect. Furthermore, in a new LDT experiment using seven-letter targets that we have recently conducted, we obtained no evidence of inhibitory form priming for low-frequency targets preceded by high-frequency primes (e.g., *private–PRIMATE*); indeed, there was a nonsignificant trend (of 14 ms) toward facilitation. It therefore seems likely that word length is an important factor in masked form priming, which accords with the theoretical account offered by the IA model.

Conclusion

The IA model has been remarkably successful in accounting for both word-superiority data and data from the LDT. The model's ability to explain data from the unprimed LDT was demonstrated by Grainger and Jacobs (1996), and Davis (2003) found that the model offered a good account of facilitory effects in the masked priming version of the LDT. The present article shows that this model also successfully predicts rather subtle aspects of inhibitory masked priming data.

In spite of these successes, though, there are some aspects of the model that are clearly unsatisfactory. The model's use of separate slots to code each letter position is simplistic and conflicts with experimental data (e.g., Davis, in press; Davis & Bowers, 2004; Perea & Lupker, 2003a, 2003b, 2004). This method of coding letter position also prevents the model from handling words of differing length in a unitary fashion: Different networks must be simulated to test four-letter words, five-letter words, and so on. Another important limitation of the IA model is that it says nothing about how words are learned. Davis (1999) has developed a model that is similar in spirit to the IA model but that seeks to overcome these problems. The SOLAR (self-organizing lexical acquisition and recognition) model incorporates mechanisms of lexical inhibition similar to those in the modified interactive activation model described here. However, it offers a more satisfactory account of letter position coding, is able to simultaneously code words of varying length, and has the capacity to self-organize its own representations. Future work on this and related competitive network models should help to focus experimental investigations of visual word recognition.

