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Sandwich Priming: A Method for Overcoming the Limitations of Masked Priming by Reducing Lexical Competitor Effects

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An orthographically similar masked nonword prime facilitates responding in a lexical decision task (Forster & Davis, 1984). Recently, this masked priming paradigm has been used to evaluate models of orthographic coding—models that attempt to quantify prime-target similarity. One general finding is that priming effects often do not occur when prime-target similarity is moderate, a result that the authors interpret as being due to uncontrolled effects of lexical inhibition. In the present research, a new version of the masked priming paradigm, sandwich priming, was introduced in an effort to minimize the impact of lexical inhibition. Masked sandwich priming involves briefly presenting the target itself prior to the presentation of each prime. Results indicate that the new paradigm was successful. The predicted priming effects were observed for Guerrera and Forster's (2008) T-All primes (e.g., *avacitno*–VACATION) and for primes differing from their targets at 3 letter positions (e.g., *coshure*–CAPTURE)—effects that are not found with the conventional masked priming paradigm. In addition to demonstrating the usefulness of the sandwich priming technique, these results also support the assumption that inhibitory processes play an important role in lexical processing.

Keywords: sandwich priming, orthographic coding, lexical competition, masked priming

One of the most frequently used experimental paradigms in the study of visual word recognition is masked priming (e.g., Evett & Humphreys, 1981; Forster & Davis, 1984; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006). In this paradigm, a prime stimulus is presented (typically for around 50 ms) immediately prior to a target word to which participants respond. Although participants report being unaware of the prime, their response latencies indicate that they are, nevertheless, influenced by its presence. For example, it has been found that responses to the target word *NURSE* are faster when the prime is the related word *doctor* than when the prime is an unrelated word like *butter* (e.g., Bodner & Masson, 2003; Bourassa & Besner, 1998; Perea & Gotor, 1997).

Participants' lack of awareness of the prime is useful for investigators, as it allows them to examine various relationships between primes and targets without concerns that participants are employing conscious strategies to predict the target on the basis of the prime. Masked priming has, in fact, been used to investigate many aspects of lexical processing, including orthographic input coding (e.g., Davis & Bowers, 2006; Grainger et al., 2006; Guerrera & Forster, 2008; Perea & Carreiras, 2006; Perea & Lupker, 2003, 2004; Schoonbaert & Grainger, 2004), phonological recoding (e.g., Ferrand & Grainger, 1992; Rastle & Brysbaert, 2006), morphological processes (e.g., Frost, Forster, & Deutsch, 1997; Giraudo & Grainger, 2001; Rastle, Davis, & New, 2004), lexical selection mechanisms (e.g., Davis & Lupker, 2006; Segui & Gringer, 1990), homophony (e.g., Ferrand & Grainger, 2003), and semantic processing (e.g., Bodner & Masson, 2003; Bourassa & Besner, 1998).

In recent years, masked form priming (i.e., masked priming in which there is form overlap between the prime and target) has become the principal technique for investigating orthographic input coding. In these types of experiments, the magnitude of priming effects is commonly interpreted as a measure of the extent to which the prime activates the lexical unit for the target word. In essence, the assumption is that whenever form primes facilitate target processing, the orthographic codes of the prime and target must be similar. For example, in an early form priming study, Forster, Davis, Schoknecht, and Carter (1987) found that responses to target words were faster when the prime was one letter different from the target than when the prime was an unrelated word (e.g., form-related prime-target pairs like *anxwer–ANSWER* produced faster reaction times than unrelated prime-target pairs like *follow–ANSWER*). This result suggests that the orthographic codes for the one-letter different primes were sufficiently similar to those for the target to preactivate its lexical representation. Computational models, such as the interactive activation (IA) model (McClelland & Rumelhart, 1981), are able to provide a good account of such facilitatory priming effects (Davis, 2003).

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Transposed-Letter (TL) Priming

There is, however, another aspect of Forster et al.'s (1987) results that poses problems for the original IA model. In one of their prime conditions, primes were formed by transposing two adjacent letters (e.g., *anwser–ANSWER*). This condition resulted in strong priming effects that were numerically larger than those for one-letter different primes and that were virtually identical in size to those observed for identity primes (e.g., *answer–ANSWER*). The reason that this result is problematic for the original IA model is that this model assumes that the set of features appropriate to each letter is unambiguously slotted into its appropriate position in the orthographic code, allowing the process of letter identification to take place independently at all letter positions. This type of orthographic coding scheme is variously referred to as *channel-specific*, *position-specific*, *slot coding*, or *conjunctive coding*, and variants of this scheme have been used in many other computational models (e.g., Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Grainger & Jacobs, 1996; Harm & Seidenberg, 1999; Zorzi, Houghton, & Butterworth, 1998). A consequence of this type of coding is that transposing a letter pair would cause the two letters to activate features in different slots than they would in the base word. Thus, according to this type of coding, the TL prime *anwser* should be less similar to *ANSWER* than is the one-letter replacement prime *anxwer*. Indeed, TL primes should be no more similar to their base words than two-letter replacement primes (e.g., *anvmer*).

The prediction that two-letter replacement primes and TL primes are equally similar to their base words has now been examined and falsified in a number of studies (e.g., Perea & Carreiras, 2006; Perea & Lupker, 2003; Schoonbaert & Grainger, 2004). For example, Perea and Lupker (2003) demonstrated that a TL nonword like *jugde* is a far superior prime for its base word *JUDGE* than is a replacement-letter nonword like *jupte*. Perea and Lupker (2004) further demonstrated that this TL superiority in masked priming is obtained even when the transposed letters are not adjacent (e.g., *caniso–CASINO*; see also Lupker, Perea, & Davis, 2008).

Although TL priming effects pose a problem for position-specific coding models, such as the original IA model, these effects can be accommodated by recent models that incorporate more flexible coding schemes—schemes based on relative rather than absolute coding of letter positions (e.g., Davis, 1999; Dehaene, Cohen, Sigman, & Vinckier, 2005; Gómez, Ratcliff, & Perea, 2008; Grainger & van Heuven, 2003; Whitney, 2001). For example, Davis's (1999) self-organizing lexical acquisition and recognition (SOLAR) model uses a spatial coding scheme in which letter codes are position-independent, so that the TL nonword *jugde* and its base word, *JUDGE*, share the same set of letter units. Because *JUDGE* and *jugde* share five letter units, whereas *JUDGE* and *jupte* share only three letter units, *jugde* should be the better prime. Other recent models (Dehaene et al., 2005; Grainger & van Heuven, 2003; Whitney, 2001) assume that word identification depends upon the activation of open-bigrams—ordered pairs of letters—so that *JUDGE* is represented by bigram nodes such as JU, JD, UD, and so forth. Because *JUDGE* shares more open bigrams with *jugde* than with *jupte*, the expectation is that *jugde* will be a better prime.

More Extreme Transpositions

To date, virtually all of the empirical studies on TL similarity have investigated the effect of transposing a single pair of letters. However, anecdotal considerations (e.g., the well-known "Cambridge email") suggest that more extreme disruptions of letter order should also lead to strings that are orthographically similar to their base words, a suggestion that is consistent with the predictions from the newer, flexible letter position coding models. For example, consider the situation in which each of the letter pairs within a word is transposed, as when the base word *VACATION* is transformed to the letter string *avacitno*. Is the transformed string still orthographically similar to the base word after this series of letter transpositions? According to current models, the answer appears to be yes.

These models all specify procedures for computing the similarity of pairs of letter strings, so that it is possible to calculate model-based orthographic similarity scores (match values) for any two letter strings. For example, using these procedures, one can compute the predicted match values for pairs of the general form 12345678 and 21436587 (i.e., where each of the letter pairs within a word is transposed). The discrete open-bigram coding model (Grainger & van Heuven, 2003) predicts a match value of .67. A match value of .64 is predicted by the original version of the SERIOL model (Whitney, 2001), although the current version of the model predicts a smaller match value of .39 because of the mismatch of the external letters in this pair. Likewise, the basic spatial coding model, which weights each letter position equally, predicts a match value of .64, whereas a slightly more sophisticated spatial coding model that assigns twice as much weight to external letters than to internal letters predicts a smaller match value of .51. Although there is some variability across these predictions, the more important point is that each of the models clearly predicts a nonzero match value. If orthographic similarity is the key to priming, one would therefore expect that primes formed by transposing all letter pairs should give rise to significant facilitatory priming effects.

This expectation was tested by Guerrera and Forster (2008). Their results showed that primes like *avacitno* (for the target word *VACATION*)—which they refer to as T-All primes—did not produce any priming relative to all-letter different control primes. On the surface, this result appears to contradict the predictions of flexible position coding models. Guerrera and Forster therefore concluded that this finding challenged these models: "It is clear that the absence of priming in the T-All condition is problematic not only for a coarse coding scheme, but also for all three of the models under consideration, which predicted strong priming in this condition" (p. 134).

A Competitive Network Account of the Limitations on Masked Form Priming

In this article, we challenge the above conclusion; indeed, we show that the absence of significant T-All priming is exactly what is predicted by at least one version of these models. Our argument is that the apparent discrepancy between predictions based on orthographic similarity values and empirical results from masked form priming experiments reveals a fundamental limitation of the conventional masked priming methodology. To explain this limitation, we first provide some background concerning the explanation of priming effects in competitive network models, such as IA and SOLAR.

As noted previously, regardless of the nature of orthographic coding, all models of word identification regard orthographic priming in the lexical decision task as a phenomenon that arises not at the level of the orthographic code but within the lexicon. That is, what the orthographic code of the prime does is to activate lexical units consistent with that code. Priming is assumed to occur whenever the activation level of the target is increased by the prime, that is, whenever the target's lexical unit is one of the units that the prime activates. The degree of activation of any particular lexical unit certainly is a function of the similarity of the prime and target, however, it is also a function of the nature of the interactions within the lexicon.

More specifically, consider how lexical processing unfolds within the IA model, because that model's lexical structure serves as the basis for the lexical structures of most of the orthographic coding models mentioned above. Once any lexical unit receives activation from the orthographic level, it begins to send inhibition to other lexical units. The degree of inhibition it can send is a function of its activation level, which is a function of both its frequency in the language and the amount of activation it has received from the orthographic level. As a result, in a masked priming experiment, the activation of the target's lexical unit at any point in time will be a function of (a) the target's frequency, (b) the orthographic similarity of the target to the current input, (c) the degree to which other lexical units have been activated by the prime, and (d) the frequencies of those lexical units. In such a situation, it is possible for the inhibitory influences to outweigh any facilitation provided by the presentation of an orthographically similar prime.

The key assumption being made here is that there is competition between activated lexical units that manifests itself in mutual inhibition during word recognition. Indeed, at present, there is good evidence for this lexical inhibition assumption (e.g., Bowers, Davis, & Hanley, 2005; Davis & Lupker, 2006; De Moor & Brysbaert, 2000; Segui & Grainger, 1990).

Lexical Competitor Effects

It follows from the above discussion that form priming effects depend not only on match values but also on the presence or absence of lexical competitors. The prime lexicality effect reported by Davis and Lupker (2006) provides a good example of lexical competitor effects. Davis and Lupker reported an experiment in which target words were preceded by one-letter different primes that were either nonwords (e.g., *scort–SNORT*) or words (e.g., *sport–SNORT*); these prime conditions were compared with unrelated nonword and word prime conditions, respectively. From the perspective of orthographic similarity, *scort* and *sport* are equally similar to the target *SNORT* (e.g., the SOLAR model predicts a match value of 4/5 = .80 in both cases), and so one might expect equivalent priming effects following the logic outlined earlier and utilized by Guerrera and Forster (2008). However, the results showed that nonword primes produced a robust facilitation effect (26 ms, on average, for low-frequency targets), whereas word primes produced a robust *inhibitory* priming effect (34 ms, on average, for low-frequency targets).

