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Is zjudge a Better Prime for JUDGE Than zudge Is?: A New Evaluation of Current Orthographic Coding Models

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Three masked priming paradigms, the conventional masked priming lexical-decision task (Forster & Davis, 1984), the sandwich priming task (Lupker & Davis, 2009), and the masked priming same-different task (Norris & Kinoshita, 2008), were used to investigate priming for a given target (e.g., JUDGE) from primes created by either adding a letter to the beginning of the target (e.g., zjudge) or replacing the target's initial letter (e.g., zudge). Virtually all models of orthographic coding that allow calculation of orthographic similarity measures predict that zjudge should be the better prime because zjudge contains all the letters in JUDGE in their correct order whereas zudge does not. Nonetheless, Adelman et al.'s (2014) megastudy data indicated no difference in the effectiveness of these two prime types. The present experiments provide additional support for the conclusion of no difference between these two prime types with the only observed difference being a small zudge prime advantage in Experiment 1b (sandwich priming). These results suggest that models of orthographic coding/word recognition may be well served by allowing inconsistent information (e.g., the "z" in both zjudge and zudge indicates that the presented prime is not JUDGE) to be given considerable weight during the orthographic coding/word recognition process.

Public Significance Statement
To understand the reading process, it is crucial to understand how the orthographic coding process is carried out. Our findings suggest that the importance of negative information in that process (e.g., there is not a "j" in the word being read) has been overlooked in most models of the reading process, implying that the importance of positive information may be being overstated in current models and in reading instruction.

Keywords: lexical decision, masked priming, orthographic coding models

Over the past two decades, there has been a considerable increase in the efforts of word recognition researchers to understand the nature of the "orthographic code" (Grainger, 2008). The orthographic code is the mental representation of the letters/characters in the word being read, a representation that is assumed to drive all subsequent processing (e.g., lexical, semantic, etc.). This representation must contain not only information about the letters'/characters' identities but also their order. That is, successful reading requires that both types of information be successfully identified so as not to mistake the word *face* for the word *fact* or the word *trial* for the word *trail*.

The task most frequently used to investigate the nature of the orthographic code has been the conventional masked priming lexical-decision task (Forster & Davis, 1984). In this task, a lowercase prime that, on "related" trials, is orthographically similar to the subsequent target, is initially and briefly presented. It is followed by an uppercase target presented in the same physical position as the prime on the computer screen. The target serves as a backward mask for the prime. The result is that the prime is rarely, if ever, available to consciousness. Nonetheless, priming effects do emerge. That is, responding is faster following related primes than following unrelated primes (Davis & Lupker, 2006; Forster & Davis, 1984; Segui & Grainger, 1990), at least when those primes are nonwords (e.g., hoise-HOUSE vs. brean-HOUSE).

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In the years since this paradigm was invented, a number of orthographic coding models have been proposed and, in many cases, integrated into models of word recognition (Adelman, 2011; Davis, 2010; Gómez, Ratcliff, & Perea, 2008; Grainger & Van Heuven, 2003; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Norris & Kinoshita, 2012; Norris, Kinoshita, & Van Caasteren, 2010; Schoonbaert & Grainger, 2004; Whitney, 2001; Whitney & Marton, 2013). Initially, it was assumed that one could test between these models simply by examining the size of the priming effects produced by various types of related primes in the conventional task. That is, it was assumed that the size of the priming effects would document the orthographic similarity of the primes and targets, providing support for some of the models but not for others.

Unfortunately, that assumption has been proven wrong by the fact that the sizes of the priming effects in the conventional task depend on other factors, for example, the lexicality of the prime (Davis & Lupker, 2006; Segui & Grainger, 1990—word primes produce much smaller priming effects than nonword primes, often producing inhibition rather than facilitation), as well the size/density of the orthographic neighborhood activated by the prime (Forster, Davis, Schokencht, & Carter, 1987; Nakayama, Sears, & Lupker, 2008) and the target word's frequency (Davis & Lupker, 2006). As a result, two new paradigms, the sandwich priming paradigm (Lupker & Davis, 2009) and the masking priming same-different task (Duñabeitia, Kinoshita, Carreiras, & Norris, 2011; Kinoshita & Norris, 2009; Norris & Kinoshita, 2008), paradigms that appear to be less affected by these extraneous factors than the conventional task is, have been developed as additional tools for investigating the orthographic coding process. Because these tasks will be used in the present investigation, they will be described in greater detail below.

The specific focus of the present experiments is a contrast between two prime types that was initially reported in the masked form priming megastudy by Adelman et al. (2014). That contrast is between primes in which the initial letter in the target is replaced (e.g., zudge-JUDGE) and primes in which the replacement letter is added to the front of the target (i.e., zjudge-JUDGE). As will be discussed below and documented in simulations using the easyNet software (Davis, Adelman, & Gubian, 2016), most current models of orthographic coding regard zjudge as being more orthographically similar to JUDGE than zudge is. The reason is that zjudge contains all the letters in JUDGE in their correct order whereas zudge does not and, in addition, the letter that is missing in zudge is the initial letter, a letter that is thought to have special significance in the word recognition process (Aschenbrenner, Balota, Weigand, Scaltritti, & Besner, 2017; Blais et al., 2009; Briihl & Inhoff, 1995; Bruner & O'Dowd, 1958; Guérard, Saint-Aubin, Poirier, & Demetriou, 2012; Humphreys, Evett, & Quinlan, 1990; Inhoff & Tousman, 1990; Jordan, 1990; Jordan, Thomas, Patching, & Scott-Brown, 2003; McCloskey, Fischer-Baum, & Schubert, 2013; McCusker, Gough, & Bias, 1981; Scaltritti & Balota, 2013; Scaltritti, Dufau, & Grainger, 2018; White, Johnson, Liversedge, & Rayner, 2008). Hence, as will be documented in the simulations, most models predict that zjudge should be a better prime for JUDGE than zudge is. Adelman et al., however, reported no significant difference between the two prime types and, in fact, numerically, there was a small priming advantage for zudge-type primes (24 ms) over zjudge-type primes (22 ms), a result that would appear to present more than a minimal challenge to most current models of orthographic coding.[1]

