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# Superset Versus Substitution-Letter Priming: An Evaluation of Open-Bigram Models

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In recent years, a number of models of orthographic coding have been proposed in which the orthographic code consists of a set of units representing bigrams (open-bigram models). Three masked priming experiments were undertaken in an attempt to evaluate this idea: a conventional masked priming experiment, a sandwich priming experiment (Lupker & Davis, 2009) and an experiment involving a masked prime same-different task (Norris & Kinoshita, 2008). Three prime types were used, first-letter superset primes (e.g., *wjudge-JUDGE*), last-letter superset primes (e.g., *judgew-JUDGE*) and standard substitution-letter primes (e.g., *juwge-JUDGE*). In none of the experiments was there any evidence that the superset primes were more effective primes, the prediction made by open-bigram models. In fact, in the second and third experiments, first-letter superset primes were significantly worse primes than the other two prime types. These results provide no evidence for the existence of open-bigram units. They also suggest that prime-target mismatches at the first position produce orthographic codes that are less similar than mismatches at other positions. Implications for models of orthographic coding are discussed.

*Keywords:* open-bigram, masked priming, orthographic coding

In recent years there has been a noticeable increase in interest among reading researchers in the process referred to as "orthographic coding" (Davis, 2010; Grainger, 2008; Grainger & van Heuven, 2003; Whitney, 2001). Orthographic coding refers to the process of constructing an abstract representation of the letter string being read that then serves as the code allowing access to lexical information. In order to read successfully, this code must accurately specify not only the identities of the letters in the word being read but also the positions of those letters. That is, if identity information is not successfully coded, readers may confuse words like *gate* and *game*, whereas, if position information is not successfully coded, readers may confuse anagrams like *trial* and *trail*.

Although both identity and position must be coded accurately for successful reading, recent research has also made it clear that the coding system for position is somewhat imprecise. That is, readers do confuse anagram letter strings like *jugde* with their base words (i.e., *judge*) (Chambers, 1979; O'Connor & Forster, 1981; Perea & Lupker, 2003a, 2003b, 2004) and anagram words like *trial* and *trail* (Andrews, 1996) while at the same time, as shown by the now-famous "Cambridge e-mail," readers have little trouble reading when the letter strings they are reading contain sets of transposed letters (e.g., "eervy letetr by iesltf" can be easily interpreted as "every letter by itself").

One approach to trying to describe the way position information is represented in the orthographic code has been to assume that letter positions are coded in a fashion that, although precise enough to normally allow successful reading, is nonetheless, noisy. For example, Gómez, Ratcliff, and Perea (2008), in their Overlap model, have assumed that the position of a letter (e.g., the *d* in *judge*) can be described in terms of a probability distribution with a mean in the correct position (i.e., the third) but with a variance indicating that there is some probability that the letter could be in the second or fourth position. Similar assumptions about letter position uncertainty are made in Davis's (2010) Spatial-Coding model, Norris and colleagues' Bayesian Reader model (Norris & Kinoshita, 2012; Norris, Kinoshita, & van Casteren, 2010) and Adelman's (2011) Letters in Time and Retinotopic Space (LTRS) model.

In contrast to these types of models, there are now a number of models that code letter position by postulating a set of representations between the letter and word level, representations of the bigrams in the word being read (Grainger & van Heuven, 2003; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Schoonbaert & Grainger, 2004; Whitney, 2001). For example, when the word *judge* is read, letter-level representations are initially activated with those representations then activating representations for bigrams *ju*, *jd*, *jg*, *ud*, and so forth that represent the ordering of letter pairs in the word. The reason that an anagram like *jugde* can be potentially misinterpreted as *judge* is that *jugde*

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will activate virtually all the same bigrams as *judge* with the only exception being the *dg* bigram. These types of models are referred to as "open-bigram" models.

At present, there are a number of open-bigram models in the literature. They vary in terms of a number of assumptions. For example, a now-common assumption is that bigrams are not activated if the distance between letters is too great (Schoonbaert & Grainger, 2004). In Schoonbaert and Grainger's model, referred to as the "constrained open-bigram" model, letter pairs with more than two letters between them do not activate the associated bigram (i.e., the *je* bigram is not activated when reading *judge*). A second potential assumption is that the degree of activation of bigram units is a function of the distance between the two letters of the bigram (i.e., the *ju* bigram is more activated than the *jd* bigram when reading *judge*) (Whitney, 2001). Other models assume edge bigrams (Whitney & Marton, 2013), that is, bigrams that indicate which letters are end letters by having a space next to them (e.g., the bigrams $^{*}j$ and $e^{*}$ are activated when reading *judge*). There is even a model, the overlap open-bigram model (Grainger et al., 2006), that assumes that reverse-order bigrams can be activated (i.e., the bigram unit for *uj* would be activated when reading *judge*).

There has been renewed interest in these types of models recently because there have been a few papers showing that although transposing other types of characters, for example, numbers and symbols, can also create confusion, those effects are somewhat different from the effect of transposing letters (Duñabeitia, Dimitropoulou, Grainger, Hernández, & Carreiras, 2012; Massol, Duñabeitia, Carreiras, & Grainger, 2013). These types of results have led open-bigram proponents to argue that there is something more than just positional noise producing transposition effects with letters. Potentially, there is also the impact of open-bigram units, an impact that would not exist for number or symbol pairs.

Even if one accepts the idea that these data indicate that there is a qualitative difference between letters and number or symbols, it's not clear that they provide much support for the existence of open-bigram units during orthographic coding. Therefore, what is really needed is some demonstration that open-bigram models provide a better explanation of some empirical results in reading research than the other types of orthographic coding models do.

Unfortunately, because of the numerous assumptions involved in the different versions of open-bigram models, it's been somewhat difficult to empirically examine the open-bigram idea, per se. For example, Lupker and Davis (2008), using a masked priming lexical-decision task involving Lupker and Davis's (2009) sandwich priming technique, demonstrated that a reversed interior letter prime like *cetupmor* primes a target like *computer* when compared with the control prime *cifagnar*, a result that follows directly from Davis's (2010) Spatial-Coding model. According to any version of open-bigram models the only open bigrams potentially shared by *cetupmor* and *computer* are the edge bigrams $^{*}c$ and $r^{*}$. Because these bigrams are also contained in the control prime *cifagnar*, the implication is that open-bigram models would not predict that *cetupmor* will be a better prime for *computer* than *cifagnar* would be. However, one version of open-bigram models, Grainger and van Heuven's (2003) unconstrained open-bigram model, can predict some priming from *cetupmor* because, in that model, all potential bigrams are activated, including the *ce, ct, cu*, and so forth bigrams, bigrams that are not contained in *cifagnar*. Therefore, although this version of the model is no longer favored by open-bigram theorists (e.g., Grainger et al., 2006), the ability of the model to potentially predict a priming effect from *cetupmor* means that that effect does not challenge the open-bigram idea, per se.

As a second example, Kinoshita and Norris (2013) using the masked prime same-different task (to be described in more detail subsequently) also reported priming effects in situations that open-bigram models would not predict. For example, two-letter target words like *of* were primed by transposed letter primes (*fo*) and longer targets (e.g., *abolish*) were primed by letter pairs separated by more than two letters (e.g., *bs*). Once again, however, there is one open-bigram model (Grainger et al., 2006) that suggests that transposed-letter bigrams are activated and there is another model (Grainger & van Heuven, 2003) in which the *bs* bigram would be activated when reading *abolish*. Therefore, once again, one can argue that these demonstrations of priming in situations in which most open-bigram models would predict no priming does not challenge the open-bigram idea, per se.

In the present research, a slightly different approach was taken. As in most attempts to evaluate the open-bigram idea against its competitors, the masked priming paradigm (Forster & Davis, 1984) was used. However, rather than trying to find priming effects in situations in which most open-bigram models would not predict priming effects, conditions were created that, according to the open-bigram principle, should most favor finding priming effects. In particular, in the main conditions of interest, the primes used were "superset" primes, primes that contain all the target's letters (Welvaert, Farioli, & Grainger, 2008; Van Assche & Grainger, 2006). As Welvaert et al. (2008) and Van Assche and Grainger (2006) have demonstrated, superset primes created by inserting a letter into the middle of a target (e.g., *juwdge*) can be very effective primes because the relative positions of all the target's letters are maintained. In the present experiments, the superset primes were created in a slightly different way, by adding a letter to either the beginning or end of the target word (i.e., *wjudge* or *judgew* for the target *judge*) which, of course, will also maintain the relative positions of all the target's letters.