This prime lexicality effect is quite consistent with the IA model (Davis, 2003), although Davis and Lupker (2006) noted that modifications to the assumptions of the original model were required to capture the pattern of facilitation and inhibition effects in their data. The key implication of the prime lexicality effect, for present purposes, is that the orthographic similarity of the prime and target is not sufficient to predict the magnitude of form priming; indeed, knowing the degree of orthographic overlap is not even sufficient to predict the *direction* of priming effects. Although the prime *sport* is orthographically similar to the target *SNORT*, it is more similar to one of the target's lexical competitors, that is, the word *SPORT*. The activation of this competitor interferes with the activation of the target; according to competitive network models, like the IA and SOLAR models, this interference is a consequence of lateral inhibition between lexical representations.

Lexical Competitor Effects in the Context of T-All Priming

The theoretical background outlined above provides the basis for our claim that the absence of masked form priming for T-All primes (Guerrera & Forster, 2008) reflects lexical competitor effects. That is, the reason that the T-All prime *avacitno* is not an effective prime for the target *VACATION* is not that there is no orthographic similarity between the codes for these two letter strings but rather that *avacitno* is *more* similar to words like *AVIATION*, which compete with the target word during the identification process.

The above claim concerning the relationship between lexical competitor effects and the absence of T-All priming can be made more concrete by considering some activation functions from a simulation of an IA model in which the position-specific coding scheme has been replaced by spatial coding (a model using a position-specific coding scheme would, of course, clearly not predict T-All priming). Further details concerning this model and the procedure for simulating masked priming are described below. Figure 1 plots the activation functions over time when the target *VACATION* is preceded by either the T-All prime *avacitno* (lines marked by squares) or the unrelated prime *etorcism* (lines marked by triangles); both of these prime-target pairs are from the stimulus set of Guerrera and Forster (2008). The activities of two nodes are depicted. The filled-in shapes denote the activity of the target word node (i.e., *VACATION*), whereas the unfilled shapes denote the activity of the competing word node (i.e., *AVIATION*).

Consider first the pattern of activation over the first 50 cycles of processing, when the prime is being presented to the model. In the case of the unrelated prime, neither the target word node nor its competitor becomes activated; indeed, both nodes settle at the minimum activation level. In the case of the T-All prime, there is a slight increase in the activity of the target node from its resting activation, but its activity remains just below zero at the conclusion of the prime—there is no sign of the "lift-off" that is required to produce a facilitation effect. By contrast, lift-off is achieved for the

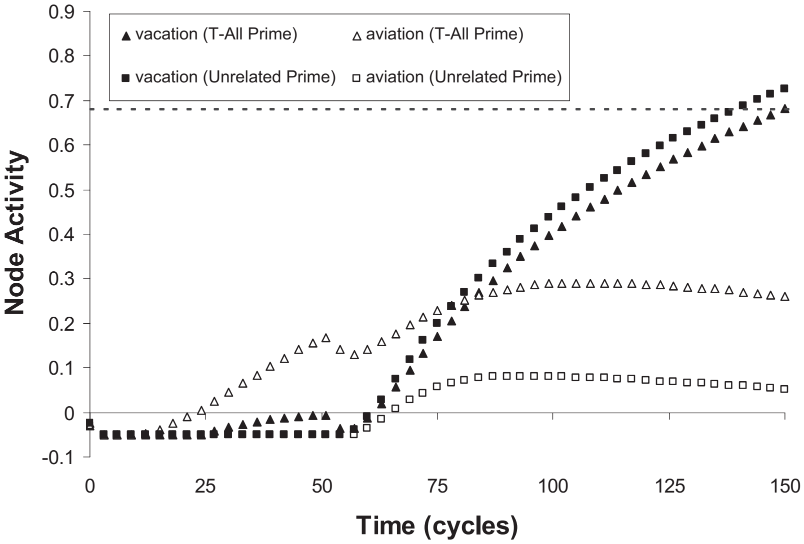

Figure 1. Activation functions over time for two nodes (*VACATION* and *AVIATION*) given two different prime types (i.e., *avacitno–VACATION* and *etorcism–VACATION*), assuming conventional masked priming. The target replaces the prime on Cycle 51.

AVIATION word node, which is a substantially better match with the prime than is *VACATION*.[1]

Now consider the pattern of activation after the target is presented (on Cycle 51). In the case of the unrelated prime, the activity of the target word node grows steadily and exceeds threshold on Cycle 139. In contrast, the *AVIATION* word node becomes weakly activated because of its similarity to *VACATION*; however, that activation is rapidly suppressed by the node for *VACATION*. In the case of the T-All prime, however, the *AVIATION* word node is already preactivated and, hence, is able to attain a much greater activity (peaking at .29) before it begins to be suppressed by the target word node. This additional competition provided by the activated *AVIATION* word node slows the activation of the target word node, such that it does not exceed threshold until Cycle 149, that is, 10 cycles later than when the prime was unrelated.

It is important to note that T-All primes do not always result in inhibitory priming in this model. Often, those nodes that are highly activated by the prime will not be strongly activated by the target itself. As a result, their activation dies off quite quickly upon target presentation, meaning that they are able to provide only a moderate degree of inhibition to the target. In such cases, the prime would not facilitate recognition of the target; however, it would not tend to inhibit it either. In other cases, strong facilitation can be observed from T-All primes, if the prime matches the target considerably better than it matches any other word (e.g., for the prime-target pair *awrrnayt–WARRANTY*, which is another of the pairs from Guerrera and Forster's, 2008, set). Such variation in the magnitude of predicted priming effects nicely demonstrates the point that these models do not inevitably predict that priming effects will directly reflect the magnitude of the match between prime and target. In any case, it is the above example with the target *VACATION* that is particularly instructive, as it clearly illustrates why T-All primes do not necessarily produce facilitation in competitive network models like the SOLAR model.

Sandwich Priming

On the basis of the discussion so far, it should be clear that, because of inhibitory processes in the lexicon, orthographic match values do not necessarily provide a good means of predicting priming effects. The same observation has been made by van Heuven and Grainger (2007), and, of course, Guerrera and Forster (2008) came to a similar conclusion in considering the absence of priming for their extreme transposition primes. This realization poses something of a problem for researchers, given that masked priming has previously been seen as the most effective tool for testing models of orthographic input coding. In the remainder of this article, we propose a new methodological solution to overcome this problem and report simulations and experimental data testing the validity of this methodology.

The starting point for the new methodology is the insight that the limitations on masked form priming that are imposed by lexical competition might be overcome if it were possible to somehow mute the influence of the inhibitory processes in the lexicon. Under such a scenario, not only would similarity scores provide a good way of predicting priming effects, but also form priming effects in general should be increased. Demonstrating that it is possible to create a situation of this sort, hence, providing a tool for evaluating various models of orthographic coding, was the main goal of the present research.

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[1] There are also other nodes that compute a better match with the prime *avacitno* than *VACATION* does, including *CAPACITY*, *RAPACITY*, and *SAGACITY*, all of which share the letter sequence *a-acit* with the prime, and *VIVACITY*, which shares the letter sequence *vacit*. Thus, even if the *AVIATION* word node were disabled, the target word node would not become activated by this prime. This situation is fairly typical among Guerrera and Forster's (2008) T-All primes, which often match the target less well than they match other words.

As noted, according to models based on the IA model, the inhibition that a lexical unit receives is a function of the activation level of that unit itself as well as the activation levels of other word nodes. The unit that is highest in activation will be the most potent inhibitor of the others. To try to make the target's lexical unit the most potent inhibitor at the point in time when it is actually presented as a target, we designed a new methodology for masked priming. The sequence of events on each trial in this methodology is depicted in Figure 2. On every trial there are two masked primes. The first is always identical to the target. The second is the prime of interest, either an orthographically similar letter string or an unrelated letter string. The expectation is that the brief (approximately 33 ms) presentation of the first prime will boost the target word node's activation level far enough above the activation levels of the nodes for all orthographically similar words that their ability to inhibit target processing will be severely diminished. As a result, the only important determinant of the size of the priming effect will essentially be the orthographic similarity between the prime and target (i.e., to what extent the second prime activates the target). Because the target stimulus is presented twice on every trial (as the first prime and then again as the visible target), with the prime of interest sandwiched between, we refer to this technique as *sandwich priming*.

An Example of How Sandwich Priming Can Overcome Lexical Competitor Effects

The examples shown in Figure 1 illustrate how conventional T-All priming can fail to produce facilitation because of lexical competitor effects. Figure 3 plots the activation functions for the same nodes and prime-target pairs as in Figure 1 but this time using sandwich priming. The target stimulus is presented for the first 40 cycles, followed by the prime of interest for 50 cycles, followed by the target stimulus again, and the model is then allowed to continue processing until a word node exceeds the activity threshold. As can be seen, the initial presentation of the target stimulus boosts the activity of the target node (to a level of .37) but gives a weaker boost to the activity of competing nodes (the *AVIATION* node reaches an activation level of only .08). In effect, the sandwich prime has enabled the target word node to achieve lift-off. This modification to the starting point of node activities means that the T-All prime now has a very different impact. Although the match with the target node is not sufficient to sustain the target node activity at the same level, it is good enough to maintain a moderate activity level (by contrast, an unrelated prime allows target node activity to decay to the minimum activity level). Furthermore, this activity level is strong enough to prevent competing nodes from becoming strongly activated, even those that are a better match to the prime than is the target. Thus, at target onset, the target node has an activity of .22, whereas its closest competitor (*AVIATION*) has an activity of less than .07. This headstart enables the target to reach threshold relatively rapidly, 25 cycles earlier than is the case when the prime of interest is an unrelated letter string. That is, the use of sandwich priming transforms an inhibitory priming effect of 10 cycles into a facilitation effect of 25 cycles.

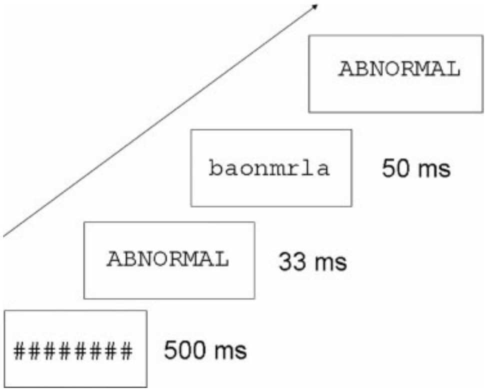

Figure 2. A schematization of the sequence of events on each trial in the sandwich priming methodology.

Introduction to the Experiments

To summarize the argument so far, we began by discussing the use of masked priming to test models of orthographic input coding, and then noted a type of prime (T-All primes) for which facilitation effects in masked form priming are not observed, even though such effects might appear to be expected on the basis of the match values generated by models of orthographic input coding. We then argued that the absence of priming reflects lexical competitor effects and suggested a general means by which the effects of lexical competition can be reduced, on the basis of preactivation of the target. Finally, we have suggested a specific experimental technique for implementing this approach, a methodological variant of masked priming that we call sandwich priming. In the remainder of this article, we present experimental data testing this methodology and comparing it directly with the more conventional three-field masked priming method. In Experiment 1, we sought to replicate the absence of T-All priming using the conventional methodology and to investigate whether T-All priming can be observed when sandwich priming is used. In Experiment 2, we tested another situation in which the priming effects obtained in conventional masked priming experiments deviate from what might be expected on the basis of theoretical match values obtained from current models of orthographic input coding. Our hypothesis was that the use of sandwich priming would enable priming to be observed in conditions in which it does not occur when the conventional technique is used.

Experiment 1

Experiment 1 was, then, an examination of whether the sandwich priming technique produces the increased priming effect that is predicted on the basis of simulations like that shown in Figure 3. In Experiment 1a, we used Guerrera and Forster's (2008) T-All stimuli in a conventional masked priming experiment in an attempt to replicate their null effect. In Experiment 1b, we used these same stimuli in a sandwich priming experiment with the expectation being that we would observe noticeable priming. We also report IA simulations of both these experiments using the exact same stimuli.