At present, there does not appear to be a direct replication of the zjudge-zudge contrast in the literature. There have been a few studies other than Adelman et al.'s (2014) investigating priming from primes containing not only the whole target but also an extra letter or two ("superset" primes; Ktori, Midgley, Holcomb, & Grainger, 2015; Lupker, Zhang, Perry, & Davis, 2015; Van Assche & Grainger, 2006; Welvaert, Farioli, & Grainger, 2008), although only Lupker et al.'s experiments involved zjudge-type primes, that is, superset primes created by adding a letter to the front of the target. The specific contrast that Lupker et al. investigated, however, is not the contrast of interest here. Rather, their most relevant contrast with respect to the present context was between the zjudge-type primes and juzge-type primes, that is, primes in which a middle letter, rather than the initial letter, was substituted.

What Lupker et al.'s (2015) results showed was no zjudge-type prime advantage over juzge-type primes and, in fact, in two of their three experiments (the sandwich priming and same-different task experiments) there was a zjudge-type prime disadvantage. The lack of a zjudge-type prime advantage in the contrast with juzge-type primes does cause a problem for certain types of orthographic coding models, in particular, many of the open-bigram models in which the letters in the middle of the word play a central role in determining which open bigrams are activated. However, this result may not necessarily cause a serious problem for models that assume that having the target's initial letter in the prime is important in the priming process (e.g., SERIOL—Whitney, 2001; Spatial-coding—Davis, 2010) because the target's initial letter is contained in both zjudge- and juzge-type primes. The lack of a zjudge-type priming advantage in the zudge-zjudge contrast, however, the contrast investigated here and by Adelman et al. (2014), would appear to be quite problematic for most of the current models.

More specifically, Adelman et al.'s (2014) results present a serious challenge for every model that assumes that target activation is derived from "positive evidence," that is, how well the set of letters in the prime match the set of letters in the target. Unfortunately, however, the empirical contrast created in Adelman et al.'s experiment is itself problematic because separate unrelated (i.e., control) conditions were not used for the two types of related primes. Rather, a single unrelated condition was used in which those primes were the same length as the zudge-type primes and, hence, were always shorter than the zjudge-type primes. If longer unrelated primes had been included to serve as the control primes for the zjudge-type primes, it's certainly possible that they may

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[1] The older, slot-coding models, for example, McClelland and Rumelhart's (1981) Interactive-Activation model, would not necessarily predict a zjudge-type prime advantage because the four letters shared by zudge and JUDGE are in the same absolute positions (i.e., slots) whereas none of the letters shared by zjudge and JUDGE are in the same absolute positions. These models, however, have very little ability to predict most of the priming effects in the more recent literature, for example, transposed-letter priming effects (e.g., Perea & Lupker, 2003, 2004). Similarly, models based on the idea that letter positions are coded relative to end letters positions (e.g., Fischer-Baum, Charny, & McCloskey, 2011) would not necessarily predict a zjudge-type prime advantage. However, those types of models also would have difficulty explaining other lexical processing phenomena such as transposed-letter priming effects.

have produced longer latencies and, hence, a larger zjudge priming effect.[2] This particular confound was removed in the present experiments as the unrelated primes for each condition were the same length as the related primes for that condition.

The Newer Experimental Paradigms

As noted, more recently, two new experimental paradigms for examining orthographic coding have been developed, paradigms that appear to provide a clearer view of the orthographic coding process than that provided by the conventional masked priming lexical-decision task. One is Lupker and Davis's (2009) sandwich priming paradigm. In this paradigm, an additional initial prime is presented on each trial with that prime being identical to the target (e.g., judge would precede either the prime zjudge, the prime zudge or any unrelated prime for the target JUDGE). The result of doing so is that priming effects are enhanced (e.g., Davis & Lupker, 2017; Lupker & Davis, 2009).

According to Davis's (2010) Spatial-coding model, there are two reasons for the increase in priming. One is that the initial prime (i.e., the target) activates that target, allowing it to be a stronger competitor during the lexical activation process when it is ultimately presented as a target. The second is that when the first prime is removed, all activated word nodes, most importantly the target word's node, begin to decay. If a second prime is presented immediately, it affects the rate of decay of the target word's node with that rate being a function of the second prime's orthographic similarity to the target.[3] In the published version of the Spatial-coding model's simulation of the sandwich priming task (Davis, 2010), it is this second factor that is mainly responsible for the enhanced priming. Because the sandwich priming paradigm enhances the sizes of the priming effects, it has the potential to allow a clearer answer to the question of how orthographically similar various primes are to their targets.

The second new paradigm is the masked priming same-different task (Duñabeitia et al., 2011; Kinoshita & Norris, 2009; Norris & Kinoshita, 2008, 2012). This task involves an initial presentation of a visible reference stimulus, followed by a brief masked prime and, subsequently, a target. The task is to decide whether the target and reference stimulus are the same. When they are the same, orthographically similar primes produce significant priming effects, effects that are essentially independent of the frequency or lexical status of the target (e.g., Duñabeitia et al., 2011; Kinoshita & Norris, 2009; Norris & Kinoshita, 2008). The implication of this independence is that this task seems to tap directly into the orthographic coding process, suggesting that this task also provides a better way of answering the question of how similar two letter strings are to one another than is provided by the conventional masked priming lexical-decision task.