Creating supersets by adding a letter to the beginning or end of the target, rather than the middle, was felt to be a better way of examining open-bigram models because the primes would not increase the separation of any of the letters in the relevant bigrams, which could potentially decrease the probability that some bigram units are activated (i.e., an interior letter superset prime like *juwdge* may not activate the *jg* and *ue* bigram units that are required when reading the word/target *judge* because the letters in those bigrams may be too far apart). Indeed, Welvaert et al. (2008) nicely demonstrated that when superset primes are created by adding letters to the middle of the target word (e.g., *juwdge*, *juwrdge*), the priming effect is reduced by approximately 11 ms per letter added. Welvaert et al. suggested that this pattern could be explained in terms of a letter-to-word inhibition effect resulting from the prime activating letters not in the target. However, it could just as easily be explained within the framework of open-bigram models as being because of the added internal letters reducing the number of target-relevant open bigrams activated by the prime. In fact, as Welvaert et al. reported, both SERIOL

(Whitney, 2001) and the overlap open-bigram model did a very good job of accounting for their results without assuming a letter-to-word inhibition process.

These prime conditions were contrasted with a standard substitution-letter prime condition (i.e., *juwge*). Substitution-letter primes like *juwge* activate considerably fewer bigrams involved in reading *judge* (i.e., all four bigrams involving the letter *d* are not activated by *juwge*) than the first- and last-letter superset primes do. Hence open-bigram models would predict that there will be a considerably smaller priming effect from these primes than from the superset primes. Indeed a calculation of similarity scores from the version of SERIOL described in Whitney (2004) indicates that the superset primes have an average similarity score with the targets used in the present experiments of .93 whereas the average similarity score for the substitution-letter primes and the targets used here is .66. Some of the other open-bigram models (e.g., Grainger & van Heuven, 2003) would produce similarity scores of 1.00 for the superset primes because those primes activate all the open bigrams needed by the target. The reason the most recent version of SERIOL does not do so is that the primes would not activate the appropriate edge bigram on the end of the prime containing the added letter.

In contrast to the predictions of SERIOL, Davis's (2010) Spatial-Coding model finds little to discriminate among the three prime types, producing similarity scores of .88 for all of them. However, as Lupker and Davis (2009) have noted, similarity scores are not perfect predictors of priming effects in a conventional masked priming experiment. The reason is that orthographically similar primes can activate not only lexical representations for the targets but also lexical representations for other orthographically similar words. Those activated representations then compete with the representation for the target, slowing its activation. This problem is especially acute when the additional words whose representations are activated by the prime are also orthographically similar to the target because they will then get some activation from the target presentation as well, further increasing their ability to compete.

In an effort to try to control the impact of differential lexical competition in the three prime-type conditions, the primes that were selected had very few neighbors (Coltheart, Davelaar, Jonasson, & Besner, 1977). In the substitution-letter prime condition, the only prime neighbor was the target. In the two superset prime conditions, the primes were not Coltheart et al. neighbors of the targets because they were one letter longer than the targets; however, the average neighborhood size of the primes was 0.5. As a result, for these stimuli, Davis's (2010) Spatial-Coding model did predict equivalent priming in the three conditions (39 ms in the two superset conditions, 36 ms in the substitution-letter condition).[1]

Experiments 2 and 3 were additional attempts to try to examine the open-bigram proposal in circumstances in which the impact of lexical competition has been more strongly controlled. Recently, two experimental techniques have been developed in an effort to accomplish exactly this purpose, Lupker and Davis's (2009) sandwich priming technique and Norris and Kinoshita's (2008) masked prime same-different task. The details of these techniques will be described before the relevant experiment.

## Method

### Experiment 1

**Participants.** The participants were 66 University of Western Ontario undergraduate students who participated for partial course credit. All had normal or corrected-to-normal vision and were native speakers of English.

**Materials.** The target stimuli consisted of 78 English words (average CELEX frequency: 43.3 per million, average orthographic neighborhood size (as defined in Coltheart et al., 1977): 2.5; average length: 6.4 letters) and 78 orthographically legal nonwords that matched the words in terms of average neighborhood size (2.5 orthographic neighbors) and length (6.4 letters). For each word and nonword target six types of primes were created, each representing a condition in the experiment: 1) primes created by adding a letter to the front of the target (related first-letter superset condition; e.g., *zbegun—BEGUN*), 2) primes created by adding a letter to the end of the target (related last-letter superset condition; e.g., *begunz—BEGUN*), 3) primes created by replacing an internal letter of the target (related substitution-letter condition; e.g., *bezun—BEGUN*), 4) unrelated first-letter superset primes created by re-pairing the primes and targets from the related first-letter superset condition (e.g., *zbegun—STERN*), 5) unrelated last-letter superset primes created by re-pairing primes and targets from the related last-letter superset condition (e.g., *begunz—STERN*), and 6) unrelated substitution-letter primes created by re-pairing primes and targets from the related substitution-letter condition (e.g., *bezun—STERN*).

In order to use all six prime types and make sure each target would appear only once to a participant, six sets of materials (lists) were created. Across the lists, all 156 targets were primed by all six types of primes, with a different prime for the single presentation of a given target in each list. Each list contained an equal number of each prime type. That is, each list contained 13 trials of each prime type across the word targets and 13 trials of each prime type across the nonword targets. Thus, all manipulations of interest were within-subject.

The primes in all the experiments were displayed in lowercase in size 12 New Courier font (e.g., zbegun), whereas all the targets were displayed in uppercase in size 14 New Courier font (e.g., BEGUN) so that the targets would cover the same area of the screen as the superset primes that were one letter longer than their targets. The specific order of presentation of the targets within each list was pseudorandomized for each participant using Forster

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[1] Adelman et al. (2014) in their megastudy of priming effects have recently reported priming effects of 29 ms, 27 ms and 23 ms in the last-letter superset, first-letter superset and substitution-letter prime conditions. Because of the large quantity of data collected, a difference of 3 ms is a statistically significant difference, implying that the substitution-letter primes were not as effective as the superset primes in that data set. Unfortunately, it isn't possible to draw any firm conclusions from that data pattern with respect to the issues investigated here for two reasons. First, no attempt was made to control for the orthographic neighborhoods of the primes (and targets) and, therefore, it is quite possible that the different prime conditions produced different levels of lexical competition. Second, although all of the unrelated primes were the same length as their targets (six letters), the related primes were longer than their targets in the superset prime conditions (seven letters), but not in the substitution-letter prime condition.

and Forster's (2003) DMDX software. All of the stimuli used are listed in the Appendix.

**Procedure.** Participants were tested individually. Participants were told that their task was to indicate whether the strings of letters presented on the computer screen were English words or not, by pressing the right-shift key if they thought the letter string was a word and the left-shift key if they thought it was not. They were also told to do this as quickly and as accurately as possible. No mention was made of the number of stimuli that would be presented on each trial or of the existence of the masked primes.

Each trial consisted of the presentation of three stimuli. First, a row of nine (#########) hash marks was presented for 550 ms to serve as a fixation mark, followed immediately by the prime (e.g., zbegun) for 55 ms, followed by the target for 3 s (e.g., BEGUN), or until a response was made. Each stimulus was presented in the center of a 17-in PC monitor, using Forster and Forster's (2003) DMDX software. Targets (words or nonwords) appeared as black characters on a white background. Reaction times (RTs) were measured from the target's onset until the participant's response.

When the participant responded to a trial, the target disappeared from the screen and the next trial began. All participants received six practice trials involving a novel set of stimuli before the 156 experimental trials. No participants mentioned any awareness of the primes. The entire experiment lasted approximately 10 min.

## Results

For both the word and nonword data, 2 × 3 × 6 analyses of variances (ANOVAs) were conducted, both by subjects ($F_1$) and by items ($F_2$), with Relatedness (related vs. unrelated) and Prime Type (first-letter superset, last-letter superset, substitution-letter) as within-subject and within-item factors and List (which is the counterbalancing factor) as a between-subject and between-item factor. Incorrect responses and RTs less than 250 ms or greater than 1600 ms were excluded from the latency analysis. Similar exclusion criteria were applied to the nonword data except that 1800 ms was set as the upper-limit criterion for those targets, instead of 1600 ms. Doing so led to the exclusion of 2.0% of the word latencies and 2.8% of the nonword latencies. The mean RTs and error rates of word and nonword targets from the subject analyses are shown in Table 1.