If the sandwich priming technique does successfully increase the size of priming effects (making them more reflective of prime-target match values), it will be a powerful tool for evaluating the

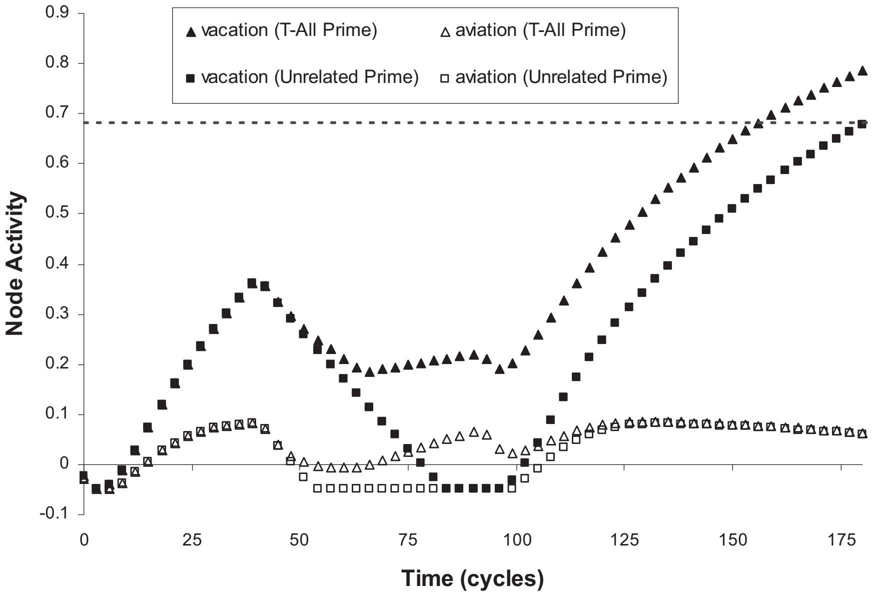

Figure 3. Activation functions over time for two nodes (*VACATION* and *AVIATION*) given two different prime types (i.e., *avacitno–VACATION* and *etorcism–VACATION*), when the sandwich masked priming technique is used. The target stimulus is presented for the first 40 cycles and is then replaced by the prime of interest (*avacitno* or *etorcism*). The target replaces this prime on Cycle 91.

various models of orthographic coding. To begin with, it will allow us a better means of evaluating the models in terms of the reality of their calculated match values. Equally important, it will allow us to better reevaluate other failures to find masked priming effects in situations in which match values were of reasonable size (Schoonbaert & Grainger, 2004; also see Grainger, 2008), results that, in some cases, have had considerable impact on the development of orthographic coding models. Those effects may have been null because the primes do not activate the lexical units of the targets, as the models assume. On the other hand, they may have been null because the inhibitory processes were sufficient to prevent priming effects from being seen.

Experiment 1a

Method

Participants. The participants were 24 undergraduates from the University of Western Ontario (London, Ontario, Canada) who received course credit for their participation. All reported having normal or corrected-to-normal vision.

Stimuli and apparatus. The target stimuli were the 96 eight-letter words and the 96 orthographically legal eight-letter nonwords used by Guerrera and Forster (2008). (See Appendix A.) The mean frequency of the target words was 33.8 (Kuçera & Francis, 1967; range = 1–375). The mean neighborhood size (Coltheart, Davelaar, Jonasson, & Besner, 1977; Davis, 2005) was .5. The T-All primes for both target types were constructed by pairwise transposing the first and second, third and fourth, fifth and sixth, and seventh and eighth letters of the target (e.g., the T-All prime for the target *VACATION* was *avacitno*). The unrelated primes for both target types were orthographically legal nonwords that were generated by Guerrera and Forster using the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002). Each participant saw each target only once. To counterbalance the stimuli, we arbitrarily divided both the word targets and the nonword targets into two sets with a size of 48. One set of each type of targets was primed by a T-All prime, with the other set being primed by an unrelated prime for half the participants. For the other half of the participants, the sets of both word and nonword targets were primed by the opposite prime type.

Both Experiment 1 and Experiment 2 were run with DMDX experimental software produced by Forster and Forster (2003). Stimuli were presented on a SyncMaster monitor (Model No. 753DF). Presentation was controlled by an IBM-clone Intel Pentium. Stimuli appeared as black characters on a white background. Responses to stimuli were made by pressing one of two keys on the keyboard.

Procedure. Participants were run individually. Each participant sat approximately 18 in. (63.72 cm) in front of the computer screen. Participants were instructed to respond to strings of letters presented on the computer screen by pressing one key (the right key) if the letters spelled an English word, or another key (the left key) if the letters did not spell a word. They were also told that a string of number signs (i.e., "########") would appear prior to the string of letters. They were not told of the existence of the prime. They were also told to respond to each target as quickly and as accurately as possible.

On each trial, the participants saw the string of number signs for 500 ms followed by the presentation of the prime for 55 ms in lower case letters. The target then appeared in upper case for either 3 s or until the participant responded. All stimuli were presented in 12-point Courier New font.

Participants performed five practice trials before beginning the experiment and were given the opportunity both during the practice trials and immediately afterwards to ask the experimenter any questions to clarify any confusion concerning what was required.

Results

Reaction times longer than 1,500 ms were excluded from the analyses of correct latencies (this criterion affected 59 word trials and 96 nonword trials out of a total of 4,704 trials).

Word data. In the latency data, the 9-ms advantage for T-All primes (718 ms vs. 727 ms) was nonsignificant in both the subject analysis, $t_1(23) = 1.22$, $SE = 7.39$, *ns*, and the item analysis, $t_2(95) = 1.60$, $SE = 6.91$, *ns*. In the error data, the 1.0% advantage for T-All primes (4.8% vs. 5.8%) was also nonsignificant in both analyses: $t_1(23) = 1.63$, $SE = 0.64$, *ns*; $t_2(95) = 1.12$, $SE = 0.56$, *ns*.

Nonword data. There was no effect of prime type in either the latency or the error data (all ts < 1.0).

Experiment 1b

Method

Participants. The participants were 20 undergraduates from the University of Western Ontario who received either course credit or monetary reimbursement for their participation. All reported having normal or corrected-to-normal vision. None had participated in Experiment 1a.

Stimuli and apparatus. The primes, targets, and computer equipment were the same as used in Experiment 1a.

Procedure. There was only one procedural difference between Experiments 1a and 1b. On all trials in Experiment 1b, the target word itself was presented in lower case for 33 ms immediately following the forward mask and immediately prior to the T-All or unrelated prime.

Results

Reaction times longer than 1,500 ms were excluded from the analyses of correct latencies (this criterion affected 25 word trials and 68 nonword trials out of a total of 3,920 trials).

Word data. In the latency data, the 40-ms advantage for T-All primes (651 ms vs. 691 ms) was significant in both the subject analysis, $t_1(19) = 4.61$, $SE = 8.91$, $p < .001$, and the item analysis, $t_2(95) = 4.68$, $SE = 9.37$, $p < .001$. In the error data, the 1.2% advantage for T-All primes (2.9% vs. 4.1%) was nonsignificant in both analyses: $t_1(19) = 1.53$, $SE = 0.75$, *ns*; $t_2(95) = 1.37$, $SE = 0.42$, *ns*.

Nonword data. There was no effect of prime type in either the latency or error data (all ts < 1.0).

Simulation 1

Method

Procedure. The procedure for simulating conventional masked priming was identical to that adopted by Davis (2003) and Davis and Lupker (2006). At the beginning of each trial, the activity of all the nodes in the model were set to their resting levels, and the prime was input to the model for a duration of 50 cycles. The target was then input to the model, and the model was allowed to continue processing toward an equilibrium state. We adopted the *letter-reset* assumption of Davis and Lupker, according to which the onset of the target has the effect of resetting letter-level activities. When the activity of a word node reached the level of the response criterion (set to .68), a unique identification was assumed to have been made. (Note that, unlike with the multiple read-out model [Grainger & Jacobs, 1996], local word unit activation provides the only basis for making "yes" responses.) Identification latencies were measured from target onset.

The procedure for simulating sandwich priming was identical, with the exception that the prime of interest was preceded by a presentation of the target stimulus for 40 processing cycles. At the onset of the prime, the letter level activities were reset, in keeping with the letter-reset assumption.

The model was tested on exactly the same stimuli as used in the experiment. The model included a vocabulary of 5,446 eight-letter words. The parameters were similar to those used in previous IA simulations (Davis, 2003; Davis & Lupker, 2006; McClelland & Rumelhart, 1981), but some changes were required to replace the slot-coding scheme of the original model with spatial coding; the full list of parameter settings can be found in Appendix C. Furthermore, the assumptions concerning word node decay were modified, as discussed below.

Results

All words were classified correctly by the model. In the conventional priming simulation, the mean latency for exceeding threshold was 80.0 cycles for targets preceded by control primes and 70.9 cycles for targets preceded by T-All primes. We did not conduct a statistical test of this difference, as this simulation did not include any sources of random noise. However, we note that the magnitude of the predicted priming effect (9.1 cycles) is numerically comparable with the size of the observed (nonsignificant) priming effect (9 ms).[2]

In the sandwich priming simulation, the mean latency for exceeding threshold was 79.1 cycles for targets preceded by control primes and 42.8 cycles for targets preceded by T-All primes. The magnitude of the predicted priming effect (36.3 cycles) was only slightly smaller numerically than the observed priming effect of 40 ms.

Discussion

As anticipated on the basis of Guerrera and Forster's (2008) results, there was no significant priming in Experiment 1a. That is,

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[2] For the parameter values that we use, we typically observe a fairly good correspondence between values in cycles (in the simulations) and in milliseconds (in the data) for our priming effects, both here and in our previous modeling (e.g., Davis & Lupker, 2006; Perry et al., 2008). Whether one gets an approximate millisecond-cycle correspondence depends, of course, upon the scaling constant that is used in the simulations, a parameter that determines the size of the time slices. Thus, the fact that we often observe a one-to-one correspondence is, in essence, no more relevant to the model's viability than if we had typically found, for example, a 10-to-1 correspondence. In general, of course, the most important test of any model is whether there is a good qualitative relationship between the model's predictions and the empirical data.

T-All primes produced very little priming (9 ms) for these targets in a conventional masked priming experiment. In contrast, the sandwich priming technique led to a significant 40-ms priming effect in Experiment 1b. That is, presenting the target itself as an initial prime prior to the same primes used in Experiment 1a allowed the orthographically similar primes to produce a large priming effect.

The results of the simulations showed a pattern that was qualitatively and quantitatively very similar to that observed in Experiments 1a and 1b. The essential absence of priming in Experiment 1a, using the conventional priming technique, and the significant priming effect in Experiment 1b, using the sandwich priming technique, follows directly from our analysis of the interactions within the lexicon. That is, as described above, when conventional priming is used, T-All primes will often partially activate a number of lexical units other than that of the target. The result is an increase in the amount of lexical competition that the target receives in the T-All condition (in comparison with that created by unrelated primes), which can prevent the target node from achieving a positive activity by the time the target itself is presented. As a result, T-All primes tend to confer little or no processing advantage on the target word node, leading to a null priming effect. The sandwich priming technique, involving the initial presentation of the target, is designed to activate the target's lexical unit to a level that should nullify much of the impact of the lexical competitors activated by the prime. As a result, the processing benefit provided (i.e., the priming) by T-All primes should be evident, as was the case in Experiment 1b.

In conclusion, the results of Experiment 1, as well as the simulation results, support the argument that the sandwich priming technique has the potential to provide a clearer view of the impact of orthographic similarity on target activation. In Experiment 2, we sought to apply this technique to another situation in which priming effects are smaller than might be expected on the basis of match values.