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Appendix A

Stimuli in Experiment 1

Word targets

axle, ible, thug, shug, ABLE; able, axue, door, doir, AXLE
blur, blae, gasp, gisp, BLUE; blue, glur, yeah, yeap, BLUR
drum, crug, jazz, jozz, DRUG; drug, prum, sofa, nofa, DRUM
germ, tarm, wavy, waly, TERM; term, gelm, plan, slan, GERM
oven, evon, folk, filk, EVEN; even, ovin, much, mich, OVEN
thud, phus, fern, cern, THUS; thus, chud, baby, biby, THUD
turf, tuln, chew, shew, TURN; turn, tarf, view, vien, TURF
duly, luty, veil, veel, DUTY; duty, dily, join, joen, DULY
frog, frem, pulp, pule, FROM; from, wrog, this, chis, FROG
itch, unch, meek, mees, INCH; inch, otch, vary, vory, ITCH
icon, irol, maul, jaul, IRON; iron, ican, edge, eage, ICON
oily, ondy, aura, auta, ONLY; only, oiby, them, chem, OILY
sigh, lign, atom, alom, SIGN; sign, sogh, army, almy, SIGH
knit, unid, chef, ches, UNIT; unit, krit, glad, flad, KNIT
awry, anay, edit, erit, AWAY; away, ewry, used, usel, AWRY
clue, clab, pond, pand, CLUB; club, clie, desk, desh, CLUE
nigh, hiph, romp, remp, HIGH; high, nogh, eyes, eles, NIGH
fury, jory, twin, twan, JURY; jury, fuby, knee, kwee, FURY
aria, alea, noun, nout, AREA; area, oria, kept, kopt, ARIA
alto, anso, quiz, quoz, ALSO; also, elto, such, sush, ALTO
verb, vedy, yolk, yolt, VERY; very, velb, into, isto, VERB
moth, boch, puny, puly, BOTH; both, moph, next, nect, MOTH
drip, drot, chum, shum, DROP; drop, drik, busy, buse, DRIP
lazy, ludy, stem, spem, LADY; lady, lozy, huge, buge, LAZY
omen, opan, flux, frux, OPEN; open, omep, girl, pirl, OMEN
trek, treb, lava, liva, TREE; tree, crek, film, falm, TREK
wren, whun, void, poid, WHEN; when, wreg, said, soid, WREN
burp, buln, jive, jave, BURN; burn, murp, swim, swin, BURP
defy, feny, prim, pril, DENY; deny, dify, goal, gial, DEFY
hurl, lurt, scan, scap, HURT; hurt, nurl, eggs, egge, HURL
skid, skun, puff, poff, SKIN; skin, skud, grow, trow, SKID
stew, snep, curl, corl, STEP; step, otew, fair, foir, STEW
abort, adout, slime, slume, ABOUT; about, acort, which, waich, ABORT
abode, abeve, flirt, flist, ABOVE; above, ibode, girls, firls, ABODE
alter, afler, blown, bloun, AFTER; after, alten, going, goind, ALTER
angel, anver, mould, mourd, ANGER; anger, andel, shock, shork, ANGEL
ankle, engle, porch, borch, ANGLE; angle, ankie, shoot, shoft, ANKLE
abide, asine, furry, turry, ASIDE; aside, abice, occur, olcur, ABIDE
weave, lenve, groom, croom, LEAVE; leave, wenve, front, cront, WEAVE
thief, choef, syrup, sarup, CHIEF; chief, thien, usual, usuan, THIEF
polar, silar, buddy, bundy, SOLAR; solar, podar, theme, thete, POLAR
lance, dalce, mirth, firth, DANCE; dance, lante, shirt, phirt, LANCE
gruel, crull, poppy, popsy, CRUEL; cruel, grual, fifth, finth, GRUEL
draft, drist, spoon, shoon, DRIFT; drift, drast, solve, soive, DRAFT
vault, faurt, ozone, ozene, FAULT; fault, vauld, minor, mikor, VAULT
cello, hollo, strut, scrut, HELLO; hello, celto, hurry, hurny, CELLO
knack, knosk, flute, plute, KNOCK; knock, knask, juice, jurce, KNACK
yearn, loarn, hoist, coist, LEARN; learn, yoarn, music, musil, YEARN
regal, leral, smock, smick, LEGAL; legal, regat, youth, yoush, REGAL
manic, sagic, dwell, dwoll, MAGIC; magic, menic, upset, urset, MANIC
medic, melia, fluff, cluff, MEDIA; media, sedic, throw, shrow, MEDIC
rotor, modor, scalp, scilp, MOTOR; motor, rotar, chain, chail, ROTOR
otter, ouler, smash, smaph, OUTER; outer, ottur, cabin, capin, OTTER
farce, borce, puppy, punpy, FORCE; force, fared, south, pouth, FARCE
niece, poece, shrug, thrug, PIECE; piece, niepe, staff, slaff, NIECE
queer, cueen, villa, vilta, QUEEN; queen, quaer, apply, ipply, QUEER
repay, retly, motto, motta, REPLY; reply, repag, joint, jount, REPAY
loyal, royel, hedge, hidge, ROYAL; royal, loyan, twice, twide, LOYAL
thump, trumb, vocal, vodal, THUMB; thumb, thurp, rival, dival, THUMP
udder, unver, hippy, hilpy, UNDER; under, udser, point, poant, UDDER
onion, ulion, chalk, chark, UNION; union, oncon, table, taple, ONION
untie, until, gamma, camma, UNTIL; until, urtie, small, scall, UNTIE
skate, stite, chunk, churk, STATE; state, skafe, round, cound, SKATE
mouse, hause, frail, frain, HOUSE; house, moude, thing, phing, MOUSE

(Appendixes continue)

Appendix A (*continued*)