What is also important to note about the masked priming same-different task is that on "different" trials (i.e., when the reference stimulus and target are different), primes similar to the targets do not produce a priming effect. However, there is often inhibition when the prime is similar to the reference stimulus on those "different" trials (Perea, Moret-Tatay, & Carreiras, 2011). Hence, what the task appears to be documenting is the orthographic similarity of the prime and the reference stimulus rather than the prime and the target. Both new paradigms, along with the conventional masked priming lexical-decision task, were used in the present investigation of the zjudge-zudge contrast.

Experiment 1a employed a conventional masked priming lexical-decision task, Experiment 1b employed a sandwich priming task, and Experiment 1c employed a masked priming same-different task. In all experiments, the nature of the added/substituted letter was also manipulated. That is, one set of participants received primes in which that letter was a consonant (e.g., zjudge and zudge) whereas the other set received primes in which that letter was a vowel (i.e., ojudge and ougde). One could imagine that primes like zjudge could potentially suffer from the fact that they contain an orthographic illegality (i.e., "zj" is a bigram that rarely, if ever, occurs in English). In contrast, the vowel primes create few, if any, bigram illegalities in either the ojudge or ougde conditions.

Model Predictions

Recently, the easyNet software package has become available online (http://adelmanlab.org/easyNet/) giving researchers the ability to simulate performance in both the conventional masked priming lexical-decision task and the sandwich priming task. EasyNet simulations were performed for two models, Davis's (2010) Spatial-coding model and Grainger and Van Heuven's (2003) open-bigram model. In addition, predictions were provided for Adelman's (2011) Letters in Time and Retinotopic Space (LTRS) model by the model's creator.[4] The Spatial-coding model was taken as being representative of what Davis and Lupker (2017) referred to as "noisy position models." Further, two versions of the Spatial-coding model were examined, one containing the "end-letter marking" assumption, an assumption that gives special status to the initial and final letters in the orthographic code, and one in which that assumption is dropped. This assumption is the default assumption in the model and it may be important for the zjudge-zudge comparison as the zjudge-type primes do contain the target's initial letter (albeit not in the initial position).

Grainger and Van Heuven's (2003) open-bigram model was taken as a representative of what Davis and Lupker (2017) referred to as "local context" models. The Grainger and Van Heuven model served as the basis for subsequent open-bigram models from those researchers (i.e., Grainger et al., 2006; Schoonbaert & Grainger, 2004) and has proven to be quite successful at explaining data from many orthographic priming experiments (Adelman et al., 2014). (In Experiment 1c, in which the same-different task was used, it was possible to examine a few additional open-bigram models.)

A third model evaluated was, as noted, Adelman's (2011) LTRS model. This model is especially interesting because it differs from

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[2] Although there does not appear to be any reliable data suggesting that prime length, per se, affects target latencies when the primes are unrelated, one issue that is created by using primes that are different lengths than their targets is that it changes the spatial relationship on the computer screen between a prime and its target. Because the target is supposed to act as a backward mask for the prime, its ability to mask could certainly be somewhat different when the prime and target are different lengths versus when they are the same length.

[3] For a similar account of the additional priming in the sandwich priming task see Trifonova and Adelman (2018).

[4] We thank James Adelman for providing us with these predictions.

the other two types of models in a potentially important way (as will be discussed more fully below). That is, it is much more sensitive to the existence of inconsistent information (e.g., the “z” in both zjudge and zudge) than the existence of consistent information (i.e., the fact that zjudge contains all the letters in JUDGE).

The predictions for the three models based on the primes and targets used in Experiments 1a (conventional priming) are contained in Table 1 as are the predictions for the Spatial-coding model and the open-bigram model for Experiment 1b (sandwich priming). As noted, some participants received primes in which the added/substituted letter was always a consonant (e.g., zudge/zjudge) whereas others received primes in which the added/substituted letter was always a vowel (e.g., oudge/ojudge). Although one can imagine that this factor might matter to participants, the models’ predictions did not vary as a function of the nature of the added/substituted letter. Therefore, the predictions in Table 1 are averages of the vowel and consonant conditions.

A convenient feature of the Spatial-coding model is that it is scaled in such a way as to provide predicted effect sizes in ms. As is obvious from Table 1, that model predicts a larger priming effect in both the conventional and sandwich priming tasks for the zjudge-type primes, 12 versus 28 ms in the conventional task and 40 versus 49 ms in the sandwich priming task for the zudge-type versus zjudge-type primes, respectively, when the end-letter marking assumption is maintained. Dropping the end-letter marking assumption causes the predicted priming effects and the zudge-zjudge difference to grow slightly (15 vs. 37 ms and 43 vs. 60 ms for the zudge-type and zjudge-type primes in Experiments 1a and 1b, respectively). However, the general pattern essentially remained the same. The model predicts that zjudge should be a better prime than zudge in both situations. Note also that the model does make the expected prediction that priming effects will be larger in the sandwich priming task than in the conventional task.

The essential reason that the model predicts a zjudge-type prime advantage is because of how the model calculates orthographic similarity scores. Specifically, the model yields a high similarity score between two letter strings when the full letter pattern contained in one is also contained in the other, even when that pattern is shifted. A good example would be the words CAT and HOUSECAT. The motivation for this way of calculating orthographic similarity scores is that the model should have a means of elevating the similarity of words of this type because those words often share meanings. The lack of a match between the HOUSE in HOUSECAT and any letters in CAT does affect the calculated orthographic similarity score; however, the orthographic similarity score for these words is mainly driven by the fact that the letter string C-A-T is contained in both words.