Experiment 2

The Limits of Replacement Letter Priming

In a recent review article, Grainger (2008) has made an interesting observation concerning the limits of (conventional) masked form priming:

> One would . . . expect a . . . graded influence of the number of substituted letters on substitution priming. However, the evidence at present suggests that priming effects are practically absent as soon as two letters are substituted compared with an all-different letter baseline (e.g., Schoonbaert & Grainger, 2004). Future research will need to test parametric manipulations of number of substituted letters . . . in more sensitive measurement conditions. (p. 11)

It is indeed somewhat surprising that form priming effects drop off so rapidly as the number of replaced letters increases. As the above passage indicates, it is not necessarily the case that form priming effects are entirely absent once two letters have been replaced, but they are certainly greatly diminished. For example, Schoonbaert and Grainger (2004, Experiment 4) manipulated target length (five or seven letters) and position of replacement (initial, medial, or final) and, hence, tested six separate conditions in which target words were preceded by primes constructed by changing two letters of the target (e.g., *ruefl–RURAL*; *johinal–JOURNAL*). Only one of these conditions showed evidence of significant priming relative to unrelated primes (for the remaining five conditions, the maximum facilitatory priming effect was 3 ms). Perea and Lupker (2004) reported two experiments in which two-letter different primes (e.g., *caviro–CASINO*) were compared with unrelated primes. The first of these experiments showed a nonsignificant 7-ms priming effect, whereas the second experiment showed a significant 18-ms priming effect. To summarize, then, primes in which a single target letter is replaced produce reasonable form priming effects, whereas primes in which two target letters are replaced have most often not produced significant priming, although a very small priming effect may be present (cf. Perea & Lupker, 2003; Peressotti & Grainger, 1999). To foreshadow our results, in Experiment 2, we show that primes in which three or more letters are replaced produce no evidence of form priming in the conventional masking priming situation.

On the surface, this pattern of results, which we shall refer to as the *multiple letter replacement constraint*, poses a problem for all of the current orthographic coding schemes. These schemes predict that orthographic similarity values should decrease approximately linearly as more letters are substituted (at least for the replacement of successive internal letters). Thus, the absence of robust masked form priming effects once two target letters have been replaced appears to raise a theoretical challenge. It is well-established that primes formed by simply deleting two letters of the target (e.g., *grdn–GARDEN*) give rise to robust priming effects (e.g., Peressotti & Grainger, 1999; Schoonbaert & Grainger, 2004). Therefore, the absence of priming in the case of pairs like *gurdin–GARDEN* cannot be attributed simply to the absence of two of the target letters.

It is also difficult to explain this phenomenon as reflecting the direct inhibitory influence of incompatible *letters*, both on theoretical grounds (see Davis, 1999, for a discussion of arguments against letter-word inhibition) and on the basis of the finding that the use of a prime created by the addition of incompatible letters (e.g., *12d34d567*) has a smaller, graded influence on the magnitude of masked priming effects (Welvaert, Farioli, & Grainger, 2008, have reported a cost of around 10 ms per additional letter in the prime).

An alternative and, we would argue, more plausible explanation for the absence of priming from three-letter different primes is that it reflects lexical competitor effects. For example, consider the situation in which a target word like *CAPTURE* is preceded by the three-letter different prime *coshure*. It is possible to examine word-level activity in an IA model with a vocabulary of seven-letter words when the prime *coshure* is presented. The word nodes that still have positive activity levels after 50 cycles (the prime duration used in Davis, 2003, and Davis & Lupker, 2006) are words that differ from *coshure* at two letter positions (e.g., *CONJURE*, *COSTUME*, *POSTURE*, and *COUTURE*). In addition, a large number of words that overlap partly with *coshure* are briefly activated but are then rapidly suppressed. These include the target word *CAPTURE*, as well as words like *GESTURE*, *TORTURE*, *COMPARE*, *CONSUME*, and *CONFUSE*. Thus, despite the fact that the prime *coshure* and the target *CAPTURE* have a reasonably high orthographic similarity score and, hence, *coshure* would be expected to activate the lexical unit for *CAPTURE* to at least some degree very early in processing, the model actually predicts a null priming effect (relative to an unrelated prime).

The extent of lexical competitor effects across various prime-target pairs will clearly vary according to the particular letters that are substituted and the resulting similarity of the prime to other stimuli. Nevertheless, the basic observation here—that replacing target letters has the effect not only of reducing the number of common letters between prime and target but also of increasing the number of competitors that enjoy greater overlap with the prime than the target does—provides a plausible account of the pattern of priming effects observed when letters of the target are replaced.

If the above analysis is correct, replacement letter primes should provide good grounds for testing the utility of the sandwich priming technique. That is, the initial presentation of the target should enable it to overcome lexical competitor effects to a great extent. Thus, one would expect that the initial presentation would allow form priming to be observed from primes differing from the target at more than two letter positions. To probe this effect systematically, in Experiment 2, we parametrically varied the number of letters in seven-letter targets that were replaced in the prime, between one and five. In Experiment 2a, we employed the conventional masked priming methodology. On the basis of previous findings (e.g., Perea & Lupker, 2003, 2004; Peressotti & Grainger, 1999; Schoonbaert & Grainger, 2004), we expected to find robust form priming when the prime and target differed by one letter, some trace of priming when the prime and target differed by two letters, but no priming when more than two letters were replaced. In Experiment 2b, we employed the sandwich masked priming methodology. Our prediction was that this methodology would reduce the influence of target competitors, enabling form priming to be obtained when the prime and target differed by two or more letters.

Experiment 2a

Method

Participants. The participants were 36 undergraduates from Royal Holloway, University of London (Egham, Surrey, England) who received course credit or a small cash payment for their participation. All were native speakers of English who had normal or corrected-to-normal vision.

Stimuli and apparatus. The target stimuli were 60 seven-letter words and 60 orthographically legal seven-letter nonwords (see Appendix B). The mean frequency of the target words was 53.1 per million (CELEX; Baayen, Piepenbrock, & van Rijn, 1993; range = 20–145). The mean neighborhood size (Coltheart et al., 1977) was 0.3 for words and 0.1 for nonwords (range = 0–2 in both cases). Each target was paired with six different primes. These primes were constructed by replacing one, two, three, four, five, or all seven of the target's letters with letters that did not occur elsewhere in the target. All primes except those in the seven-letter replacement condition (the all-letter-different [ALD] condition) maintained the first and last letter of the target. Each participant saw each target only once. To counterbalance the stimuli, we constructed six different versions of the experiment, such that each target was paired with a different prime in each version.

Stimuli were presented on a SyncMaster monitor (Model No. 793DF). Presentation was controlled by an IBM-clone Intel Pentium. Stimuli appeared as black characters on a white background. Responses to stimuli were made by pressing one of two buttons on custom-made button boxes.

Procedure. Participants were run individually or in groups of up to 4. The experiment began with 10 practice trials, after which the participant was allowed to proceed on to the main experiment when he or she was ready. There were three stimulus fields on each trial: (1) a forward mask, consisting of seven number signs (#######) in 20-point Courier New font, presented for 500 ms; (2) a lowercase prime, presented in 12-point Courier New font for 50 ms; and (3) the uppercase target stimulus presented in 20-point Courier New font. The screen location of the prime stimulus was set so that it would be masked by both the forward mask and the target. The target stimulus remained on the screen until the participant responded. In all other respects, the procedure was identical to that in Experiment 1a.

Results

Reaction times longer than 1,500 ms were excluded from the analyses of correct latencies (this criterion affected 4 word trials and 4 nonword trials out of a total of 4,320 trials). Mean latencies and error rates are shown in Table 1.

Latency data. The main effect of prime condition was highly significant in the analysis for word stimuli: $F_1(5, 150) = 3.89$, $MSE = 1{,}103$, $p < .005$; $F_2(5, 270) = 5.08$, $MSE = 1{,}621$, $p < .001$. As can be seen in the left panel of Figure 4, the magnitude

Table 1
Mean Reaction Times and Error Percentages (in Parentheses) by Condition for Experiments 2a (Conventional Priming) and 2b (Sandwich Priming)

	No. of letters replaced					
Target	1	2	3	4	5	ALD
Words						
Expt 2a	496 (2.2)	501 (2.5)	517 (3.3)	514 (4.2)	525 (3.9)	518 (5.0)
Expt 2b	552 (1.9)	576 (2.7)	582 (3.8)	601 (3.8)	602 (6.3)	609 (4.4)
Nonwords						
Expt 2a	575 (2.2)	579 (3.9)	571 (4.4)	575 (2.8)	578 (1.9)	588 (4.2)
Expt 2b	668 (4.8)	665 (5.2)	668 (5.8)	671 (2.7)	671 (1.9)	672 (5.6)

Note. ALD = all letters different; Expt = Experiment.

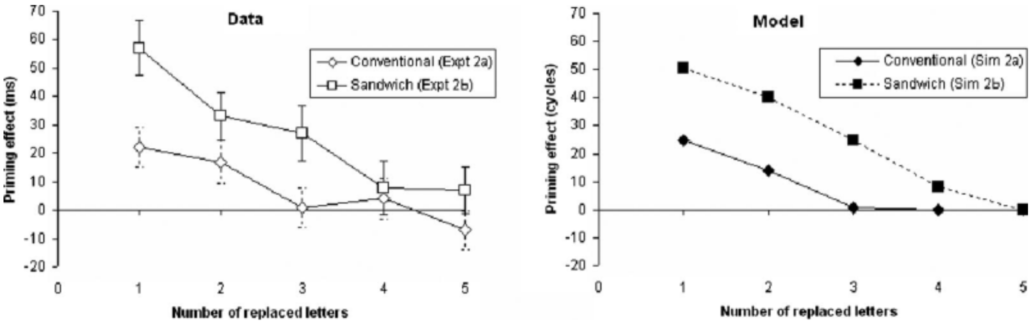

Figure 4. Priming effects in milliseconds in Experiments 2a and 2b (left panel) and in cycles in Simulation 2 (right panel) as a function of number of replaced letters in the prime. Error bars represent standard errors. Expt = Experiment; Sim = Simulation.

of priming (relative to the ALD condition) decreased with the number of replaced letters; the linear trend was significant: $t_1(150) = 2.94$, $p < .005$; $t_2(270) = 3.08$, $p < .005$. Dunnett's test was used to compare each of the first five conditions with the ALD condition. On the basis of this test, differences of 20 ms or more are significant at an alpha level of .05. By this criterion, significant facilitation was observed for primes that differed from the target by one letter, and a nearly significant facilitation effect was found for primes that differed from the target by two letters (this effect would be significant using a one-tailed test). Primes that differed from the target by more than two letters did not show any evidence of priming. This result agrees with the summary of Grainger (2008). Interestingly, primes that differed from targets by five letters (i.e., all interior letters) showed a trend toward inhibitory priming, relative to ALD primes. This result is consistent with the possibility that competitors of the target were activated by the prime, leading to target inhibition. That is, because a prime like *cvxknze* activates the target *CAPTURE* substantially less than it does a competitor of the target like *CAPSIZE*, it is actually associated with slower decision latencies than a completely unrelated prime that activates neither the target nor its competitors.

The main effect of prime condition did not approach significance in the nonword analysis: $F_1(5, 150) = 0.60$, $MSE = 1{,}814$, $p > .05$; $F_2(5, 270) = 0.70$, $MSE = 2{,}523$, $p > .05$.

Error data. The mean error rate was 3.5% for words and 3.2% for nonwords. There was no effect of prime condition on the accuracy of lexical decision responses for either word targets, $F_1(5, 150) = 1.20$, $p > .05$; $F_2(5, 270) = 1.23$, $p > .05$, or nonword targets, $F_1(5, 150) = 1.46$, $p > .05$; $F_2(5, 270) = 1.52$, $p > .05$.

Experiment 2b

Method

Participants. The participants were 48 undergraduates from Royal Holloway, University of London who received course credit for their participation. All were native speakers of English who had normal or corrected-to-normal vision.

Stimuli and apparatus. The stimuli and apparatus were identical to those in Experiment 2a.

Procedure. The procedure was identical to Experiment 2a, except that the four-field sandwich priming technique was used (i.e., the prime of interest was immediately preceded by a prime that was identical to the target). This initial presentation of the target was for 33 ms, and it was presented in Courier 8-point font to minimize visual overlap between the three presented letter strings.