Nonword targets

ally	anly	dish	diph	AWLY	alert	adert	climb	climp	ABERT
clip	clib	soap	doap	CLID	unity	inity	solve	sorve	ANITY
duet	duin	self	sulf	DUIT	fibre	fubre	tough	toush	FABRE
harm	hirm	bait	boit	HURM	delve	velve	straw	steaw	LELVE
taut	raut	dish	dich	LAUT	noise	noish	cream	cleam	NOIST
shed	shec	plot	plit	SHEY	quilt	qualt	prize	preze	QUALT
tube	tume	lamb	vamb	TUCE	chest	shest	rapid	ralid	THEST
blew	blet	acid	acil	BLEN	dense	vense	trick	trich	WENSE
arch	arce	bomb	bolb	ARCA	ingot	ungot	spell	sperl	ANGOT
soon	souk	myth	ryth	SOUN	drone	drope	pitch	putch	DRODE
with	lith	plus	plas	DITH	snuff	sluff	shame	chame	KNUFF
flat	blat	prey	brey	GLAT	mafia	mufia	crown	trown	MEFIA
gnat	snat	shed	sheb	KNAT	poker	poter	blind	blild	POMER
pram	plam	bulk	vulk	PHAM	salon	sulon	coach	doach	SILON
thin	thip	golf	galf	THID	paint	maint	cheek	theek	VAINT
acid	alid	grey	gley	AXID	check	chenk	storm	shorm	CHELK

Note. Related word, related nonword, unrelated word and unrelated nonword primes for high and low-frequency members of each word pair (in capital letters) and for nonword targets (in capital letters)

Appendix B

Stimuli in Experiment 2

Word targets		Nonword targets	
No shared Neighbor	Shared neighbor	No shared neighbor	Shared neighbor
heard, crown, BEARD	trace, major, BRACE	bunch, crime, BINCH	cheat, punch, CHEAM
blood, trial, BLOOM	brave, straw, BRAKE	clean, whine, CLEAM	crime, trail, CRUME
brown, heavy, BLOWN	crash, nurse, BRASH	patch, plate, DATCH	greed, munch, DREED
tribe, speak, BRIBE	brick, stuff, BRISK	drove, skull, DROSE	drown, wheel, DROWL
blood, tribe, BROOD	check, short, CHUCK	plate, gleam, FLATE	flare, gauge, FLERE
bunch, dream, BUTCH	class, stock, CLASP	fudge, scrap, FUNGE	wheel, lunge, GHEEL
chose, bunch, CHASE	nurse, towel, CURSE	gleam, drown, GLEAT	grasp, fudge, GRASK
crown, guide, CLOWN	daily, short, DAIRY	judge, train, JEDGE	lunch, shout, LANCH
carry, truck, CURRY	flame, brick, FLAKE	lunge, speak, LUDGE	munch, trace, MINCH
dream, choose, DREAD	craft, slide, GRAFT	noise, clean, NOIST	nurse, chick, NURKE
blame, blood, FLAME	green, straw, GREET	plane, steal, PLONE	train, shone, PRAIN
flung, stove, FLING	major, flame, MANOR	punch, greed, PUNCE	purse, think, PURVE
guide, naval, GLIDE	short, trace, SHOOT	singe, treat, RINGE	gauge, drove, SAUGE
glass, brown, GLOSS	slide, green, SLIME	scrap, flare, SCRUP	which, lunch, SHICH
heavy, quite, HEAVE	stock, brave, SMOCK	chick, bunch, SHICK	shine, trait, SHINK
board, flung, HOARD	short, while, SNORT	skull, tense, SKULT	shout, nurse, SLOUT
naval, blood, NAVEL	stuff, train, STIFF	speak, which, SMEAK	smirk, judge, SMIRM
price, blame, PRICK	straw, class, STRAP	spoon, theft, SPOAN	steal, would, STEAT
spent, price, SCENT	straw, track, STRAY	syrup, throb, STRUP	tense, cheat, TENGE
stove, heard, SHOVE	sense, daily, TENSE	shone, smirk, THONE	think, singe, THONK
speak, carry, SPEAR	train, check, TRAIT	throb, plane, THREB	theft, shine, THUFT
quite, glass, SUITE	track, craft, TRUCK	trace, spoon, TRARE	treat, purse, TREAM
trial, spent, TRIAD	while, sense, WHALE	trail, syrup, TROIL	trait, grasp, TRUIT
truck, board, TRUCE	towel, crash, VOWEL	whine, noise, WHINT	would, patch, WOULT

Note. Related and unrelated word primes and word and nonword targets (in capital letters).