Table 1
*Mean Response Times (RTs, in Milliseconds), Percentages of Errors and Priming Effects (PE, in Milliseconds) for Word and Nonword Targets in Experiment 1 (With 95% Confidence Intervals for Word Target Priming Effects)*

| Related | RT | % | Unrelated | RT | % | PE | 95% CI |
|---|---|---|---|---|---|---|---|
| | | | Words | | | | |
| First-Letter | 669 | 4.3 | First-Letter | 709 | 6.3 | 40 | 26, 54 |
| Last-Letter | 662 | 4.0 | Last-Letter | 695 | 4.9 | 33 | 17, 50 |
| Substitution | 666 | 4.2 | Substitution | 701 | 5.7 | 35 | 19, 51 |
| | | | Nonwords | | | | |
| First-Letter | 824 | 9.5 | First-Letter | 812 | 10.5 | −12 | |
| Last-Letter | 814 | 10.5 | Last-Letter | 823 | 8.3 | 9 | |
| Substitution | 806 | 7.9 | Substitution | 801 | 10.8 | −5 | |

**Word latencies.** Related primes produced significantly shorter latencies than unrelated primes in both analyses, $F_1(1, 60) = 59.33$, $MSE = 2158.16$, $p < .001$; $F_2(1, 72) = 60.73$, $MSE = 2656.10$, $p < .001$. The Prime Type effect was not significant in either analysis, $F_1(2, 120) = 1.50$, $MSE = 2521.71$, $p > .20$; $F_2(2, 144) = 1.50$, $MSE = 3760.20$, $p > .20$. Most importantly, the Relatedness x Prime Type interaction was not significant in either analysis, $F_1(2, 120) = 0.21$, $MSE = 1810.31$, $p > .50$; $F_2(2, 144) = 0.29$, $MSE = 3326.19$, $p > .50$.

Because accepting a null hypothesis is always potentially problematic, techniques have been developed for estimating the probability of the null hypothesis being true given the data obtained, $p(H_o|D)$, (e.g., Masson, 2011; Wagenmakers, 2007). Applying the technique presented by Masson (2011) to the Relatedness x Prime Type interaction, yields $p(H_o|D)$ values of .990 and .991 for the subject and item analyses, respectively.

**Word errors.** As in the latency data, there was a Relatedness effect $F_1(1, 60) = 6.12$, $MSE = 0.004$, $p < .05$; $F_2(1, 72) = 5.84$, $MSE = 0.005$, $p < .05$ with fewer errors following related primes. However, there was no Prime Type effect, $F_1(2, 120) = 0.89$, $MSE = 0.003$, $p > .40$; $F_2(2, 144) = 0.92$, $MSE = 0.003$, $p > .40$ and no interaction, $F_1(2, 120) = 0.27$, $MSE = 0.004$, $p > .50$; $F_2(2, 144) = 0.18$, $MSE = 0.004$, $p > .50$.

**Nonword latencies.** Neither of the main effects nor the interaction approached significance in either analysis (all $p$s $>$.10).

**Nonword errors.** Although neither main effect approached significance (all $p$s $>$.50), there was a significant interaction, $F_1(2, 120) = 4.00$, $MSE = 0.005$, $p < .05$; $F_2(2, 144) = 3.29$, $MSE = 0.008$, $p < .05$. This interaction may very well be a Type I error. One thing to note, however, is that, for each prime type, the relatedness effect in the error data is a mirror of the relatedness effect in the latency data. Thus, the overall pattern is also consistent with there having been a small speed–accuracy trade-off on the nonword trials (see Table 1).

## Discussion

The priming effects in Experiment 1 were remarkably consistent with the predictions of Davis's (2010) Spatial-Coding model. Both superset conditions were predicted to produce 39 ms of priming with the first-letter superset condition producing 40 ms and the last-letter superset condition producing 33 ms. The substitution-letter prime condition was predicted to produce 36 ms of priming and it produced 35 ms.

In contrast, the data from Experiment 1 are not at all consistent with the predictions of the open-bigram models. Regardless of which version of open-bigram model we might consider, the superset primes were expected to be extremely similar to their targets. The substitution-letter primes were not. Therefore, the prediction is that the superset primes would be far better primes than the substitution-letter primes. The complete lack of an interaction between Relatedness and Prime Type is not at all consistent with this prediction.

## Experiment 2

As noted previously, similarity scores are not perfect predictors of priming effects in a conventional masked priming lexical decision experiment. Those priming effects are also dependent on nature of the interactions that go on at the lexical level. Orthographically related primes activate not only the target but also lexical representations of all other words to which they are orthographically similar. Those activated representations then compete with the target during target processing, slowing its activation. The competition process becomes even more intense if the target itself is orthographically similar to the activated competitors because its presentation also activates those competitors, making them even more potent. Therefore, efforts need to be taken to make sure that lexical competition doesn't differentially affect the various prime conditions.

In Experiment 1, an attempt was made to solve this problem by selecting primes that had no neighbors other than the target in the substitution-letter prime condition and primes that had virtually no neighbors at all in the two superset prime conditions. Coltheart et al.'s (1977) definition of a lexical neighbor was used for this purpose. As has been pointed out (e.g., Bowers, Davis, & Hanley, 2005; Davis & Taft, 2005), however, this definition is likely too restrictive. Word pairs in which one word is a superset of the other (e.g., *come-comet*) are likely also neighbors in the sense that the presentation of one member of the pair likely activates the lexical representation of the other member of the pair early in processing. In fact, the existence of superset priming, as observed in Experiment 1 and as reported by Welvaert et al. (2008) and Van Assche and Grainger (2006), is essentially a demonstration of that point. Therefore, one could argue that the nature of lexical activation in the three prime type conditions may not have been as well controlled as one would have liked in Experiment 1.

Fortunately, there are now techniques available for achieving even better control on the impact of the competition processes that go on at the lexical level. The technique employed in Experiment 2 is Lupker and Davis's (2009) sandwich priming technique.

Sandwich priming involves simply adding a very brief (i.e., 33 ms) presentation of the target to the normal masked priming sequence on all trials, just before the brief presentation of the prime of interest. The idea is that this extra stimulus starts target processing ahead of any processing that the prime may initiate. Because target processing has a head start, the expectation is that the target's representation can effectively inhibit any other representations that might be activated by the prime. Essentially, a playing field is created in which those other representations never reach a level of activation that allows them to become strong competitors. Therefore, the only impact the prime will have in this situation is to further activate the target. As a result, the amount of priming that is observed would then be a direct reflection of how orthographically similar the prime and target are. The typical result is that priming effects increase in size in sandwich priming experiments and, in fact, often very small effects in the conventional masked priming paradigm become large enough to be significant when using sandwich priming (Lupker & Davis, 2008, 2009).

Experiment 2 was, therefore, a sandwich priming experiment using the same primes and targets as used in Experiment 1. The expectation is that, to the extent that priming effects were being diminished by lexical competition in Experiment 1, those effects will increase in size in Experiment 2. If differential lexical competition in the various conditions was the reason that the advantage for superset primes predicted by the open-bigram models did not emerge in Experiment 1, that advantage should now emerge in Experiment 2. In contrast, Davis's (2010) Spatial-Coding model predicts that any difference between the two experiments will only be in the overall size of the priming effects, which should increase to approximately 60 ms in all conditions.

## Method

**Participants.** The participants were 78 University of Western Ontario undergraduate students who participated for partial course credit. All had normal or corrected-to-normal vision and were native speakers of English.

**Materials.** The stimuli created for Experiment 1 were also used in Experiment 2.

**Procedure.** As in Experiment 1, participants were told that their task was to indicate whether each string of letters presented on the computer screen was an English word or not, by pressing the right-shift key if they thought the letter string was a word and the left-shift key if they thought it was not. They were also told to do this as quickly and as accurately as possible. No mention was made of the number of stimuli that would be presented on each trial or of the existence of the masked primes.

Each trial consisted of the presentation of four stimuli. First, a row of nine (#########) hash marks was presented for 550 ms to serve as a fixation mark, followed immediately by the target word in lowercase (e.g., begun) for 33 ms, followed by the second prime (e.g., zbegun), also in lowercase, for 55 ms, followed by the target for 3 s (e.g., BEGUN), or until a response was made. Each stimulus was presented in the center of a 17-in PC monitor, using Forster and Forster's (2003) DMDX software. All stimuli appeared as black characters on a white background. Reaction times were measured from the target's onset until the participant's response.