Results

Reaction times longer than 1,500 ms were excluded from the analyses of correct latencies (this criterion affected 9 word trials and 13 nonword trials out of a total of 5,760 trials). Mean latencies and error rates are shown in Table 1.

Latency data. The main effect of prime condition was significant in the analysis for word stimuli: $F_1(5, 210) = 11.98$, $MSE = 1{,}787.68$, $p < .001$; $F_2(5, 270) = 15.91$, $MSE = 2{,}065.45$, $p < .001$. As can be seen in the left panel of Figure 4, the magnitude of priming (relative to the ALD condition) decreased with the number of replaced letters; the linear trend was significant: $t_1(210) = 6.60$, $p < .001$; $t_1(270) = 6.87$, $p < .001$. Dunnett's test was used to compare each of the first five conditions with the ALD condition. On the basis of this test, differences of 23 ms or more are significant at an alpha level of .05. By this criterion, significant facilitation was observed when primes differed from the target by one, two, or three letters but not when primes differed from the target by four or five letters. There was no effect of prime condition for nonword targets: $F_1(5, 210) = 0.08$, $MSE = 2{,}440.79$, $p > .05$; $F_2(5, 270) = 0.28$, $MSE = 3{,}553.89$, $p > .05$.

Error data. The mean error rate was 3.8% for words and 4.3% for nonwords. There was an overall effect of prime condition on the accuracy of responses to word targets that was significant in the subject analysis, $F_1(5, 210) = 4.10$, $MSE = 26.30$, $p < .05$, but did not quite attain significance in the item analysis, $F_2(5, 270) = 2.11$, $MSE = 48.36$, $p > .05$. However, none of the prime conditions differed significantly from the ALD condition. There was also an overall effect of prime condition on the accuracy of responses to nonword targets: $F_1(5, 210) = 3.09$, $MSE = 42.19$, $p < .05$; $F_2(5, 270) = 2.63$, $MSE = 52.47$, $p < .05$. However, the only prime condition that differed significantly from the ALD condition was the five-letter different prime condition (which was associated with fewer errors): $t_1(210) = 2.83$, $p < .05$; $t_2(270) = 2.75$, $p < .05$.

Simulation 2

Method

Procedure. The procedure for running this simulation was identical to that for Simulation 1. The only difference was the vocabulary used to test the model: Instead of the eight-letter word vocabulary, we used a vocabulary of 3,373 seven-letter words. All parameter settings were identical to those of Simulation 1.

Results

All words were classified correctly by the model. The mean latencies (in processing cycles) are shown in the right panel of Figure 4. As can be seen, there was a fairly close match between the predictions of the model and the observed priming effects. In particular, in Simulation 2a (conventional masked priming) the model showed no sign of priming when three or more letters were replaced. By contrast, in Simulation 2b (sandwich priming) the model continued to show strong priming when three letters were replaced, and it even showed a small priming effect when four letters were replaced (of equivalent magnitude to that observed in the data).

Discussion

The results of Experiment 2 are quite straightforward. In Experiment 2a, when the conventional three-field masked priming methodology was used, a robust form priming effect was observed when the prime differed from the target by one letter, a marginal priming effect was found when the prime differed from the target by two letters, and no priming was observed when the difference was three or more letters. This outcome is consistent with Grainger's (2008) summary of the masked form priming literature. In Experiment 2b, where we used exactly the same primes and targets but switched to the four-field sandwich masked priming methodology, form priming was observed when the prime differed from the target by one, two, or three letters. Critically, the sandwich priming methodology supported a significant priming effect (of 27 ms) for three-letter different primes, primes that produced no evidence of priming (a difference of 1 ms) when the conventional methodology was used. Furthermore, for the two prime conditions that showed evidence of priming with both methodologies, the size of the effect was 2–3 times greater when using sandwich priming.

These results strongly support the claim that the sandwich priming methodology provides a more sensitive index of prime-target similarity than the conventional methodology. As Grainger (2008) noted, it is somewhat surprising that form priming effects are so sensitive to the introduction of two or more letter replacements. The sandwich priming technique reveals that, in fact, priming can be observed for these primes. Why should the same prime produce a priming effect in one case but not the other? Our interpretation is that the absence of priming with the conventional methodology reflects the fact that these primes tend to activate lexical competitors of the target at least as strongly as they activate the target itself. The resulting lexical competition effectively eliminates facilitation effects. By contrast, when the sandwich priming methodology is used, the initial preview of the target gives it a head start over its competitors, which greatly reduces these lexical competitor effects. Consequently, the form overlap between the prime and target is sufficient to drive the activity of the target to a high enough level that can lead to the observation of form priming effects.

General Discussion

The present data demonstrate fairly conclusively that the sandwich priming technique can produce priming due to orthographic similarity in situations in which the conventional masked priming paradigm cannot. The interpretation we have provided is that the initial presentation of the target allows it to suppress target competitors. As a result, the priming effect that does emerge is essentially a function of only the degree to which the orthographically similar prime activates the target's lexical unit. That is, the prime drives the target's activation to a level appropriate to the degree of orthographic similarity between prime and target. This resulting boost in activation allows the lexical unit for the target to reach threshold more rapidly when the target itself is presented.

Simulating Sandwich Priming

The evidence from the simulations provides good support for our account of how sandwich priming works. It should be noted that we found that it was necessary to modify one aspect of the model to satisfactorily capture the boost to priming provided by the sandwich priming technique. In the original IA model, word nodes decay exponentially toward their resting activity level (i.e., the rate of decay is faster for more strongly activated nodes). This assumption turns out to be somewhat problematic for simulating sandwich priming, because it implies that much of the boost given to the target by the initial prime has dissipated by the time the target appears.

We were able to achieve a much better fit to the data by replacing exponential decay with a linear decay term. More precisely, we assumed that the decay rate of a given word node depends not on its current activity but on its match with the current input (full details of the revised activity equation are presented in Appendix C). It follows that there is no decay in activity for word nodes that perfectly match the present input but that activity decays relatively rapidly for word nodes that are not at all similar to the current input. This modification enables the model to provide a good account of sandwich priming effects, but it does not disrupt the model's ability to simulate effects from conventional masked priming, such as those reported by Davis and Lupker (2006).

Whether our solution here is optimal, the more important point to recognize is that the relatively large magnitude of empirically observed sandwich priming effects poses a problem for the standard assumptions of the IA model concerning activation dynamics, because these assumptions suggest that the activity of the target word node should dissipate fairly quickly after the offset of the initial prime. Our response to this discrepancy between theory and data was to modify the usual assumptions about how the activity of word nodes decays. Although it is quite possible that these priming effects could be modeled in some other way, what does seem clear is that sandwich priming phenomena do have implications for the nature of activation dynamics at the lexical level and not just for the specific issue of orthographic coding.

What Do T-All Primes Tell Us About Orthographic Coding?

According to Guerrera and Forster (2008), their lack of a priming effect for T-All primes presents a serious problem for current models of letter position coding, all of which (they have claimed) predict that T-All primes will be effective primes. They concluded that, "While the word recognition system can handle an extreme degree of transposition quite well, it requires at least some anchor points in order to contact the target lexical entry" (p. 137).

The results of Experiment 1a confirm those reported by Guerrera and Forster (2008). However, we draw a very different conclusion. As Simulation 1a shows, it is not the case that a model based on spatial coding predicts strong priming from T-All primes. Furthermore, the results of Experiment 1b and Simulation 1b show that T-All primes can give rise to large priming effects when a more sensitive priming technique is employed. Contrary to Guerrera and Forster's account, then, the results presented here suggest that T-All primes provide strong support for newer models of letter position coding. Anchor points are not required; indeed, presumably such an approach would make it difficult to explain the priming that we observed for T-All primes in Experiment 1b.

Although our simulations used the spatial coding scheme that is part of the SOLAR model, we expect that similar results would be obtained if an open-bigram coding scheme were used or, indeed, if the match values computed by Gómez et al.'s (2008) overlap model were input to a model of visual word identification. The great promise of sandwich priming, however, is that it may offer a means of adjudicating between spatial coding: SOLAR (Davis, 1999, 2006), the overlap model (Gómez et al., 2008), discrete open-bigram coding (Schoonbaert & Grainger, 2004), overlap open-bigram coding (Grainger et al., 2006), and the open-bigram coding scheme proposed in the SERIOL model (Whitney, 2001). That is, although, in general, the match values produced by the different models for any set of primes and targets tend to be quite similar, there are a number of situations in which such is not the case. This application is the subject of ongoing research.

Other Situations to Which Sandwich Priming Might Be Applied

According to the argument we have made, any situation in which facilitatory form priming is prevented because of lexical competition effects is one in which sandwich priming has the potential to produce priming effects. It is therefore interesting to consider other situations to which sandwich priming might usefully be applied.

As already noted, many experiments (including Experiment 2a) have shown that nonwords that are orthographic neighbors of a target word can function as very effective masked form primes (e.g., Davis & Bowers, 2006; Davis & Lupker, 2006; Ferrand & Grainger, 1992; Forster et al., 1987). However, one situation in which form priming appears to break down occurs when the prime and target share a lexical neighbor (e.g., van Heuven, Dijkstra, Grainger, & Schriefers, 2001). For example, in the case of a prime-target pair like *cune–CUBE*, the prime and target share the neighbors *CURE* and *CUTE*; by contrast, the prime *cobe* does not share any neighbors with *CUBE*. Thus, although *cobe* and *cune* are equally orthographically similar to *CUBE* (according to both open-bigram and spatial coding models), *cobe* is a more effective form prime for this target than is *cune*. Simulations show that competitive network models, like IA and SOLAR, correctly predict such shared neighbor effects, both for word and nonword neighbor primes (e.g., Davis, 2003; Davis & Lupker, 2006; van Heuven et al., 2001).

An analogous effect is the ambiguity effect observed in partial word priming studies (e.g., Hinton, Liversedge, & Underwood, 1998; Perry, Lupker, & Davis, 2008), in which one letter of the target is replaced by a nonalphabetic character, such as # or % (e.g., *cu#e–CUBE*). When this replacement results in a prime that is consistent with two or more words (e.g., *cu#e* is consistent with *CUBE*, *CURE*, and *CUTE*), priming effects are smaller than when the prime is consistent with only the target (e.g., *c#be–CUBE*). According to our analysis, the reduction in the size of the priming effects due to either ambiguity or having shared neighbors should essentially disappear when sandwich priming is used.

Another situation in which priming might be expected to occur, but is often not found, arises when the target has many orthographic neighbors. This *neighborhood density constraint* on form priming was originally reported by Forster et al. (1987) and has subsequently been replicated by other researchers (e.g., Perea & Rosa, 2000). One possible explanation of this phenomenon is that it reflects lexical competition. That is, targets with many neighbors also typically have primes with many neighbors and, hence, there are also many shared neighbors. As a result, the opportunity for lexical competition and, hence, inhibition to play a major role increases substantially (see Nakayama, Sears, & Lupker, 2008, for a demonstration of a situation in which the size of the prime neighborhood is a key factor in determining the pattern of priming effects). This explanation would gain weight if sandwich priming was found to eliminate the density constraint (i.e., form priming was observed for large neighborhood targets that do not exhibit priming with the conventional technique). In general, of course, if priming is observed when sandwich priming is employed but not when conventional priming is employed, it may not necessarily follow that the absence of priming in the latter case is due to lexical competition effects. Nevertheless, in such a situation a lexical competition interpretation is at least a plausible one that is worthy of further exploration.

Potential Alternative Accounts

Strategic Use of the First Prime—Whittlesea and Jacoby (1990)

We are not the first to use an experimental paradigm in which the target is presented as an initial prime that is then followed by the prime of interest. In Whittlesea and Jacoby's (1990) experiments, the stimulus sequence consisted of the target (presented for 60 ms) followed by a second prime (masking the initial prime) that was presented for 150 ms, followed by the visible presentation of the target.[3] Their key finding was that when the second prime was associated with the target (e.g., *plant–GREEN*), larger priming effects emerged if that prime was presented in mixed case (i.e.,

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[3] We thank Mike Masson for drawing our attention to the article by Whittlesea and Jacoby (1990).

pLaNt). The fact that Whittlesea and Jacoby's second prime was unmasked and the fact that Whittlesea and Jacoby were investigating associative rather than form priming mean, of course, that their results and ours are not directly comparable. Nonetheless, one can ask whether their theoretical conclusions might be relevant to our procedure.