The Grainger and Van Heuven (2003) model does not produce predicted priming effects in terms of ms but rather, produces relative priming effect sizes. As Davis and Lupker (2017) note, scaling predicted relative priming effect sizes by a factor of 10 has allowed the model to do a good job of predicting priming effects

Table 1
Predicted Priming Effects (in Cycles) in Experiments 1a and 1b for Davis’s (2010) Spatial-Coding Model With and Without the End-Letter Marking Assumption, Grainger and Van Heuven’s (2003) Open-Bigram Model, and in ms for Adelman’s (2011) LTRS Model

Davis’s (2010) Spatial-coding model						
	Experiment 1a (conventional masked priming)					
	With end-letter marking			Without end-letter marking		
Prime type	Rel	Unrel	Effect	Rel	Unrel	Effect
zjudge	79	107	28 ms	73	110	37 ms
zudge	93	105	12 ms	92	107	15 ms
	Experiment 1b (sandwich priming)					
	With end-letter marking			Without end-letter marking		
Prime type	Rel	Unrel	Effect	Rel	Unrel	Effect
zjudge	55	104	49 ms	47	107	60 ms
zudge	63	103	40 ms	62	105	43 ms
Grainger and Van Heuven’s (2003) open-bigram model						
	Experiment 1a (conventional)			Experiment 1b (sandwich)		
Prime type	Rel	Unrel	Effect	Rel	Unrel	Effect
zjudge	18.98	24.33	5.35	17.39	26.76	9.37
zudge	20.22	24.26	4.04	19.81	26.71	6.90
Adelman’s (2011) LTRS Model						
	Experiment 1a (conventional)					
Prime type	Effect					
zjudge	15 ms					
zudge	17 ms					

Note. LTRS = Letters in Time and Retinotopic Space.

in many circumstances. Using a scaling factor of 10 in the present circumstances, Grainger and Van Heuven's (2003) model predicts a 14-ms zjudge-type prime advantage (40 vs. 54 ms) in the conventional task and a 25-ms zjudge-type prime advantage (69 vs. 94 ms) in the sandwich priming task as well as predicting a larger priming effect in the latter task (see Table 1). Because the overall priming effects in Experiments 1a and 1b were actually somewhat smaller than these, a scaling factor of 5 would seem to be more appropriate, a value that would allow the model to fairly closely simulate the *overall* priming effect sizes in both experiments. If so, the predicted effect sizes reported above would be halved. The important point, however, is that regardless of what scaling factor is assumed, the model will still predict a zjudge-type prime advantage.

The essential reason the model predicts a zjudge-type prime advantage is that all the open-bigrams involved in processing JUDGE (JU, JD, JG, UD, UG, UE, DG, DE and GE) are activated when processing zjudge. Such would also be the case for most of the other open-bigram models (e.g., Grainger et al., 2006; Schoonbaert & Grainger, 2004; Whitney, 2001). As a result, as shown in Table 2 in which the orthographic similarity scores for a number of models are presented, the orthographic similarity scores that open-bigram models produce for zjudge-type primes and their targets are virtually 1.00 (except for SERIOL, Whitney, 2001, for the reasons discussed below). In contrast, a number of open-bigrams (i.e., all those involving "J") are not activated when processing zudge, meaning that zudge-type primes have similarity scores that are somewhat smaller than 1.00.

Table 1 also contains predictions from Adelman's (2011) LTRS model for the sizes of the priming effects in the conventional task. Like the Spatial-coding model, it is possible to derive predictions for priming in the conventional task in ms. What is notable is that the model does not predict a zjudge-type priming advantage. In fact, the small difference that it does predict goes in the opposite direction. The reason is that the word recognition process in the model is uniquely sensitive to negative (i.e., disconfirming) information. More specifically, evidence supporting any lexical candidate (e.g., the "e" in both zjudge and zudge for the candidate JUDGE) accumulates during prime processing. That evidence consists of both identity information (e.g., there is an "e" in the prime) and, subsequently, precise position information (e.g., there is no letter to the right of the "e" in the prime). As long as no disconfirming information is detected, what can be regarded as the activation level of all viable lexical candidates continues to increase as a function of time.

When disconfirming information (i.e., information inconsistent with a lexical candidate) is discovered, however (i.e., the "z" in both zjudge and zudge for the candidate JUDGE), the activation process for that lexical candidate stops with the relevant lexical representation maintaining whatever level of activation it had achieved (for at least a short period of time). The arrival of the main source of disconfirming information (i.e., the "z") would tend to occur at approximately the same point in time from the primes zjudge and zudge, meaning that the activation for JUDGE would reach approximately the same level following those two primes. Thus, the processing time for the prime is also a key component of the model.[5]

A couple of additional points should be made about the LTRS. First, its predictions are based on how much longer the target representation receives activation in the related versus unrelated prime conditions (i.e., the difference in activation levels achieved in the two situations). Therefore, all that can be derived is a difference score (i.e., a predicted priming effect) rather than a cycles to completion score for the four prime-type conditions.

Second, because processing time for the prime (before the disconfirming information concerning the target is identified) is a key issue for the model, the model's predictions are dependent on prime duration (55 ms in the present experiments). It is the fact that the present prime duration used was as long as it was (i.e., 55 ms) that allowed the small difference between the two prime types to emerge. With less time to process the prime (i.e., with a shorter prime duration), the system would be less likely to have sufficient time to distinguish among the various (related and unrelated) prime types (i.e., to find disconfirming information) and, of course, the overall time that the prime could continue to support the target would be shortened in any case. Therefore, with, for example, a 25-ms prime duration, the model would predict only a priming effect of 8 ms for both prime types.