When a participant responded to a trial, the target disappeared from the screen and the next trial began. All participants received six practice trials involving a novel set of stimuli before the 156 experimental trials. No participants mentioned any awareness of the primes although some reported seeing a flash before the target. The entire experiment lasted approximately 10 minutes.

## Results

The data analyses were identical to those in Experiment 1. Because of the slightly longer latencies typically found in sandwich priming, the cutoffs for the word trials were 250–1800 ms whereas the cutoffs for the nonword trials were 250–2000 ms. Using these cutoffs led to the exclusion of 1.6% of the word latencies and 1.5% of the nonword latencies. The mean latencies and error rates for word and nonword targets from the subject analyses are shown in Table 2.

**Word latencies.** Related primes produced significantly shorter latencies than unrelated primes in both analyses, $F_1(1, 72) = 102.39$, $MSE = 3049.19$, $p < .001$; $F_2(1, 72) = 143.86$, $MSE = 2403.30$, $p < .001$. The Prime Type effect was also significant in both analyses, $F_1(2, 144) = 7.36$, $MSE = 2749.85$, $p < .005$; $F_2(2, 144) = 7.99$, $MSE = 2834.60$, $p < .005$. Most importantly, the Relatedness x Prime Type interaction was significant in both analyses, $F_1(2, 144) = 3.17$, $MSE = 3802.23$, $p < .05$; $F_2(2, 144) = 3.73$, $MSE = 2990.58$, $p < .05$. The priming effect in the first-letter superset condition was smaller than in both the last-letter superset condition ($t_1(72) = 2.13$, $p < .05$, $t_2(72) = 2.37$, $p < .05$) and the substitution-letter condition ($t_1(72) = 2.25$,

Table 2
*Mean Response Times (RTs, in Milliseconds), Percentages of Errors and Priming Effects (PE, in Milliseconds) for Word and Nonword Targets in Experiment 2 (With 95% Confidence Intervals for Word Target Priming Effects)*

| Related | RT | % | Unrelated | RT | % | PE | 95% CI |
|---|---|---|---|---|---|---|---|
| | | | Words | | | | |
| First-Letter | 687 | 4.4 | First-Letter | 718 | 5.8 | 31 | 13, 50 |
| Last-Letter | 652 | 2.7 | Last-Letter | 712 | 5.2 | 60 | 42, 78 |
| Substitution | 653 | 3.9 | Substitution | 716 | 6.0 | 63 | 43, 84 |
| | | | Nonwords | | | | |
| First-Letter | 803 | 9.8 | First-Letter | 822 | 7.5 | 19 | |
| Last-Letter | 806 | 9.2 | Last-Letter | 815 | 8.1 | 9 | |
| Substitution | 798 | 6.6 | Substitution | 800 | 7.7 | 2 | |

$p < .05$, $t_2(72) = 2.41$, $p < .05$). There was no difference between the last-letter superset condition and the substitution-letter condition ($t_1(72) = 0.25$, $p > .50$, $t_2(72) = 0.06$, $p > .50$).

**Word errors.** As in the latency data, there was a Relatedness effect $F_1(1, 72) = 18.76$, $MSE = 0.003$, $p < .001$; $F_2(1, 72) = 10.22$, $MSE = 0.005$, $p < .005$ with fewer errors following related primes. However, there was no Prime Type effect, $F_1(2, 144) = 2.10$, $MSE = 0.003$, $p > .10$; $F_2(2, 144) = 1.74$, $MSE = 0.004$, $p > .15$ and no interaction, $F_1(2, 144) = 0.46$, $MSE = 0.003$, $p > .50$; $F_2(2, 144) = 0.43$, $MSE = 0.003$, $p > .50$.

**Nonword latencies.** The Relatedness effect approached significance in both analyses, $F_1(1, 72) = 3.35$, $MSE = 3510.34$, $p < .10$; $F_2(1, 72) = 3.11$, $MSE = 5237.08$, $p < .10$. Neither the Prime Type effect, $F_1(2, 144) = 1.57$, $MSE = 5005.32$, $p > .20$; $F_2(2, 144) = 2.53$, $MSE = 4012.65$, $p < .10$, nor the interaction, $F_1(2, 144) = 0.58$, $MSE = 4698.30$, $p > .50$; $F_2(2, 144) = 0.83$, $MSE = 4477.59$, $p > .40$ were significant in either analysis.

**Nonword errors.** Neither of the main effects nor the interaction approached significance in either analysis (all *p*s $>.10$).

### Discussion

Once again, there was no support for the predictions of the open-bigram models. That is, in Experiment 2, neither superset condition showed evidence of producing more priming than the substitution-letter condition. In fact, unlike in Experiment 1, the first-letter superset condition produced significantly less priming than the other two conditions. Essentially, although the sandwich priming paradigm did increase the size of the priming effect beyond that produced in the conventional priming paradigm in Experiment 1 for the substitution-letter and last-letter superset primes, it had no impact on the priming effect for first-letter superset primes. This pattern contrasts with the predictions of the Spatial-Coding model as well, which was that all three prime type conditions should yield approximately 60 ms of priming as a result of the switch of experimental paradigms.

An obvious question, therefore, is why did the sandwich priming manipulation not increase the priming effect for the first-letter superset primes? The answer most consistent with the analysis of what sandwich primes do is that there were no competitors activated by the first-letter superset primes that the sandwich primes could act to suppress. That is, the analysis Lupker and Davis (2009) provided is that the impact of presenting the target word itself before the prime of interest is that the brief target presentation causes normal competitors for the target (i.e., target neighbors) to be suppressed. Therefore, they will not be activated to any real degree by the prime of interest making them unable to have any noticeable inhibition effect on target processing. The result is a facilitation effect reflecting the actual orthographic similarity between the prime and target. If such competitors do not exist, the impact of the sandwich prime would be minimal. For substitution-letter primes and for last-letter superset primes, it appears that the sandwich primes accomplished their intended purpose. Therefore, the reason that there was not an increase in priming for the first-letter superset primes would appear to be that there were no competitors activated by those primes that the initial presentation of the target was able to suppress. A further implication is that the orthographic codes for the last-letter superset primes and the substitution-letter primes are actually more similar to those for their targets than is the case for first-letter superset primes. We will return to this issue in the General Discussion.

## Experiment 3

As noted, the sandwich priming paradigm is not the only paradigm that has the ability to minimize the contribution of lexical interactions, allowing for a better examination of the orthographic code. The other paradigm used has been the masked prime same-different task introduced by Norris and Kinoshita (2008). In this task, subjects first see a reference stimulus, which could be either a word or nonword, followed by a masked prime followed by a target. The task is to decide whether the target is the same as the reference stimulus. The standard result is that primes orthographically similar to their targets facilitate responding when the trial is a positive ("same") trial (i.e., when the reference stimulus and the target match), but not on negative ("different") trials, regardless of whether the stimuli are words or nonwords. In contrast, primes related in other ways to the target (e.g., morphologically) do not produce priming, strongly suggesting that the code being used when making same-different decisions is purely orthographic in nature (Duñabeitia, Kinoshita, Carreiras, & Norris, 2011; Kinoshita & Norris, 2009, although see Kelly, van Heuven, Pitchford, & Ledgeway, 2013, for a counterargument).

If this analysis is correct and if the orthographic code is based on open bigrams, once again, the prediction is that our superset primes will be superior to our substitution-letter primes. In contrast, based on the results in the sandwich priming task of Experiment 2, which is also assumed to document the impact of the similarity of the prime's and target's orthographic codes, one would expect that the pattern in Experiment 3 will mimic that in Experiment 2. That is, the substitution-letter and last-letter superset conditions should show good priming with the first-letter superset condition showing priming essentially equivalent to that in Experiment 1.

Alternatively, Whitney (2013) has proposed that in the masked prime same-different task, the codes used to carry out the task are not open-bigram units but the letter units that activate the open-bigram units. Further, Whitney has provided an equation that is to be used in predicting the amount of priming in this task, based on activation of those letter units. This proposal was made in response to the results of Kinoshita and Norris (2013), described above, showing that open-bigram models could not explain priming in the masked prime same-different task if the task was assumed to be carried out based on activation of open-bigram units. Whitney's proposal also leads to the prediction that our superset primes will be very effective primes, producing essentially the same amount of facilitation that one would expect from identity primes. In contrast, substitution-letter primes should produce only a proportion of that facilitation, equal to the ratio of the number of letters shared by the prime and target (i.e., n-1) to the number of letters in the target (*n*).