The account that Whittlesea and Jacoby (1990) gave was that, in some circumstances—for example when the second prime is related to the initial prime but is hard to read (e.g., *pLaNt*)—the initial prime "participates in identification of a succeeding word (the interpolated word)" (p. 549). When the initial prime does such a thing, then the initial prime "is readily available to assist identification of its repetition" (p. 549), that is, the target. In essence, when this happens, the trial becomes a repetition priming trial. In contrast, if the second prime is related to the initial prime but is easy to read, the initial prime is not recruited to help identify it and, hence, the trial is merely an associative priming trial.

One could apply this idea to the present circumstances by arguing that either (a) the initial prime was recruited in an attempt to identify the second prime only when they were sufficiently orthographically similar (the T-All primes in Experiment 1b and the one-, two-, and three-letter different primes in Experiment 2b) or (b) the initial prime was recruited in an attempt to identify the second primes on all trials but such action was unsuccessful on unrelated trials and, hence, the initial prime was disregarded. In either case, the result would be to turn the T-All prime trials in Experiment 1b and the one-, two-, and three-letter different prime trials in Experiment 2b into repetition priming trials at least some of the time, producing a large priming effect. (Presumably, the priming in the one- and two-letter different trials in Experiment 2a would need to be explained in a different fashion.)

As noted, an important difference between Whittlesea and Jacoby's (1990) experiments and ours is the fact that the second prime in their experiments was available to consciousness (i.e., being presented for 150 ms), whereas neither of our primes would have been available to consciousness. A second difference is that the second prime was a word in their experiments and a nonword in ours. Hence, it is unclear that there would have been any motivation for participants to even try to identify the second prime in our experiments even if they had the ability to do so (i.e., to identify a prime that was presented for 50 or 55 ms and then masked by the target). Nonetheless, if one was to assume that participants in our experiments were actually attempting to identify the second prime and, as a result, causing the initial prime to remain active in certain circumstances, an account like Whittlesea and Jacoby's could potentially explain our data, at least the data from Experiments 1b and 2b.

What also needs to be noted, however, is that regardless of whether one adopts an activation account, as we have done, or a retrieval account, like that proposed by Whittlesea and Jacoby (1990), the merits of the sandwich priming paradigm are clear. For there to be priming, one needs to have primes that are related (in our case, orthographically similar) to the target. Thus, the sandwich priming paradigm provides an effective means for determining whether two letter strings are orthographically similar to one another, hence, making it a useful tool for examining predictions made by the various models of orthographic coding.

Does the Second Prime Block Priming From the First? —Forster (2009)

Recently, Forster (2009) has also used a masked priming paradigm quite similar to our sandwich priming procedure. Specifically, in one version of this paradigm, there are also two masked primes prior to the presentation of the target. The question Forster asked, however, does not focus on the second prime but rather on the first. In particular, the question being asked was how well does the priming provided by the first prime survive a second prime that is unrelated to either the first prime or the target? Nonetheless, Forster's data and analysis are potentially applicable here.

What Forster (2009) showed is that when the target word is presented as the first prime with an unrelated word as the second (e.g., *computer–identify–COMPUTER*), there was priming in comparison with when the first prime was also an unrelated word (e.g., *airplane–identify–COMPUTER*). However, that priming effect was smaller than when the initial primes were reversed (e.g., *identify–computer–COMPUTER*). There was a similar phenomenon when the initial prime was a form related prime. That is, the priming for *camputer–identify–COMPUTER* was significantly less than for *identify–camputer–COMPUTER*. In fact, the priming for *camputer–identify–COMPUTER* was reduced to 0.

On the basis of these results, Forster (2009) suggested that what the second prime does is to block form priming. That is, it kills any form priming from either *camputer* or *computer* while leaving any semantic priming from the initial prime intact. Hence, *computer–identify–COMPUTER* still produces (semantic) priming. In addition, the first prime is assumed to have no impact on the priming provided by the second prime. An obvious question is whether this type of analysis might provide an alternative explanation of the present data.

Certainly, one could argue that the initial primes (i.e., the targets themselves) in the present sandwich priming experiments do provide some semantic priming. However, given that, in the sandwich priming paradigm, the target is the initial prime on both related and unrelated trials, any impact of semantic priming would be equivalent on related and unrelated trials. Similarly, regardless of the impact that the second prime has on the form priming from the first prime, that form priming from the initial prime would be equivalent on related and unrelated trials. Therefore, according to Forster's (2009) account, the differences observed in Experiments 1b and 2b could only have been due to the activity of the second primes. As the results of Experiments 1a and 2a show, however, many of those primes, by themselves, do not produce priming. Hence, there would be no reason for them to produce priming in Experiments 1b and 2b. In essence, then, Forster's analysis would not provide a means of explaining the present results. Rather, to explain those results, it appears that one would need to propose some sort of interaction between the first and second primes, a mechanism that is not contained in Forster's account.

The mechanism of interaction that we have suggested (i.e., that the initial prime severely dampens the lexical competition, allowing the second prime to act essentially on the target alone) is not, of course, the only mechanism that one could propose here (e.g., see the above discussion of Whittlesea and Jacoby, 1990). One could, for example, argue that what the second prime does is merely to interfere with the activation created by the initial prime (i.e., it deactivates the target). More dissimilar second primes produce more rapid deactivation. Whether such a proposal would actually be functionally different from the present proposal, while being consistent with what is known about inhibitory processes within the lexicon (e.g., Davis & Lupker, 2006: Nakayama et al., 2008; Segui & Grainger, 1990), is a question for future research.

Which Variant of Masked Form Priming Should Researchers Use?

There are now several variations of the masked form priming procedure available to researchers. In addition to the three-field technique that we have referred to as *conventional* masked form priming (Forster & Davis, 1984), there is also a two-field technique developed by Grainger et al. (2006) and the earlier four-field technique developed by Evett and Humphreys (1981), in which the participant's task is perceptual identification. Each of these different procedures has its own respective merits. For example, Grainger et al.'s two-field procedure, in which the prime is presented (with no forward mask) for only 33 ms, appears to be a particularly suitable technique if it is important to try to restrict (as far as possible) phonological processing of the prime. Evett and Humphreys's procedure is useful as a means of examining data-limited identification, and it avoids some of the issues that are associated with the lexical decision task (although see Davis and Forster, 1994, for a caveat). Thus, researchers may be best advised to use different variants of the masked priming procedure according to the particular goals of their research. However, for researchers seeking to investigate form priming in cases in which the prime and target are not highly similar, or are likely to be affected by lexical competitors, the sandwich priming technique introduced here holds great promise. Ultimately, our hope is that this technique will provide a critical tool in the ongoing quest to crack the code underlying visual word identification.

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Appendix A

Stimuli in Experiment 1

T-All prime	Unrelated	Target
	Word targets	
baonmrla	tonsular	ABNORMAL
hsroateg	honsumer	SHORTAGE
riiraget	barnyerd	IRRIGATE
cadameai	comferts	ACADEMIA
ofnuatni	casanoma	FOUNTAIN
cauotsci	elormity	ACOUSTIC
iltsnere	fleaworb	LISTENER
velaauet	pastrate	EVALUATE
ejporayd	pladness	JEOPARDY
avacitno	etorcism	VACATION
abknurtp	drambles	BANKRUPT
acpmiang	havities	CAMPAIGN
ujcnitno	therkins	JUNCTION
rfsemhna	enhancos	FRESHMAN
acrraieg	drescent	CARRIAGE
uhimilyt	miocesan	HUMILITY
rpporeyt	sordeaux	PROPERTY
olacitno	tarnival	LOCATION
lecertno	heftness	ELECTRON
ocmmreec	bruitful	COMMERCE
lctoihgn	fomeback	CLOTHING
oratitno	sonfines	ROTATION
yhnpsosi	airdrobs	HYPNOSIS
anivaget	draftars	NAVIGATE
baurtpyl	apethyst	ABRUPTLY
atgnbiel	dustomer	TANGIBLE
nietvrla	rotanist	INTERVAL
abhclero	blippant	BACHELOR
opssbiel	alterial	POSSIBLE
psiltnre	foremaws	SPLINTER
rpaehcre	elpousal	PREACHER
emidatet	aptivist	MEDITATE
idtsirtc	dialyzod	DISTRICT
ydanimet	cholerac	DYNAMITE
niefirro	baptosts	INFERIOR
vecaauet	fourepes	EVACUATE
iacrartf	fesserts	AIRCRAFT
rtaeuser	dislokes	TREASURE
lfxebiel	campmane	FLEXIBLE
edisngre	confrent	DESIGNER
awtsfelu	farments	WASTEFUL
poopiset	garousel	OPPOSITE
rfgaartn	ahortion	FRAGRANT
baosulet	flagbole	ABSOLUTE
efiminen	cervicad	FEMININE
pscaoisu	epissary	SPACIOUS
ivogorsu	grakeman	VIGOROUS
octnartc	thapters	CONTRACT
imtserss	ethibits	MISTRESS
neevolep	luttings	ENVELOPE
erilbael	clumsily	RELIABLE
htoeolyg	clowback	THEOLOGY
nievtnro	esgapist	INVENTOR
acapicyt	deasible	CAPACITY
ocpmsore	attiques	COMPOSER
awrrnayt	hamisole	WARRANTY

(Appendixes continue)

Appendix A (*continued*)

T-All prime	Unrelated	Target
darobael	poatherd	ADORABLE
etrrbiel	abaconda	TERRIBLE
acintsre	elcumber	CANISTER
uaittsci	honcerto	AUTISTIC
ahdnmyna	pautions	HANDYMAN
anitnola	confatti	NATIONAL
cauqiatn	trightly	ACQUAINT
caucaryc	crowbaut	ACCURACY
xelpciti	anderseb	EXPLICIT
uqdaartn	gynamics	QUADRANT
imintsre	erulsify	MINISTER
batsartc	efcesses	ABSTRACT
ivllgare	beardowg	VILLAGER
adguthre	mapsules	DAUGHTER
poitimms	glinches	OPTIMISM
awctmhna	dovernor	WATCHMAN
algnaueg	anorable	LANGUAGE
ebevareg	clipters	BEVERAGE
cadameci	gupboard	ACADEMIC
iwhtrdwa	fraduate	WITHDRAW
roginila	drafteng	ORIGINAL
rgcafelu	pontrast	GRACEFUL
asinatyr	gommerce	SANITARY
apitneec	calabush	PATIENCE
rpcaitec	taiquiri	PRACTICE
liulisno	ploseout	ILLUSION
ibtrdhya	loctoral	BIRTHDAY
ovclnaci	dobertan	VOLCANIC
awdnrere	pidelity	WANDERER
omnuatni	canodize	MOUNTAIN
isedawkl	pylinder	SIDEWALK
aceldnra	branthes	CALENDAR
saesbmel	frayfish	ASSEMBLE
opilitsc	tocility	POLITICS
ovacilez	pairness	VOCALIZE
ercaitno	emfeeble	REACTION
daehisev	gertride	ADHESIVE
afimilra	guckshot	FAMILIAR
osilidyf	elenenth	SOLIDIFY
dineityf	pandages	IDENTIFY
	Nonword targets	
ehenarsl	cataligs	HENERALS
ohmmnaod	preakage	HOMMANDO
anerewll	anatomip	NAREWELL
xelpdare	phloride	EXPLADER
baebulai	agrocity	ABBELUIA
taetdnxi	averrant	ATTENDIX
raaksngi	mossamer	ARKANSIG
abfrilem	tascists	BARFLIME
abtrelhc	tritical	BARTLECH
odnuitna	slutches	DOUNTIAN
maomatet	larnacle	AMMOTATE
rtooimyl	hatholic	TROOMILY
rbaowdbi	plounder	BROADWIB
rdiaamtn	poubloon	DRAIMANT
rbwoonms	kyclical	BROWNOSM
cspaihet	nootnote	SCAPHITE
ubhcnafu	poalesce	BUCHANUF
ubadupgs	elcircle	BUDAPUSG
ebufbbel	exorfist	BEFUBBLE
daadhcse	noldfish	ADDACHES
faeferhc	sinomial	AFFERECH
emicnayc	easenent	MECIANCY
saotacet	epigrach	ASTOCATE
daodagtn	conniter	ADDOGANT