A final point to note is that the model, as currently instantiated, makes no assumptions as to how the sandwich priming task should be modeled. As Adelman (personal communication, January 16, 2020) has indicated, there are a few possibilities for how the system could be changed to reflect processing in that task. For example, one could assume that some parameter or parameters are different in sandwich priming than in the conventional task because the presentation of the initial prime (i.e., the target) changes the visual conditions of the experiment. Or, one could assume the existence of some kind of inhibition process in the sandwich priming task that engages when incongruent information (from the prime of interest) is detected. This second type of change would be more extensive because it would involve adding parameters, not just changing existing ones. In general, however, because the priming effects would be presumed to be based on the same source in the two tasks (the length of time during which the target receives activation from the prime of interest), the relative priming effects would likely not be affected. Therefore, the model would still predict essentially equal priming in the zjudge and zudge conditions. Until the model incorporates some assumptions concerning how changing the task changes the processing, however, what the model would not predict is the larger priming effects for both prime types in the sandwich priming task.

At present, there are no publicly available simulations for generating predictions in the masked priming same-different task for any of the models being examined here. However, those predictions can be reasonably well simulated by using prime-target similarity scores for models that can produce such scores. Not included in Table 2 are any predictions for the LTRS model because, as noted, it does not allow the calculation of similarity scores. However, as just discussed when considering sandwich priming, the priming effects it predicts would be based on how long prime processing provides activation to the target. Therefore, its predictions in Experiment 1c would be essentially the same as

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[5] The small advantage for zudge-type primes is likely to attributable to the fact that the zjudge-type primes contain an addition piece of disconfirming information with respect to the target JUDGE, that the j in the prime has a letter to its left.

Table 2
Similarity Scores Between the Targets and Both Related and Unrelated Primes of Both Types From Experiments 1a, 1b and 1c According to the Spatial-Coding Model and Three Open-Bigram Models

Model	Prime type					
	zjudge			zudge		
	Rel	Unrel	Diff	Rel	Unrel	Diff
Davis's (2010) Spatial-coding	.87	.15	.72	.73	.13	.60
Schoonbaert & Grainger's (2004) open-bigram	1.00	.03	.97	.71	.02	.69
Grainger et al.'s (2006) Overlap open-bigram	.99	.04	.95	.75	.03	.72
Whitney's (2001) SERIOL open-bigram	.61	.03	.58	.30	.03	.27

its predictions in Experiments 1a and 1b (i.e., small and essentially equivalent priming effects for the two prime types) with the model, again, having no established way of predicting the expected larger overall priming effects in that task.

In Table 2, one can find the similarity scores for the Spatial-coding model as well as the two antecedents of Grainger and Van Heuven's (2003) original open-bigram model, that is, Schoonbaert and Grainger's (2004) open-bigram model and Grainger et al.'s (2006) Overlap open-bigram model, as well as for the earliest open-bigram model (SERIOL, Whitney, 2001), which places a strong weight on the prime and target matching in the initial letter position. The predictions of Schoonbaert and Grainger's (2004) and Grainger et al.'s (2006) models are virtually identical to one another (and they would also be identical to the predictions for Grainger and Van Heuven's (2003) model). Specifically, as noted above, open-bigram models regard zjudge-type primes as being very similar to their base words because those primes contain all the open bigrams involved in processing their base words due to the fact that those primes contain all the letters in their base words in their correct order. Therefore, these types of models predict very large priming effects from zjudge-type primes in Experiment 1c. More importantly, they all predict a clear zjudge-type prime advantage over zudge-type primes.

SERIOL (Whitney, 2001) does not predict as large priming effects for either prime type because neither prime type matches the target in the crucial initial letter position. However, like the other open-bigram models, it predicts a clear zjudge-type prime advantage for the same reason that the other open-bigram models do, because zjudge activates all the open bigrams relevant to the processing of JUDGE.

The predictions based on comparisons of orthographic similarity scores that are listed in Table 2 for the Spatial-coding model were derived from the version of the model that maintains the (default) end-letter marking assumption. Dropping that assumption would change the predictions only very slightly. That model also predicts that zjudge-type primes will be better primes than zudge-type primes in the masked priming same-different task.

Method

Participants

The participants were 360 University of Western Ontario undergraduate students who participated for partial course credit, 120 in Experiment 1a (44 in the consonant letter condition), 160 in Experiment 1b (80 in the consonant letter condition), and 80 in Experiment 1c (40 in the consonant letter condition). No individual participated in more than one experiment. All had normal or corrected-to-normal vision and were native speakers of English.

Materials

In Experiments 1a and 1b, the word target stimuli consisted of 80 five-letter words and 80 six-letter words, with a mean CELEX frequency of 58.3 and a mean Coltheart, Davelaar, Jonasson, and Besner (1977) neighborhood size (*N*) of 2.1. The nonword target stimuli were 160 orthographically legal nonwords (80 five-letter nonwords, 80 six-letter nonwords) with a mean Coltheart et al. *N* of 1.5. For each word and nonword target, two types of related primes were created, each representing a condition in the experiment: (a) primes created by adding a letter, either a consonant or a vowel, depending on the condition, to the beginning of the target (e.g., zjudge—JUDGE or ojudge—JUDGE), (b) primes created by replacing the first letter of the target with the same letter that was added in the zjudge-type condition (e.g., zudge—JUDGE or oudge—JUDGE). The added/substituted letter was not a letter that was contained in the target and was one of four consonants (v, w, x, or z) or one of the five vowels (a, e, i, o, or u). These four consonants were selected because, owing to their infrequent use in English, they typically produce unusual bigrams when added to the primes in the zjudge condition whereas the five vowels would do just the opposite. The unrelated conditions were created by re-pairing the primes and targets from the related conditions. The Coltheart et al. *N* values were 1.94 for the zudge-type primes and .11 for the zjudge-type primes, with the counts for the zudge-type primes, but not for the zjudge-type primes, including one for the target itself.[6]