Appendix C

Stimuli in Experiment 3

High-N words	Low-N words	High-N nonwords	Low-N nonwords
feed, cast, REED	able, door, AXLE	head, room, HEAN	self, bait, NELF
sell, boat, SILL	blue, yeah, BLUR	full, book, SULL	deep, wall, DERP
bear, till, PEAR	drug, sofa, DRUM	wife, road, WIME	leaf, grim, CEAF
race, sick, RAVE	term, plan, GERM	fear, hold, VEAR	tube, twin, GUBE
kill, bear, KILT	even, much, OVEN	none, hall, RONE	edge, club, IDGE
test, mark, PEST	thus, baby, THUD	foot, mass, FOUT	blue, wish, BLIE
note, thin, NODE	turn, view, TURF	wind, fell, WINT	dawn, cell, DIWN
rock, test, RACK	hair, town, HEIR	lose, pain, LOCE	sign, type, SIRN
rise, gold, RIPE	from, this, FROG	base, hill, BAME	plus, drew, BLUS
lack, hell, TACK	inch, vary, ITCH	park, sick, PARN	clan, weep, CLUN
size, walk, SIRE	iron, edge, ICON	pale, cool, PAKE	both, left, BOCH
lead, none, LEAK	only, them, OILY	hole, cast, FOLE	fund, text, MUND
wall, cost, MALL	sign, army, SIGH	bath, moon, DATH	gift, joke, GICT
game, cost, GAPE	unit, glad, KNIT	cast, hole, DAST	thud, kerb, THID
hold, fear, BOLD	sure, play, SURF	rare, pink, RAME	harm, blow, HURM
line, word, VINE	club, desk, CLUE	wave, luck, TAVE	shed, plot, SHEY
seem, road, SEEP	free, whom, FRET	pure, lift, DURE	gnat, fume, KNAT
name, book, FAME	jury, knee, FURY	rent, fill, YENT	sham, brew, PHAM
cent, full, DENT	trip, busy, TRIO	soul, bird, SOUT	desk, fair, NESK
five, soon, DIVE	gone, such, GENE	bell, boon, KELL	free, town, FREL
sort, mind, SORE	very, into, VERB	goal, kiss, GEAL	step, firm, STET
best, love, BUST	both, next, MOTH	rice, port, WICE	wash, fill, WESH
face, kind, LACE	drop, busy, DRIP	bore, pack, BIRE	drug, myth, DRIG
need, room, DEED	lady, huge, LAZY	sing, rear, SIND	drop, join, DRUP
part, find, CART	open, girl, OMEN	pipe, wool, DIPE	rose, bill, RESE
same, look, SANE	tree, film, TREK	cure, lock, MURE	ally, dish, AWLY
came, went, CANE	whom, kept, WHIM	sole, nick, SOLT	grid, stew, CRID
life, work, RIFE	burn, swim, BURP	doll, kick, HOLL	laud, deem, LAUM
take, long, FAKE	deny, goal, DEFY	tool, pump, TOOD	vile, poke, VILB
make, must, BAKE	hurt, eggs, HURL	fold, sunk, FOLL	arch, dumb, ARCA
most, good, MAST	skin, grow, SKID	poll, cart, POLD	dish, wool, DITH
like, your, LIME	step, fair, STEW		

Note. Related and unrelated word primes for high-N and low-N word and nonword targets (in capital letters).

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