Appendix A (*continued*)

T-All prime	Unrelated	Target
ubsrtinu	eannings	BURSITUN
marmaohc	bullrint	AMMROACH
hsgaartn	explacit	SHAGRANT
ebeviled	forwargs	BEVELIDE
pauparet	fruision	APPURATE
ogpmlise	hettings	GOMPILES
dardvose	slincher	ADDROVES
balbiasm	giabetic	ABBLAIMS
raerogyr	biscover	ARREGORY
gaegwyya	tranules	AGGEYWAY
taetgrne	gasebook	ATTERGEN
masuteys	aiplines	AMUSETSY
rdnaekst	cootsore	DRANKETS
raaiinep	envisape	ARIANIPE
htsoasyr	kraftees	THOSSARY
rgnaskpe	ainborne	GRANKSEP
naanertn	auracity	ANNARENT
hsnalura	sidactic	SHANULAR
rtnaedsr	caboofle	TRANDERS
acolewsr	dellular	CALOWERS
baubtsmo	argumelt	ABBUSTOM
raaianks	amateuls	ARIANASK
paoharts	epeglass	APHORAST
daodaled	slatfoot	ADDOLADE
pscaoktu	fartoons	SPACKOUT
tautisev	elpedite	ATTUSIVE
rdsaissc	franklon	DRASSICS
raeminto	rabinets	ARMENIOT
taetssro	althouch	ATTESSOR
gaigavsl	galaxoes	AGGIVALS
hcruitms	choctows	CHURTISM
lailitev	ascrives	ALLITIVE
gauglayl	phoirboy	AGGUALLY
onmrsats	blowfash	NORMASST
paapkcre	delerity	APPACKER
psdaeitn	communos	SPADIENT
daidinyt	daffodol	ADDINITY
naenbmel	seginner	ANNEMBLE
baubisno	hollages	ABBUSION
farfeiev	lactions	AFFRIEVE
agsuispo	edertion	GAUSSIOP
rpteehnr	fontract	PRETHERN
paopnrye	antedape	APPORNEY
lpeefrlu	abywhere	PLEERFUL
lssemhne	lathroom	SLESHMEN
gargiaes	disfavob	AGGRAISE
oftreitp	apopleky	FORTIEPT
gaaglust	curtnass	AGGAULTS
onwgehll	abandant	NOGWHELL
olroamli	enforcas	LOORMAIL
acnrfeei	apheists	CARNEFIE
laajectn	defereft	ALJACENT
rccookyr	nockpits	CROCKORY
edastrre	accestor	DESARTER
ifgaarsm	guoyancy	FIAGRAMS
rbsaltse	biweesly	BRASTLES
gaurtpyl	dronchus	AGRUPTLY
lftaehka	cirearms	FLATHEAK
iddsiasl	emassion	DISDAILS
ogmrlusa	pivision	GORMULAS
ocagtnyl	linishes	COGANTLY
rbtihcsu	desalate	BRITCHUS

(*Appendixes continue*)

Appendix A (*continued*)

T-All prime	Unrelated	Target
uaoprcta	soalhole	AUPOCRAT
ontoohdl	ebbitter	NOOTHOLD
apatilms	applauso	PATALISM
aberssse	vaylight	BARESSES
iphsacek	fluidily	PISHCAKE
xemelpta	lormulae	EXEMPLAT
ueeginsf	panknote	EUGENIFS
teihicks	nastards	ETHICISK
esrgdueg	hiplomat	SEGRUDGE
idgnedgn	danquets	DINGDENG

Note. Stimuli in Experiment 1 were taken from Guerrera and Forster (2008).

Appendix B

Stimuli in Experiment 2

Target	RL1	RL2	RL3	RL4	RL5	ALD
Words						
CENTRAL	czntral	czwtral	czwkral	czwkmal	czwkmsl	vzwkmsb
QUALITY	qvality	qvslity	qvsfity	qvsfmty	qvsfmky	gvsfmkj
INCLUDE	imclude	imzlude	imztude	imztsde	imztshe	wmztshw
TYPICAL	tjpical	tjqical	tjqvcal	tjqvral	tjqvrsl	hjqvrsd
PROTEIN	pvotein	pvmtein	pvmfein	pvmfsin	pvmfszn	qvmfszc
WORSHIP	wvrship	wvnship	wvnchip	wvnclip	wvnclzp	xvnclzq
TROUBLE	tzouble	tzvuble	tzvxble	tzvxfle	tzvxfhe	dzvxfhs
HUSBAND	hvsband	hvxband	hvxkand	hvxkwnd	hvxkwmd	lvxkwml
CHAPTER	cdapter	cdnpter	cdnqter	cdnqfer	cdnqfmr	wdnqfmz
PROVIDE	psovide	psnvide	psnmide	psnmzde	psnmzte	ysnmztx
KITCHEN	krtchen	krdchen	krdxhen	krdxlen	krdxlsn	frdxlsw
FOREIGN	fwreign	fwzeign	fwzvign	fwzvmgn	fwzvmqn	dwzvmqc
PICTURE	pvcture	pvnture	pvnkure	pvnkwre	pvnkwze	qvnkwzs
PRODUCE	pwoduce	pwxduce	pwxluce	pwxlsce	pwxlsve	jwxlsvn
SURFACE	swrface	swmface	swmhace	swmhxce	swmhxze	nwmhxzn
MACHINE	mvchine	mvshine	mvsdine	mvsdxne	mvsdxre	wvsdxrw
MEDICAL	mwdical	mwtical	mwtvcal	mwtvxal	mwtvxnl	rwtvxnf
VARIETY	vsriety	vsziety	vszmety	vszmwty	vszmwky	nszmwkg
POVERTY	pxverty	pxwerty	pxwzrty	pxwznty	pxwznhy	qxwznhg
FASHION	fmshion	fmvhion	fmvkion	fmvkcon	fmvkcxn	bmvkcxw
CAREFUL	cvreful	cvmeful	cvmsful	cvmsdul	cvmsdxl	wvmsdxk
HOLIDAY	hzliday	hztiday	hztrday	hztrkay	hztrkny	bztrknp
PROJECT	pvoject	pvnject	pvnqect	pvnqsct	pvnqsmt	gvnqsmf
JOURNEY	jvurney	jvxrney	jvxzney	jvxzmey	jvxzmsy	pvxzmsg
JUSTICE	jnstice	jnrtice	jnrdice	jnrdvce	jnrdvxe	gnrdvxw
PLASTIC	phastic	phwstic	phwntic	phwndic	phwndvc	yhwndvr
PROMISE	pxomise	pxwmise	pxwvise	pxwvcse	pxwvcze	jxwvczn
VICTORY	vwctory	vwstory	vwskory	vwskxry	vwskxny	mwskxnj
DESTROY	dvstroy	dvctroy	dvckroy	dvckmoy	dvckmxy	fvckmxp
STOMACH	sdomach	sdzmach	sdzrach	sdzrwch	sdzrwnh	vdzrwnk
CABINET	csbinet	cslinet	cslwnet	cslwvet	cslwvxt	rslwvxk
DISPLAY	dmsplay	dmvplay	dmvglay	dmvgfay	dmvgfxy	hmvgfxj
ARTICLE	axticle	axbicle	axbvcle	axbvwle	axbvwhe	nxbvwhm
PRODUCT	pxoduct	pxvduct	pxvkuct	pxvkwct	pxvkwzt	qxvkwzl
IMPROVE	icprove	icjrove	icjwove	icjwxve	icjwxze	scjwxzs
FACTORY	fzctory	fzwtory	fzwdory	fzwdsry	fzwdsny	lzwdsnj
ROUTINE	rxutine	rxwtine	rxwdine	rxwdzne	rxwdzse	vxwdzsm
VERSION	vzrsion	vzcsion	vzcmion	vzcmwon	vzcmwzn	xzcmwzx
COUNTER	cvunter	cvxnter	cvxmter	cvxmker	cvxmkzr	svxmkzs
COURAGE	cnurage	cnwrage	cnwvage	cnwvmge	cnwvmqe	xnwvmqs
FORTUNE	fsrtune	fsmtune	fsmdune	fsmdcne	fsmdcwe	hsmdcwv

Appendix B (*continued*)