## Method

**Participants.** The participants were 90 University of Western Ontario undergraduate students who participated for partial course credit. All had normal or corrected-to-normal vision and were native speakers of English.

**Materials.** The word targets and their primes created for Experiment 1 were used to create the positive/same trials in Experiment 3. In addition, 156 English words matched to the words used in the same trials on average CELEX frequency (42.4), average orthographic neighborhood size (defined as in Coltheart et al., 1977 - 2.5) and average length (6.4 letters), were selected to be used in creating the negative/different trials. Half of these added words were used as reference stimuli and half were used as targets on different trials. Reference words and targets on different trials were always the same length.

**Procedure.** Participants were told that their task was to indicate whether the initial word presented on the computer screen was the same as the second word presented on the computer screen by pressing the right-shift key if they were the same and the left-shift key if they were not. They were also told to do this as quickly and as accurately as possible. No mention was made of the number of stimuli that would be presented on each trial or of the existence of the masked primes.

Each trial consisted of the presentation of four stimuli. Initially, the reference stimulus (e.g., begun) was presented in the upper half of the screen and a row of nine (#########) hash marks was presented in the bottom half of the screen for 550 ms. Those stimuli were followed immediately by the prime (e.g., zbegun), also in lowercase, for 55 ms, followed by the target for 3 s (e.g., BEGUN) or until a response was made, both appearing in the same position on the screen as the row of hash marks. Each stimulus was presented in the horizontal center of a 17-in PC monitor, using Forster and Forster's (2003) DMDX software. All stimuli appeared as black characters on a white background. Reaction times were measured from the target's onset until the participant's response.

When the participant responded to a trial, the target disappeared from the screen and the next trial began. All participants received six practice trials involving a novel set of stimuli before the 156 experimental trials. No participants mentioned any awareness of the primes. The entire experiment lasted approximately 10 minutes.

## Results

The data analyses were identical to those in Experiment 1 for both the same and different trials. The cutoffs in both cases were 250–1600 ms. Doing so led to the exclusion of 0.5% of the same trial latencies and 0.8% of the different trial latencies. The mean latencies and error rates for both same and different trials from the subject analyses are shown in Table 3.

**Same trial latencies.** Related primes produced significantly shorter latencies than unrelated primes in both analyses, $F_1(1, 84) = 162.28$, $MSE = 2067.49$, $p < .001$; $F_2(1, 72) = 166.42$, $MSE = 1874.12$, $p < .001$. The Prime Type effect was also significant in both analyses, $F_1(2, 168) = 4.13$, $MSE = 1654.99$, $p < .05$; $F_2(2, 144) = 4.13$, $MSE = 1111.84$, $p < .05$. Most importantly, the Relatedness x Prime Type interaction was significant in both analyses, $F_1(2, 168) = 6.42$, $MSE = 1782.20$, $p < .005$; $F_2(2, 144) = 8.68$, $MSE = 1105.08$, $p < .001$. The priming effect in the first-letter superset condition was smaller than in both the last-letter superset condition ($t_1(84) = 2.07$, $p < .05$, $t_2(72) = 1.73$, $p < .10$) and the substitution-letter condition ($t_1(84) = 3.44$, $p < .005$, $t_2(72) = 4.40$, $p < .001$). The difference between the last-letter superset condition and the substitution-letter condition was slightly larger than in Experiment 2; however, it was significant only in the items analysis ($t_1(84) = 1.63$, $p > .10$, $t_2(72) = 2.30$, $p < .05$).

**Same trial errors.** As in the latency data, there was a Relatedness effect $F_1(1, 84) = 24.02$, $MSE = 0.004$, $p < .001$; $F_2(1, 72) = 21.97$, $MSE = 0.004$, $p < .001$ with fewer errors following related primes. However, there was no Prime Type effect, $F_1(2, 168) = 0.32$, $MSE = 0.003$, $p > .50$; $F_2(2, 144) = 0.38$, $MSE = 0.003$, $p > .50$. There was some evidence of an interaction, $F_1(2, 168) = 2.74$, $MSE = 0.004$, $p < .10$; $F_2(2, 144) = 2.87$, $MSE = 0.003$, $p < .10$ because the relatedness effect was slightly larger in the substitution-letter condition.

**Different trial latencies.** The Relatedness effect was significant in both analyses, $F_1(1, 84) = 4.59$, $MSE = 1918.14$, $p < .05$; $F_2(1, 72) = 4.83$, $MSE = 2254.64$, $p < .05$, reflecting the fact that latencies in the related condition were 8 ms longer than in the unrelated condition. Neither the Prime Type effect, $F_1(2, 168) = 0.39$, $MSE = 2292.23$, $p > .50$; $F_2(2, 144) = 0.45$, $MSE = 1631.67$, $p > .50$, nor the interaction, $F_1(2, 168) = 1.47$, $MSE = 1550.48$, $p > .20$; $F_2(2, 144) = 1.57$, $MSE = 1516.01$, $p > .20$ were significant in either analysis.

**Different trial errors.** The Relatedness effect was significant in both analyses, $F_1(1, 84) = 4.87$, $MSE = 0.004$, $p < .05$; $F_2(1, 72) = 10.21$, $MSE = 0.002$, $p < .005$, reflecting the fact that the error rate in the related condition was 1.2% higher than in the

Table 3
*Mean Response Times (RTs, in Milliseconds), Percentages of Errors and Priming Effects (PE, in Milliseconds) for Same and Different Trials in Experiment 3 (With 95% Confidence Intervals for Same Target Priming Effects)*

| Related | RT | % | Unrelated | RT | % | PE | 95% CI |
|---|---|---|---|---|---|---|---|
| Same trials | | | | | | | |
| First-Letter | 532 | 4.0 | First-Letter | 565 | 5.6 | 33 | 20, 48 |
| Last-Letter | 515 | 3.6 | Last-Letter | 565 | 5.7 | 50 | 38, 63 |
| Substitution | 504 | 2.9 | Substitution | 569 | 7.4 | 65 | 54, 78 |
| Different trials | | | | | | | |
| First-Letter | 589 | 3.3 | First-Letter | 589 | 2.2 | 0 | |
| Last-Letter | 591 | 4.4 | Last-Letter | 579 | 3.0 | −12 | |
| Substitution | 592 | 3.3 | Substitution | 580 | 2.2 | −12 | |

unrelated condition. Neither the Prime Type effect, $F_1(2, 168) = 2.28$, $MSE = 0.002$, $p > .10$; $F_2(2, 144) = 2.15$, $MSE = 0.002$, $p > .10$, nor the interaction, $F_1(2, 168) = 0.05$, $MSE = 0.002$, $p > .50$; $F_2(2, 144) = 0.08$, $MSE = 0.002$, $p > .50$ was significant in either analysis.

## Post-Hoc Contrasts Between Experiments

The obvious contrast in the present research was between Experiment 1, the conventional masked priming experiment, which showed equivalent priming effects in the three conditions, and the other two experiments that showed an interaction between prime type and relatedness. Additional analyses were undertaken to compare the target latencies in Experiment 1 to those in each of the other two experiments. Specifically, two 2 (Experiment) × 2 (Relatedness) × 3 (Prime Type) × 6 (List) analyses were undertaken. For brevity, only effects involving Experiment are reported here.

In the contrast between Experiments 1 and 2, there was a significant Relatedness by Experiment interaction, $F_1(1, 132) = 5.00$, $MSE = 2644.18$, $p < .05$; $F_2(1, 144) = 6.87$, $MSE = 2529.70$, $p < .01$ reflecting the larger priming effect in Experiment 2. The Experiment by Relatedness by Prime Type interaction was marginal in both analyses, $F_1(2, 132) = 2.65$, $MSE = 2896.81$, $p < .08$; $F_2(2, 144) = 2.69$, $MSE = 3158.38$, $p < .07$, consistent with the idea that the relationship between the first-letter superset condition and the other conditions was different in the two experiments.

A similar pattern emerged in the contrast between Experiments 1 and 3. There was a significant Relatedness by Experiment interaction, $F_1(1, 132) = 5.23$, $MSE = 2105.27$, $p < .05$; $F_2(1, 144) = 5.43$, $MSE = 2265.11$, $p < .05$ reflecting the larger priming effect in Experiment 3. The Experiment by Relatedness by Prime Type interaction was significant in the subject analysis and marginal in the item analysis, $F_1(2, 132) = 3.62$, $MSE = 1793.91$, $p < .05$; $F_2(2, 144) = 2.71$, $MSE = 2215.63$, $p < .07$, consistent with the idea that the relationship between the first-letter superset condition and the other conditions was different in the two experiments.