To use all four prime types and make sure each of the 320 targets would appear only once to a participant, the targets were divided into four sets of 80, each containing 40 words and 40 nonwords, and four lists of materials were created. Across the lists, all 320 targets were primed by all four types of primes, with a

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[6] There was also a small difference between the two prime types on a different measure of neighborhood size, OLD20 (Yarkoni, Balota, & Yap, 2008). Also according to this measure, zudge-type primes appear to come from denser neighborhoods (2.06) than zjudge-type primes (2.54). Hence, although the differences are quite small, zjudge-type primes likely activate fewer lexical representations than zudge-type primes. Therefore, if anything, this small difference should give the zjudge-type primes a slight priming advantage.

different prime for the single presentation of a given target in each list. All lists contained an equal number of each prime type. Thus, all prime type manipulations were within-subject manipulations. In contrast, the type of letter manipulation (consonants vs. vowels used in the primes) was a between-subject manipulation.

In Experiment 1c, the word targets and their primes from Experiments 1a and 1b were used to create the "same" trials. "Different" trials were created by selecting 160 five-letter words and 160 six-letter words and using half of each as reference stimuli and the other half as target stimuli. Therefore, no nonword targets were used in Experiment 1c. For the reference stimuli and the "different" targets, the mean CELEX frequencies were 31.9 and 43.5, respectively, and the mean Coltheart et al. (1977) *N* values were 1.3 and 2.1, respectively. Each reference-target pair involved two words of the same length.[7] In addition, the reference stimuli and their "different" targets were orthographically dissimilar as they contained no letters in the same letter position. The four types of primes were also used on "different" trials with the relationship that defined the trial being the relationship between the prime and the reference stimulus rather than the prime and the target (the "zero-contingency" procedure, Perea et al., 2011). The word and nonword targets for the two lexical decision tasks, as well as the reference and target stimuli for "same" and "different" trials in the same-different task, along with their associated primes in all conditions, can be found at https://osf.io/2ds5h/.

The primes in all the experiments were displayed in lowercase in 12-pt New Courier font, whereas the reference stimuli (also in lowercase) and the targets (in uppercase) were displayed in 14-pt New Courier font. The specific order of presentation of the targets within each list was pseudorandomized for each participant with no randomization constraints using Forster and Forster's (2003) DMDX software.

Procedure

Participants were tested individually. In Experiments 1a and 1b, participants were told that their task was to indicate whether the letter strings presented on the computer screen are English words or not by pressing the right shift-key if they think the letter string is a word and the left shift-key if they think it is nonword, responding 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. In Experiment 1c, participants were told that they would first see a (reference) word on the computer screen, followed by a second (target) word shortly thereafter. Their task was to indicate whether the two words are the same, pressing the right shift-key if they are the same and the left shift-key if they are different.

In Experiment 1a, trials consisted of the presentation of three stimuli in the same location in the middle of the computer screen. Initially, a row of six hashtags (######) was presented for 550 ms, serving as a fixation mark. It was followed immediately by the (lowercase) prime for 55 ms, followed by the (uppercase) target for 3 s or until a response was made. In Experiment 1b, trials consisted of the presentation of four stimuli in the same location in the middle of the computer screen. Initially, the row of six hashtags was presented for 550 ms. It was followed immediately by the (lowercase) target word for 33 ms, followed by the (lowercase) prime of interest for 55 ms, followed by the uppercase target for 3 s or until a response was made.

In Experiment 1c, trials consisted of the presentation of four stimuli. Initially, the reference stimulus (in lowercase) was presented in the upper half of the screen and the row of six hashtags was presented in the lower half of the screen for 550 ms. Those stimuli were followed immediately by the lowercase prime for 55 ms, followed by the uppercase target for 3 s or until a response was made. Both of these stimuli appeared in the same position on the screen as the row of hashtags. Each stimulus was presented in the vertical center of a 17 in. PC monitor that allowed for an 11 ms refresh rate. All stimuli appeared as black characters on a white background. Reaction times (RTs) were measured from the target's onset until the participant's response.

As soon as the participant responded to a trial, the target disappeared from the screen and the next trial began. All participants in each experiment received 8 practice trials involving a novel set of stimuli prior to the 320 experimental trials. No participants mentioned any awareness of the primes. The entire experiment, in all cases, lasted between 10 and 20 min. This research was approved by the University of Western Ontario REB (Protocol # 108007).

Results

Prior to the analyses, we removed the data for one word (enact) and two nonwords (slills and myrtie) from Experiments 1a and 1b (the lexical decision experiments) because of their high (>45%) error rates in those experiments. Response times faster than 250 ms or slower than 1600 ms were also removed as outliers (1.0% and 5.7% of the data for the word and nonword targets, respectively, in Experiment 1, 0.9% and 1.7% for the word and nonword targets, respectively, in Experiment 2, and 1.2% and 1.5%, respectively, for the "same" and "different" trials in Experiment 3).[8] The remainder of the correct responses and the error rates were analyzed using a generalized linear mixed-effects model (GLMM) with a 2 (Prime Type: zjudge-type vs. zudge-type) × 2 (Relatedness: Related vs. Unrelated) × 2 (Prime Letter: Vowel vs. Consonant) design separately for the word and nonword targets in Experiments 1a and1b and for the "same" and "different" trial conditions in Experiment 1c. Prime Type, Relatedness (both within-subject and within-item factors), and Prime Letter (a between-subject and within-item factor) were fixed effects and subjects and items (the target stimuli) were random effects.