Target	RL1	RL2	RL3	RL4	RL5	ALD
KINGDOM	kvngdom	kvrgdom	kvrpdom	kvrphom	kvrphxm	tvrphxw
UNIFORM	uviform	uvwform	uvwhorm	uvwhxrm	uvwhxsm	cvwhxsz
TRIUMPH	tciumph	tcvumph	tcvsmph	tcvswph	tcvswyh	bcvswyl
DELIGHT	dslight	dsfight	dsfxght	dsfxyht	dsfxybt	ksfxybk
CLIMATE	cbimate	cbwmate	cbwvate	cbwvste	cbwvsfe	nbwvsfn
HOSTILE	hzstile	hzntile	hznkile	hznkvle	hznkvbe	dznkvbw
SOLDIER	sxldier	sxtdier	sxtkier	sxtkver	sxtkvwr	nxtkvwc
MUSICAL	mxsical	mxvical	mxvncal	mxvnzal	mxvnzwl	rxvnzwk
SERVANT	scrvant	scmvant	scmzant	scmzwnt	scmzwct	xcmzwcd
FORMULA	fnrmula	fnvmula	fnvwula	fnvwzla	fnvwzda	knvwzds
NETWORK	nxtwork	nxhwork	nxhzork	nxhzsrk	nxhzsvk	mxhzsvf
PAYMENT	pvyment	pvqment	pvqrent	pvqrwnt	pvqrwzt	gvqrwzf
RESPOND	rcspond	rcwpond	rcwjond	rcwjznd	rcwjzxd	vcwjzxh
FACULTY	fwculty	fwxulty	fwxslty	fwxshty	fwxshky	bwxshkp
FUNERAL	fxneral	fxveral	fxvzral	fxvzsal	fxvzscl	kxvzsct
UPRIGHT	ujright	ujcight	ujcvght	ujcvyht	ujcvyft	xjcvyfk
FORGIVE	fxrgive	fxsgive	fxspive	fxspmve	fxspmce	txspmcw
COSTUME	cvstume	cvxtume	cvxkume	cvxknme	cvxknze	wvxknzw
STORAGE	Shorage	shwrage	shwcage	shwcvge	shwcvye	xhwcvyn
			Nonwords			
TROBIDE	twobide	twmbide	twmhide	twmhzde	twmhzfe	lwmhzfx
VIDILAR	vsdilar	vshilar	vshzlar	vshztar	vshztmr	nshztmx
LETCHEN	lstchen	lsdchen	lsdwhen	lsdwfen	lsdwfxn	ksdwfxr
DAPIMAL	dzpimal	dzyimal	dzynmal	dzynxal	dzynxsl	hzynxsf
SCRALGE	svralge	svnalge	svnzlge	svnzhge	svnzhje	wvnzhjm
DORPLEX	dwrplex	dwmplex	dwmjlex	dwmjbex	dwmjbcx	fwmjbcn
DIFTURE	dsfture	dskture	dskbure	dskbwre	dskbwne	hskbwnz
WURBACE	wzrbace	wzvbace	wzvhace	wzvhnce	wzvhnme	xzvhnmx
OVELAGE	onelage	onclage	oncfage	oncfwge	oncfwje	mncfwjz
POURCIL	psurcil	pszrcil	pszmcil	pszmwil	pszmwvl	gszmwvd
BILERCE	bslerce	bsderce	bsdwrce	bsdwxce	bsdwxne	hsdwxnv
SLUVENT	sbuvent	sbrvent	sbrxent	sbrxznt	sbrxzmt	wbrxzmk
FURBOSE	fwrbose	fwmbose	fwmhose	fwmhcse	fwmhcve	lwmhcvx
BEFERCE	bvferce	bvkerce	bvkxrce	bvkxzce	bvkxzne	dvkxzns
KELEFIT	kslefit	ksbefit	ksbxfit	ksbxhit	ksbxhrt	dsbxhrd
AXPRAIN	asprain	asyrain	asyzain	asyzwin	asyzwmn	csyzwmc
TEPULAR	txpular	txjular	txjmlar	txjmhar	txjmhwr	fxjmhws
STOROMY	sboromy	sbxromy	sbxvomy	sbxvnmy	sbxvncy	wbxvncp
DEANITY	dxanity	dxvnity	dxvsity	dxvswty	dxvswhy	fxvswhg
FOLANCE	frlance	frtance	frtvnce	frtvsce	frtvswe	drtvswx
BEDITAL	bxdital	bxfital	bxfstal	bxfshal	bxfshzl	kxfshzk
SONFACT	swnfact	swzfact	swzhact	swzhmct	swzhmvt	xwzhmvb
MEVEROP	mzverop	mzwerop	mzwsrop	mzwscop	mzwscxp	nzwscxy
DERFELT	dsrfelt	dszfelt	dszkelt	dszkclt	dszkcbt	hszkcbh
AMAGOUR	avagour	avcgour	avcqour	avcqzur	avcqzxr	svcqzxw
BOLEFOM	bslefom	bshefom	bshvfom	bshvtom	bshvtwm	dshvtwc
CALPETE	cmlpete	cmfpete	cmfqete	cmfqste	cmfqshe	wmfqshx
CHONITY	cfonity	cfrnity	cfrwity	cfrwsty	cfrwsky	xfrwskp
CODSELT	cvdselt	cvkselt	cvkzelt	cvkzrlt	cvkzrht	wvkzrhb
ELKEROR	etkeror	etderor	etdwror	etdwxor	etdwxmr	stdwxmv
FILPION	fmlpion	fmdpion	fmdqion	fmdqvon	fmdqvrn	hmdqvrw
HALBONY	hvlbony	hvfbony	hvftony	hvftrny	hvftrzy	dvftrzj
IMBELSE	iwbelse	iwtelse	iwtzlse	iwtzdse	iwtzdxe	cwtzdxn
LIDANCE	lmdance	lmfance	lmfwnce	lmfwrce	lmfwrxe	hmfwrxs
MAFSTER	mvfster	mvdster	mvdcter	mvdcker	mvdckzr	wvdckzn
NERVRAL	nxrvral	nxzvral	nxzmral	nxzmsal	nxzmscl	wxzmscf
PADEFIC	pxdefic	pxkefic	pxkwfic	pxkwlic	pxkwlrc	jxkwlrs
PEVULTY	pzvulty	pzculty	pzcxlty	pzcxbty	pzcxbfy	jzcxbfj
PRELACY	pselacy	pswlacy	pswfacy	pswfzcy	pswfzvy	gswfzvj
REDIVAL	rcdival	rchival	rchwval	rchwnal	rchwnsl	xchwnsb
SPORVET	syorvet	sywrvet	sywzvet	sywzcet	sywzcnt	xywzcnh

(*Appendixes continue*)

Appendix B (*continued*)

Target	RL1	RL2	RL3	RL4	RL5	ALD
SEVITOR	snvitor	sncitor	sncxtor	sncxdor	sncxdmr	wncxdmz
TRAMIAL	tcamial	tcwmial	tcwsial	tcwszal	tcwszvl	kcwszvb
WHASBER	wkasber	wkmsber	wkmvber	wkmvter	wkmvtnr	ckmvtnc
EPILADE	egilade	egmlade	egmfade	egmfwde	egmfwte	xgmfwtn
SQUEANE	syueane	syweane	sywrane	sywrmne	sywrmve	xywrmvz
TOSHURE	tnshure	tnxhure	tnxbure	tnxbmre	tnxbmce	fnxbmcw
OULBARD	oxlbard	oxkbard	oxkhard	oxkhwrd	oxkhwvd	nxkhwvt
THAGGER	tlagger	tlmgger	tlmqger	tlmqjer	tlmqjwr	klmqjwv
SWALVEN	sralven	srxlven	srxtven	srxtzen	srxtzcn	mrxtzcm
MABICAL	mnbical	mnfical	mnfscal	mnfsval	mnfsvxl	wnfsvxt
GREMMAR	gvemmar	gvsmmar	gvswmar	gvswcar	gvswcxr	qvswcxn
QUANDEL	qxandel	qxcndel	qxcvdel	qxcvkel	qxcvkzl	yxcvkzb
MERFORY	mwrfory	mwcfory	mwctory	mwctzry	mwctzsy	xwctzsq
ONATELF	ovatelf	ovctelf	ovchelf	ovchxlf	ovchxdf	mvchxdb
CONGARM	cwngarm	cwxgarm	cwxparm	cwxpsrm	cwxpszm	vwxpszv
CONDIAL	crndial	crvdial	crvhial	crvhsal	crvhszl	xrvhszb
GEBADIC	grbadic	grladic	grlvdic	grlvkic	grlvkwc	prlvkwn
CANVENT	cxnvent	cxsvent	cxswent	cxswznt	cxswzmt	rxswzmk
DEFLARE	dvflare	dvhlare	dvhtare	dvhtnre	dvhtnwe	kvhtnwc

Note. RL1 refers to primes in which one letter of the target has been replaced; RL2 refers to primes in which two letters of the target have been replaced; RL3 refers to primes in which three letters of the target have been replaced; RL4 refers to primes in which four letters of the target have been replaced; RL5 refers to primes in which five letters of the target have been replaced; ALD = all letters different.

Appendix C

Description of the Model

The simulations reported in this article used a modified interactive activation (IA) model in which the position-specific coding scheme of the original model was replaced with a spatial coding scheme, as in the self-organizing lexical acquisition and recognition (SOLAR) model. The changes required to accomplish this modification are described in this appendix.

Input to Letter Nodes and Spatial Coding

The network included 10 sets of feature and letter units (rather than four, as in the original model). These sets of letter units represent different input "channels" but are not assigned to specific serial positions; rather, letter position is encoded dynamically, via a spatial code (Davis, 1999). Letter nodes compute their activities on the basis of input from feature units, as in the original IA model (though with word-letter feedback set to zero). These letter node activities provide a continuous measure of the degree of perceptual evidence for the letter in question. Position information is coded separately, using the simplest form of spatial coding, that is, the first letter of the stimulus was assigned a code of 1, the second a code of 2, and so on (it is arbitrary whether a primacy or a recency gradient is used, provided that a corresponding gradient is encoded in the weights connecting letter nodes to word nodes). There is uncertainty associated with these position codes, which is captured by assuming that each of the letters of the stimulus is coded by a weighted Gaussian function centered on the veridical position of that letter. This can be expressed mathematically in terms of functions for the j^{th} letter defined as follows:

$$f_j(x) = a_j N(j, \sigma), \qquad \text{(C1)}$$

where a_j is the activity of the j^{th} letter, and $N(j, \sigma)$ is a normal distribution with mean j and standard deviation σ. A value of 1.25 was chosen for σ, as in previous modeling (this value is the default that is used for the MatchCalc program available from Colin J. Davis's website).

Input to Word Nodes

We suppose that one effect of learning is that each word node "knows" which letters to attend to, that is, which letters make up the particular word that it codes. Thus the word node that codes *STOP* only considers inputs from the letter nodes for S, T, O, and P. Unlike the coding scheme of the original IA model, then, spatial coding assumes that the only bottom-up input to word nodes comes from potentially compatible letter nodes, that is, there is no inhibition from incompatible letter nodes (thus the gamma letter-word parameter of the original model is set at zero). For the i^{th} word node, this set of letters is denoted L_i, and the number of letters in this set (i.e., the length of the word) is denoted l_i (e.g., $L_{STOP} = \{S, T, O, P\}$, and $l_{STOP} = 4$). The weight between a letter node and a word node is simply the expected position of that letter in that word; for example, the weight from the S letter node to the STOP word node is $z_{\mathrm{S,STOP}} = 1$. Davis (1999) has described how the SOLAR model is able to self-organize so as to learn appropriate weights following exposure to a vocabulary.

Computation of Match Values

Each word node computes a match value that describes the degree to which the word that it codes matches the current input stimulus. The method we describe here (superposition matching) has been described previously in Davis and Bowers (2006), and it is discussed in detail in Davis (2009). The first step involves computing a set of signal-weight differences. The signal-weight difference function $d_{ji}(x)$ computed for the j^{th} letter associated with the i^{th} matcher is simply an amplified normal distribution centered on $j - e_{ji}$, where e_{ji} is the expected position of the j^{th} letter in the i^{th} comparison word, that is,

$$d_{ji}(x) = a_j N(j - e_{ji}, \sigma). \tag{C2}$$

As in (C1), the amplification term a_j in (C4) reflects the activity associated with the j^{th} letter. The superposition $S_i(x)$ of a set of l_i signal-weight difference functions is then

$$S_i(x) = \sum_{j \in Li} d_{ji}(x), \tag{C3}$$

where the set L_i refers to the set of letter nodes associated with the i^{th} comparison word. A match value M_i can then be found by dividing the peak of the superposition function by the number of comparison letters (l_i), that is,

$$M_i = \frac{k\max(S_i(x))}{l_i}, \tag{C4}$$

where $\max(S_i(x))$ returns the largest value taken by the function $S_i(x)$, and k is a scaling constant set equal to $\sigma\sqrt{2\pi}$ to ensure that the maximum value of M_i is 1. This maximum value is obtained only when the difference functions overlap perfectly. The minimum value of M_i is 0, which occurs when the input stimulus does not include any of the letters contained in the comparison word. Thus, the set of equations C2–C4 produce a match value that lies between 0 and 1.

This match value was cubed, to contrast-enhance differences between nodes (Davis, 1999, squared the match value; the effect of cubing is functionally similar), and then multiplied by α_{LW}, a parameter from the original IA model that controls the rate at which word node activity grows relative to letter activity.

Word-Level Dynamics

As discussed in the text, the activity equation for word nodes was modified slightly from the original IA formulation to change the nature of word activity decay. In the original equation the decay component can be written as $-A_W(x_i - r_i)$, where A_W is a decay rate constant, x_i is the current word node activity, and r_i is the resting activity. This component was replaced by the term $-A_W[1 - r_i - 10 P_i]^+$, where P_i is the excitatory input to the word node, and the notation $[x]^+$ means $\max(x, 0)$, that is, ensuring that the full decay term is a negative value. The parameter was set to 0.2. Overall, this decay term implies that word nodes decay (toward the minimum word node activity) at a rate that depends on how well they match the current input stimulus.

Parameter Settings

The full set of parameter values was as follows:

$\alpha_{FL} = .28$ (feature-letter excitation)
$\gamma_{FL} = 6$ (feature-letter inhibition)
$\alpha_{LW} = .4$ (letter-word excitation)
$\sigma = 1.25$ (letter position uncertainty)
$\gamma_{WW} = .4$ (word-word inhibition)
$A_L = 0$ (letter node decay rate)
$A_W = .2$ (word node decay rate)
$B = 1.0$ (maximum letter and word activity)
$C = -0.05$ (minimum letter and word activity)
fgain = 0.05 (parameter for scaling word frequency in resting activities)
$\mu = .68$ (local activity threshold for word identification)
$\alpha_{WL} = 0$ (word-letter feedback)
$\gamma_{LW} = 0$ (letter-word inhibition)
dt = .05 (step-size – temporal scaling parameter)

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