### Discussion

The main question being addressed in Experiment 3 was whether we would find any support for the open-bigram idea in the masked prime same-different task. If one assumes that this task is carried out using open-bigram units, the prediction is for more priming in the two superset conditions than in the substitution-letter condition. If one assumes that, although open-bigram coding does occur, open-bigram units play little role in this task, as argued by Whitney (2013), the same prediction holds. The data, however, show no evidence of that pattern. Instead, they show a clear priming advantage in the substitution-letter condition in comparison with the first-letter superset condition (paralleling the results in the sandwich priming task used in Experiment 2) and some evidence of an advantage of the substitution-letter condition over the last-letter superset condition, although that difference was not large enough to be significant in the subject analysis.

What should also be noted is that, as in Experiment 2, these data are not obviously consistent with the Spatial-Coding model (Davis, 2010) either. The similarity scores in the three conditions are equivalent. Further, there is no reason to expect any of the conditions to be differentially affected by lexical competition because the general argument is that the code being used when making same-different decisions is orthographic in nature (Duñabeitia et al., 2011; Kinoshita & Norris, 2009). Therefore, the most straightforward prediction of the Spatial-Coding model would have been equal priming effects in the three conditions. This issue, as well as the issue of the relationship between the tasks used in Experiments 2 and 3, will be returned to in the General Discussion.

## General Discussion

The purpose of the present research was to provide an examination of the proposal that the orthographic code used in reading is based on open-bigram units. Three experiments were undertaken in which priming effects for both first-letter (e.g., *wjudge-JUDGE*) and last-letter (e.g., *judgew-JUDGE*) superset primes were contrasted with priming effects for the more standard substitution-letter primes (e.g., *juwge-JUDGE*). According to open-bigram models, these particular superset primes should provide strong priming because virtually all the open-bigrams units relevant to target processing would be activated by the primes. In contrast, the substitution-letter primes would activate considerably fewer open-bigram units relevant to target processing, implying that priming effects in this condition would be smaller than in the two superset conditions.

The results provided no support for the predictions of the open-bigram models. Experiment 1 employed the conventional masked priming procedure. In that experiment the three prime types produced essentially equivalent priming effects, a result predicted by Davis's (2010) Spatial-Coding model. In Experiment 2, the sandwich priming paradigm was used in order to get a strong control on the impact of lexical competition, a process that, at least in theory, could have differentially impacted the different conditions in Experiment 1. Again, there was no evidence of better priming from the superset primes and, in fact, the first-letter superset primes were significantly worse than the other two prime types. More specifically, as is typical with the sandwich priming manipulation, the priming effects were larger than those in the conventional masked priming situation (i.e., Experiment 1) for the last-letter superset and substitution-letter primes. Such was not the case, however, for the first-letter superset primes. This pattern was also somewhat at odds with the predictions of the Spatial-Coding model, which were that there would be equivalent priming in the three prime-type conditions. Finally, in the masked prime same-different task of Experiment 3, once again, there was no evidence that superset primes were better primes than substitution-letter primes. Instead, first-letter superset primes were again the weakest primes and last-letter superset primes now showed some evidence of being less effective than substitution-letter primes. These results were not predicted by either an open-bigram account assuming the orthographic code used in this task is the same one used in normal reading or Whitney's (2013) more recent account based on an extension of SERIOL.

With respect to the main issue being investigated here, whether it would be possible to find evidence for open-bigram units based on our superset manipulation, the clear answer was no. Every one of these experiments produced results inconsistent with the predictions made based on the existence of open-bigram units. What was also clear, however, is that a somewhat unexpected pattern emerged in Experiments 2 and 3. In both experiments, there was a large difference between the first-letter superset condition and the other conditions. The obvious question is, what, if any, are the implications of this pattern for models of orthographic coding?

There is a straightforward explanation of at least part of the difference between Experiment 1 and the other two experiments in terms of the methodology used. As previously noted, the impact of lexical competition should have been much less in Experiments 2 and 3 than in Experiment 1. That is, although primes (and targets) were selected so as to minimize the number of Coltheart et al. (1977) neighbors they possessed, there were undoubtedly other words in the neighborhood, that is, other words that were activated by the primes. Those words, which, in most cases, were also activated by the related targets, created competition during target processing, muting the priming effect. The sandwich priming manipulation in Experiment 2 involves the brief presentation of the target on all trials. The presumed impact is to inhibit the activation of potential lexical competitors. Hence, the size of the priming effect should more closely reflect the orthographic similarity of the prime and target. The masked prime same-different task in Experiment 3 is presumed to be carried out based solely on orthographic codes. Hence, by definition, it is unaffected by lexical competition. Therefore, the size of the priming effect in that task should also more closely reflect the orthographic similarity of the prime and target. The fact that the two tasks produced quite similar patterns is consistent with this analysis. More importantly, what this analysis implies is that, the orthographic codes of, for example, *wjudge* and *judge* are less similar than those of *judgew* and *judge* as well as those of *juwge* and *judge*.

This implication is at least somewhat consistent with a number of proposals concerning orthographic coding currently in the literature (Brühl & Imhoff, 1995; Guérard, Saint-Aubin, Poirier, & Demetriou, 2012; Humphreys, Evett, & Quinlan, 1990; Jordan, 1990; Jordan, Thomas, Patching, & Scott-Brown, 2003; White, Johnson, Liversedge, & Rayner, 2008). Those researchers have all claimed that external letters play a more important role in word recognition than internal letters. Jordan (1990), for example, argued that the end letters form a perceptual unit based on results showing that it was easier to report a target letter in a 500 ms two-letter display when the letters represented a legitimate beginning and ending of an English word (e.g., *d* k) than when they did not (e.g., s z). Jordan et al. (2003) further demonstrated that it was more difficult to read text when the two end letters of words were degraded than when other pairs of letters were degraded, including the initial two letters in the word. Humphreys et al. (1990), using a masked prime perceptual identification task, showed that targets were more readily identified when the four-letter primes shared first and last letters with their targets than when the primes and targets shared any other letter pairs (Experiment 1b), although the importance of end letters was much less clear in the remainder of their experiments. Those authors argued that end letters served as anchor points to aid in the coding of other letters.

Although these ideas could potentially explain the weaker priming effect from our first-letter superset primes, they are also based on the idea that the last letter is quite important too. Therefore, they would not seem to be completely consistent with the pattern reported here. That is, if end letters are important, one would expect that mismatching last letters in the prime and target would be just as problematic as mismatching first letters in the prime and target, a result that did not occur in the present Experiments 2 and 3.

Others researchers have argued for the importance of just the first letter. For example, Brühl and Imhoff (1995) using a boundary technique while monitoring eye movements during online reading have shown that providing the correct initial letters of the subsequent word is more helpful than providing other letters (including both external letters). Those authors, however, attributed this effect to the fact that the initial letters of a subsequent word were the most visible when that word was in the periphery. In contrast, White et al. (2008) did argue for the importance of first letters in general following their demonstration that transposing the initial letters of a word while reading was more harmful than transposing other letter pairs. Those authors suggested that initial letters might receive more activation than later letters (with the possible exception of last letters), which may cause initial letters to play a more important role in driving lexical activation.

The proposal that units representing the first letter in a word gain extra activation is reasonably consistent with the present data. Further, the general idea is not necessarily inconsistent with the Overlap model (Gómez et al., 2008), Davis's (2010) Spatial-Coding model or a number of the open-bigram models. In the Overlap model, letters in the end positions have less variability in the calculation of their position. That is, they are more clearly located in the first or last positions. In the Spatial-Coding model, units representing end letters will be tagged as being end letters. In both models, these assumptions serve to increase the similarity of the orthographic codes for letter strings and words sharing end letters. Presently, however, neither model makes a distinction between the nature of representations for the first versus the last letter. In the case of the Overlap model, it's unclear that the assumption of reduced variability in the position of the last letter can be dropped, which may be a bit problematic for the model. In the case of the Spatial-Coding model, the existence of last letter units is not a core assumption of the model and could easily be dropped. More crucially, however, when considering the model's ability to predict the present data, the impact of this extra component for first letters in the model is quite small. Therefore, in order to explain the data from Experiments 2 and 3, a parameter adjustment would be necessary.