In the latency analyses, a common practice has been to use linear mixed-effects models and to normalize raw RTs with a reciprocal transformation (e.g., $\text{invRT} = -1{,}000/\text{RT}$) because linear models assume a normally distributed dependent variable,

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[7] After the experiment, it was discovered that the six-letter target CHEESE was mistakenly paired with the five-letter reference stimulus FUDGE. Hence, there were actually 81 five-letter reference stimuli on the "different" trials.

[8] Upon inspection of the data, it was noted that using a lower value for the upper cut-off, such as 1500 ms (e.g., Lupker & Davis, 2009), resulted in a somewhat high number of outliers, especially in Experiment 1a. Nonetheless, analyses were also done using 1,500 ms as the upper cut-off rather than 1,600 ms, analyses that did not alter the pattern of results reported here. The data and R scripts used to run all the analyses can be found at https://osf.io/2ds5h/.

an assumption that the typically positively skewed distribution of raw RTs fails to fulfill. However, nonlinear transformations systematically alter the pattern and size of interaction effects, rendering such transformations inappropriate when the research interest lies in interactions, as it does in the present experiments (Balota, Aschenbrenner, & Yap, 2013; Lo & Andrews, 2015). For this reason, consistent with more recent practices (e.g., Cohen-Shikora, Suh, & Bugg, 2019; Colombo, Spinelli, & Lupker, 2020; Lupker et al., 2019; Spinelli, Perry, & Lupker, 2019; Yang, Chen, Spinelli, & Lupker, 2019), we used a GLMM analysis because generalized linear models, unlike linear models, do not assume a normally distributed dependent variable and can, therefore, better accommodate the distribution of raw RT data without requiring a transformation of those data.[9]

A Gamma distribution was used to fit the raw RTs, with an identity link between the fixed effects and the dependent variable (Lo & Andrews, 2015). Note that, in the current version of lme4, convergence failures for generalized linear mixed-effects models, especially more complex models run on large data sets, are frequent, although many of those failures reflect false positives (Bolker, 2020). To limit the occurrence of convergence failures, we kept the random structure of the model as simple as possible by using only random intercepts for subjects and items. The default optimizer still failed to converge in most cases; however, it returned estimates that were equivalent to that of the BOBYQA optimizer, an optimizer which managed to converge in all cases (although it required restarting the estimation process in some cases, as reported below). In the following, we report the results from this optimizer.

Prior to running the model, R-default treatment contrasts were changed to sum-to-zero contrasts (i.e., contr.sum) to help interpret lower-order effects in the presence of higher-order interactions (Singmann & Kellen, 2018). The model was fit by maximum likelihood with the Laplace approximation technique. The lme4 package, Version 1.1–18-1 (Bates, Mächler, Bolker, & Walker, 2015), was used to run the generalized linear mixed-effects model. Pairwise comparisons for simple main effects, when necessary, were conducted using the emmeans package, Version 1.3.1 (Lenth, 2018). The subject mean latencies and error rates for Experiments 1a, 1b, and 1c are shown in Table 3.

Experiment 1a, Word Trials

Latency. There were significant main effects of Relatedness, $\beta = -11.28$, $SE = .92$, $z = -12.22$, $p < .001$, Prime Type, $\beta = -3.07$, $SE = .96$, $z = -3.20$, $p = .001$, and Prime Letter, $\beta = 13.42$, $SE = 2.18$, $z = 6.16$, $p < .001$. These effects reflected the fact that latencies were shorter following related primes, following zudge-type primes, and when the initial (added/substituted) letter in the prime was a vowel, respectively. However, none of the interactions, including the Relatedness by Prime Type interaction, was significant (all ps $> .10$).[10]

Errors. There were significant main effects of Relatedness, $\beta = .13$, $SE = .04$, $z = 3.43$, $p < .001$, and Prime Letter, $\beta = -.22$, $SE = .09$, $z = -2.36$, $p = .018$. Error rates were lower following related primes and when the initial (added/substituted) letter was a vowel. None of the other effects, including the Relatedness by Prime Type interaction, was significant (all ps $> .10$).

Experiment 1a, Nonword Trials

Latency. The initial model failed to converge. We restarted the initial model from the apparent optimum, as per the recommended troubleshooting procedure (see "convergence" help page in R), and report the results from that model, which did converge. The only significant effect was that of Prime Letter, $\beta = 21.93$, $SE = 3.24$, $z = 6.77$, $p < .001$. Responding was faster when the initial (added/substituted) letter was a vowel (749 ms) than when it was a consonant (791 ms). There was also a trend toward there being an interaction between Prime Type and Prime Letter, $\beta = 2.00$, $SE = 1.20$, $z = 1.67$, $p = .096$, reflecting the fact that the latency difference between primes in which the initial letter was a vowel and primes in which the initial letter was a consonant was slightly larger for zudge-type primes (48 ms) than for zjudge-type primes (37 ms). No other effects were significant (all ps $> .15$).