In the open-bigram models, the extra impact of end letters comes about because of either higher activation levels (SERIOL—Whitney, 2001) or the existence of edge bigrams (Whitney & Marton, 2013). As in the other models, either of these assumptions increases the similarity of the orthographic codes for letter strings and words sharing end letters. Also as in those other models, no distinction is made between first and last letters (i.e., edge bigrams exist for both first and last letters) whereas the data suggest that first letters play a much more important role than last letters. Finally, as noted when considering the predictions in Experiment 1, the impact of the edge bigrams on processing is not large. Therefore, some additional assumptions would be necessary in order to account for the large difference between the first-letter superset condition and the others observed in Experiments 2 and 3 in terms of edge bigrams if one were to continue to advance an open-bigram account. It's possible, of course, that the assumption of higher activation levels for bigrams involving first letters in the 2001 version of SERIOL may have more success; however, that assumption seems to no longer be part of the model.

There are two additional issues that may be important in thinking about the pattern of priming effects in Experiments 2 and 3.

The first follows from Chanceaux and colleagues (Chanceaux & Grainger, 2012; Chanceaux, Mathôt, & Grainger, 2013) research on "flanker effects." In both of the superset conditions, the added letter serves as a flanker that has the impact of reducing the perceptibility of the letter it flanks. Thus, the first letter in the target would be less readily perceived in the first-letter superset condition than in the other conditions as would be the final target letter in the final-letter superset condition. More importantly, Chanceaux et al. (2013) have shown that left flankers are more potent than right flankers which, for the stimuli used here, could imply that the second letter in the prime might be the hardest letter to perceive. If so, the letter that is first letter of the target would be the hardest letter to perceive in first-letter superset primes. In final-letter superset and substitution-letter primes, it would be the second letter (of both the prime and target) that would be the hardest letter to perceive in the prime.

The question would be whether these ideas could help explain the weaker priming from first-letter superset primes in Experiments 2 and 3. The answer is potentially yes as long as one adds the assumption that the first letter in the target word is, for some reason, the most crucial letter required in establishing the orthographic code (i.e., the models would still need to be changed in some way to reflect the importance of the first letter). The reasoning would be as follows. Model calculations of orthographic similarity are all based on the idea that the reader knows the identity of the letters in the letter string being read. However, early in (prime) processing readers don't really know what the letters are and, therefore, according to this line of reasoning, early in processing what the system may be calculating in the first-letter superset condition is the orthographic similarity between a prime like *w**udge* and the lexical representation for *judge* (where * represents having very little knowledge about the letter in that position). In contrast in the substitution-letter condition, what the system might be calculating is the similarity between *j**wge* and *judge* and in the final-letter superset condition, the similarity between *j**dgew* and *judge*. If first letters are especially important, the lack of information about the existence of the *j* in the first-letter superset prime may diminish the similarity score substantially, hence diminishing the priming effect in that condition.

What this analysis also predicts, of course, is that a substitution prime involving the first letter (e.g., *yudge*) would be an even less effective prime than *wjudge* (because the *y* is the wrong letter and the *u* is so difficult to perceive). Although there does not appear to be a direct comparison of this sort in the literature, certainly not one involving a sandwich priming or masked prime same-different task, Adelman et al.'s (2014) megastudy did contain these two conditions. For the reasons listed in footnote 1, one does have to be careful in making this comparison; however, priming effects for primes like *yudge* were indistinguishable from priming effects for primes like *wjudge* (in fact, the actual difference was 2 ms in the nonpredicted direction).[2]

The second additional issue that may be important in thinking about the disadvantage for first-letter superset primes is that that disadvantage observed for first-letter superset primes only emerged in two tasks that are relatively new to the field, sandwich priming (Experiment 2) and masked prime same-different (Experiment 3) tasks. There was no evidence of this disadvantage in the conventional masked priming task (Experiment 1) nor in the megastudy (see footnote 1). That fact opens up the possibility that there may be some type of additional analysis going on in the newer tasks that, in some way, artifactually produced this disadvantage. For example, possibly the existence of a representation of the target (either as an initial prime in sandwich priming or as a reference stimulus in the masked prime same-different task), may have caused participants to engage some sort of left-to-right processing/matching on the prime of interest, processing that can only analyze a few of its letters before the target arrives. A mismatch at the initial position may mute the priming effect for first-letter superset primes through some sort of inhibitory process in a way that somewhat parallels the priming pattern in the masked onset priming literature (Dimitropoulou, Duñabeitia, & Carreiras, 2010; Forster & Davis, 1991; Kinoshita, 2003; Schiller, 2008). Although there is no obvious mechanism for how this process might work in these tasks, in contrast to how it follows as a logical consequence of phonological coding in the masked onset priming literature, the present data provide no evidence against such a proposal. If this proposal were correct, however, the implication would still be that the present data provide no evidence for the superior priming from the superset primes predicted by the open-bigram models.[3]

## Adelman's (2011) LTRS Model

There is one additional way of thinking about the different size priming effects in the three conditions in Experiments 2 and 3. In Adelman's (2011) model, priming effects are viewed as being a function of the amount of time that the prime activates the target before sufficient evidence is obtained that they are not identical. That is, early perceptual processing of a prime like *juwge* will activate the processing structures for *judge* until the system recognizes that there is a *w* rather than a *d* in the third position. No lexical competition processes are assumed to contribute to the effects.

In all the experiments reported here, the model would predict that the substitution-letter primes would be the most effective primes and the first-letter superset primes would be the least effective primes because detecting a mismatch in the middle of a word is more difficult than detecting one at the end of a word, which is more difficult than detecting one at the beginning of a word. Thus, the model would get the general pattern in Experiment 3 correct although it would have a bit less success with the pattern in Experiment 2. It would have even less success with the pattern in Experiment 1 although it was the conventional masked priming task that served as one of the main tasks motivating the model.

A final point to be made is that, for the same reasons that the model would predict the substitution-letter priming advantage, the model would also predict that priming effects would increase as target length increases for all prime types (i.e., it is harder to detect mismatches in longer strings). Although no attempt was made to match the five-, six-, seven- and eight-letter targets on any factors (e.g., frequency), meaning that a comparison between them is potentially problematic, there was little evidence for the predicted relationship in the data of Experiment 1. Overall priming effects for the five-, six-, seven- and eight-letter targets were 36, 31, 36 and 41 ms, respectively.

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[2] We thank an anonymous reviewer for bringing these issues to our attention.

[3] We thank Dennis Norris for bringing this idea to our attention.

## Sandwich Priming Versus the Masked Prime Same-Different Task

As noted above, two techniques have recently been introduced into the literature that allow an investigation of the nature of the orthographic code in a situation where lexical competition should not impact the data, sandwich priming and the masked prime same-different task. The present research appears to represent the first opportunity to contrast these two techniques. The similarity of results in Experiment 2 and 3 indicates that, at least in the present situation, they may be telling the same story. In the same-different task, an orthographic code for the reference stimulus is presumed to be initially established. On same trials (i.e., when the reference and the target match), a prime orthographically similar to the target will provide evidence for components of that code, which will incline participants toward a same response. Thus, the size of the priming effect should provide a good measure of the orthographic similarity of the reference/target and the prime. On different trials, although the prime will be orthographically similar to the target on related trials it will not be orthographically similar to the reference on either related or unrelated trials because the reference and the target are different stimuli. Thus, as is typically observed, there will be no priming effect on different trials (Duñabeitia et al., 2011; Kinoshita & Norris, 2009; Norris & Kinoshita, 2008).

In sandwich priming the role of the initial prime, the target word itself, is to kill off the activation of target neighbors diminishing the impact of lexical competition. Therefore, whatever priming the prime produces by further activating the target is a reflection of the similarity of the prime's and target's orthographic codes. If all of these assumptions are correct, the implication is that the priming patterns in the two tasks should be parallel because, in both cases, they document the similarity of the prime's and target's orthographic codes. The very similar priming effects in Experiments 2 and 3 nicely support these assumptions.

One thing to note here is that neither of these explanations is based on the idea that preactivation of letter level representations is the source of any priming effects. In the sandwich priming task, the orthographic codes are driving lexical activation that is the source of the priming effects. In the masked prime same different task, the prime does not activate the letter level representations of the target facilitating its processing (and any target activation it provides at the lexical level is irrelevant to the task). It merely provides evidence for the orthographic code established by the reference stimulus. As a result, there is no priming for targets that do not match the reference (i.e., on different trials). Note further that this analysis is consistent with the finding that nonword targets do not typically show priming in a lexical-decision task even when primed by themselves.

## Conclusions

The idea of open-bigram units as a level of representation when reading words is an interesting one. However, to this point, models based on the open-bigram assumption have not had any more success explaining masked priming data than most other types of models. In the present research an effort was made to garner evidence for the existence of open-bigram units by examining priming situations where open-bigram models would predict a strong priming effect. No such effect was found across three experiments. Therefore, it appears that models not based on the existence of open-bigram units, such as Davis's (2010) Spatial-Coding model or Gómez et al.'s (2008) Overlap model, are more likely to provide a better account of the orthographic coding process.

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(*Appendix follows*)

# Appendix

## Word Targets and Primes Used in Experiments 1, 2, and 3

| | Primes | | | | | |
|---|---|---|---|---|---|---|
| Targets | SSF-Rel | SSL-Rel | Sub-Rel | SSF-Unrel | SSL-Unrel | Sub-Unrel |
| STERN | zstern | sternz | stzrn | zbegun | begunz | bezun |
| BEGUN | zbegun | begunz | bezun | zstern | sternz | stzrn |
| SPINE | zspine | spinez | spzne | zevils | evilsz | evzls |
| EVILS | zevils | evilsz | evzls | zspine | spinez | spzne |
| ARISES | zarises | arisesz | arzses | zscream | screamz | sczeam |
| BRIGHT | zbright | brightz | brzght | zarises | arisesz | arzses |
| SCREAM | zscream | screamz | sczeam | zbright | brightz | brzght |
| DESERVES | zdeserves | deservesz | deszrves | zpainters | paintersz | paizters |
| PAINTERS | zpainters | paintersz | paizters | zdeserves | deservesz | deszrves |
| PROPOSE | zpropose | proposez | prozose | zrailway | railwayz | raizway |
| RAILWAY | zrailway | railwayz | raizway | zpropose | proposez | prozose |
| TRIBUNE | ztribune | tribunez | trizune | zrocking | rockingz | roczing |
| ROCKING | zrocking | rockingz | roczing | ztribune | tribunez | trizune |
| SPEND | vspend | spendv | spvnd | vblown | blownv | blvwn |
| BLOWN | vblown | blownv | blvwn | vchill | chillv | chvll |
| CHILL | vchill | chillv | chvll | vspend | spendv | spvnd |
| ALWAYS | valways | alwaysv | alvays | vstated | statedv | stvted |
| ROUNDS | vrounds | roundsv | rovnds | vkissed | kissedv | kivsed |
| STATED | vstated | statedv | stvted | valways | alwaysv | alvays |
| KISSED | vkissed | kissedv | kivsed | vrounds | roundsv | rovnds |
| PENSION | zpension | pensionz | penzion | zcleaned | cleanedz | clezned |
| CLEANED | zcleaned | cleanedz | clezned | zpension | pensionz | penzion |
| TISSUES | ztissues | tissuesz | tiszues | zamended | amendedz | amezded |
| AMENDED | zamended | amendedz | amezded | ztissues | tissuesz | tiszues |
| RECOUNTS | zrecounts | recountsz | reczunts | zclearing | clearingz | clezring |
| CLEARING | zclearing | clearingz | clezring | zrecounts | recountsz | reczunts |
| IDEAL | xideal | idealx | idxal | xwhite | whitex | whxte |
| WHITE | xwhite | whitex | whxte | xevery | everyx | evxry |
| EVERY | xevery | everyx | evxry | xideal | idealx | idxal |
| SLIPPER | xslipper | slipperx | slixper | xtightly | tightlyx | tigxtly |
| RELIEVE | xrelieve | relievex | relxeve | xpraised | praisedx | praxsed |
| TIGHTLY | xtightly | tightlyx | tigxtly | xslipper | slipperx | slixper |
| PRAISED | xpraised | praisedx | praxsed | xrelieve | relievex | relxeve |
| RELENTED | xrelented | relentedx | relxnted | xofficers | officersx | offxcers |
| OFFICERS | xofficers | officersx | offxcers | xproclaim | proclaimx | proxlaim |
| CROUCHED | xcrouched | crouchedx | croxched | xrelented | relentedx | relxnted |
| PROCLAIM | xproclaim | proclaimx | proxlaim | xcrouched | crouchedx | croxched |
| COMMIT | zcommit | commitz | cozmit | zsinger | singerz | sizger |
| SINGER | zsinger | singerz | sizger | zcommit | commitz | cozmit |
| ENACT | zenact | enactz | enzct | zgrips | gripsz | grzps |
| SLUMP | zslump | slumpz | slzmp | zenact | enactz | enzct |
| GRIPS | zgrips | gripsz | grzps | zslump | slumpz | slzmp |
| THUNDER | wthunder | thunderw | thuwder | wbottles | bottlesw | botwles |
| BOTTLES | wbottles | bottlesw | botwles | wthunder | thunderw | thuwder |
| CONFIRM | wconfirm | confirmw | conwirm | wstrives | strivesw | strwves |
| STRIVES | wstrives | strivesw | strwves | wconfirm | confirmw | conwirm |
| REPRINTS | wreprints | reprintsw | repwints | wsneakers | sneakersw | snewkers |
| SNEAKERS | wsneakers | sneakersw | snewkers | wreprints | reprintsw | repwints |
| NOTION | wnotion | notionw | nowion | wnearby | nearbyw | newrby |
| NEARBY | wnearby | nearbyw | newrby | wnotion | notionw | nowion |
| SIGHT | zsight | sightz | sizht | zbegin | beginz | bezin |
| BEGIN | zbegin | beginz | bezin | zsight | sightz | sizht |
| FORGE | zforge | forgez | fozge | znerve | nervez | nezve |
| NERVE | znerve | nervez | nezve | zsweep | sweepz | swzep |
| SWEEP | zsweep | sweepz | swzep | zforge | forgez | fozge |
| JUDGED | zjudged | judgedz | juzged | zstripe | stripez | stzipe |

(*Appendix continues*)

Appendix (*continued*)

| | Primes | | | | | |
|---|---|---|---|---|---|---|
| Targets | SSF-Rel | SSL-Rel | Sub-Rel | SSF-Unrel | SSL-Unrel | Sub-Unrel |
| STRIPE | zstripe | stripez | stzipe | zjudged | judgedz | juzged |
| TOURISTS | ztourists | touristsz | touzists | zmarching | marchingz | marzhing |
| MARCHING | zmarching | marchingz | marzhing | ztourists | touristsz | touzists |
| STATURE | xstature | staturex | staxure | xbounced | bouncedx | bouxced |
| BOUNCED | xbounced | bouncedx | bouxced | xstature | staturex | staxure |
| BLAST | xblast | blastx | blxst | xaloud | aloudx | alxud |
| ALOUD | xaloud | aloudx | alxud | xblast | blastx | blxst |
| SLAYING | xslaying | slayingx | slaxing | xqualify | qualifyx | quaxify |
| QUALIFY | xqualify | qualifyx | quaxify | xslaying | slayingx | slaxing |
| SPARK | vspark | sparkv | spvrk | vplate | platev | plvte |
| PLATE | vplate | platev | plvte | vspark | sparkv | spvrk |
| LEARN | vlearn | learnv | levrn | vunits | unitsv | unvts |
| UNITS | vunits | unitsv | unvts | vlearn | learnv | levrn |
| STRINGY | vstringy | stringyv | strvngy | vappears | appearsv | appvars |
| MATCHES | vmatches | matchesv | matvhes | vreports | reportsv | repvrts |
| APPEARS | vappears | appearsv | appvars | vstringy | stringyv | strvngy |
| REPORTS | vreports | reportsv | repvrts | vmatches | matchesv | matzhes |
| SAVAGELY | zsavagely | savagelyz | savzgely | zslightly | slightlyz | slizhtly |
| WASHED | zwashed | washedz | wazhed | zstrike | strikez | stzike |
| STRIKE | zstrike | strikez | stzike | zwashed | washedz | wazhed |
| RECKONED | zreckoned | reckonedz | reczoned | zsavagely | savagelyz | savzgely |
| SLIGHTLY | zslightly | slightlyz | slizhtly | zreckoned | reckonedz | reczoned |

*Note.* SSF = Superset first-letter; SSL = Superset last-letter; Sub = Substitution; Rel = related; Unrel = Unrelated.

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