Errors. There was a significant main effect of Prime Letter, $\beta = -.29$, $SE = .12$, $z = -2.34$, $p = .019$. Error rates were lower when the initial (added/substituted) letter was a vowel (.078) than when it was a consonant (.111). There was also an interaction between Relatedness and Prime Letter, $\beta = -.07$, $SE = .03$, $z = -2.28$, $p = .022$. When the initial (added/substituted) letter was a consonant, error rates were higher following related primes (.112) than following unrelated primes (.108), $\beta = -.23$, $SE = .09$, $z = -2.55$, $p = .011$, whereas there were no differences following related primes (.078) versus unrelated primes (.078) when the initial letter was a vowel, $\beta = .05$, $SE = .08$, $z = .58$, $p = .564$. No other effects were significant (all ps $> .10$).

Experiment 1b, Word Trials

Latency. The initial model failed to converge. We restarted the initial model from the apparent optimum, as per the recommended troubleshooting procedure, and report the results from that

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[9] Linear mixed-effects analyses using −1,000/RT as the dependent variable and traditional ANOVAs based on subject and item means for raw RTs and error rates were also performed for all experiments. Except for some discrepancies of minor importance (e.g., the effect of Prime Letter was underestimated in the linear mixed-effects models), the results were essentially the same as those of the generalized linear mixed-effects models reported in the article. Those additional results can be found at https://osf.io/2ds5h/.

[10] As noted in the Introduction, priming effects can vary as a function of both target frequency (Davis & Lupker, 2006) and prime neighborhood size/density (Forster et al., 1987). The variability in both target frequency and Coltheart et al.'s N were purposely constrained in the present stimulus set in comparison to the values used in those prior experiments. As a result, there was no statistical evidence of a relationship between these factors and the priming effect sizes in any of our analyses in any of the experiments (all ps $> .12$). When analyses were done using OLD20 measures, the zjudge-type primes, which had a less restricted range of values than the zudge-type primes, did show a significant relationship between OLD20 values and priming effect sizes in a simple correlation ($r = .220$, $p = .005$) and in a GLMM analysis ($\beta = -18.64$, $SE = 1.23$, $z = -15.14$, $p < .001$) in Experiment 1a, whereas the zudge-type primes showed a significant relationship only in the GLMM analysis ($\beta = -5.67$, $SE = 2.27$, $z = -2.50$, $p = .013$). In Experiment 1b, the relationships were a bit weaker with neither prime type showing a significant relationship in the simple correlations (both ps $> .10$), although both primes types did show a significant relationship in the GLMM analysis (for zudge-type primes: $\beta = -5.42$, $SE = 1.17$, $z = -4.64$, $p < .001$; for zjudge-type primes: $\beta = -10.52$, $SE = 1.53$, $z = -6.87$, $p < .001$). There were no significant relationships between OLD20 and priming effect sizes in Experiment 1c.

Table 3

Mean Latencies (in ms) and Error Rates (in Parentheses) in Experiments 1a (Conventional Masked Priming), 1b (Sandwich Priming) and 1c (Masked Priming Same-Different Task)

	Consonant letter primes			Vowel letter primes			
Prime type	Rel	Unrel	Effect	Rel	Unrel	Effect	95% CI
Experiment 1a (conventional masked priming)							
zjudge	639 (.052)	654 (.057)	15 (.005)	617 (.031)	638 (.033)	21 (.002)	[12, 26]
zudge	625 (.043)	655 (.063)	30 (.020)	612 (.026)	634 (.034)	22 (.008)	[17, 33]
Experiment 1b (sandwich priming)							
zjudge	579 (.034)	613 (.052)	34 (.018)	575 (.032)	609 (.057)	34 (.025)	[28, 40]
zudge	570 (.035)	615 (.051)	45 (.016)	567 (.035)	609 (.058)	42 (.023)	[38, 50]
Experiment 1c (masked priming same-different task)							
"Same" trials							
zjudge	479 (.053)	512 (.077)	33 (.024)	491 (.050)	520 (.071)	29 (.021)	[24, 38]
zudge	465 (.049)	496 (.068)	31 (.019)	471 (.045)	503 (.072)	32 (.027)	[24, 39]
"Different" trials							
zjudge	547 (.042)	534 (.027)	−13 (−.015)	559 (.032)	538 (.023)	−21 (−.009)	[−25, −8]
zudge	541 (.034)	536 (.030)	−5 (−.004)	548 (.032)	540 (.029)	−8 (−.003)	[−13, 1]

Note. 95% confidence intervals are reported for overall priming effect sizes in the latency data.

model, which did converge. There were main effects of Relatedness, $\beta = -20.06$, $SE = .70$, $z = -28.58$, $p < .001$, and Prime Type, $\beta = -2.05$, $SE = .70$, $z = -2.94$, $p = .003$. These effects indicated that latencies were shorter following related primes and following zudge-type primes, respectively. Unlike in Experiment 1a, the Relatedness by Prime Type interaction was significant, $\beta = -2.59$, $SE = .72$, $z = -3.59$, $p < .001$. This interaction reflects the fact that the priming effects were 10 ms larger for zudge-type primes. No other effects were significant (all ps $> .15$).

Errors. There was a significant main effect of Relatedness, $\beta = .27$, $SE = .03$, $z = 8.56$, $p < .001$, owing to the fact that error rates were lower following related primes. No other effects were significant (all ps $> .20$).

Experiment 1b, Nonword Trials

Latency. There was a significant main effect of Prime Type, $\beta = -2.08$, $SE = .83$, $z = -2.50$, $p = .012$, reflecting slightly shorter latencies following zudge-type primes (689 ms) than zjudge-type primes (693 ms). There was also a significant main effect of Prime Letter, $\beta = 4.63$, $SE = 2.28$, $z = 2.03$, $p = .043$. Responding was faster when the initial (added/replacing) prime letter was a vowel (687 ms) than when it was a consonant (695 ms). No other effects were significant (all ps $> .15$).

Errors. The only significant effect was that of Relatedness, $\beta = -.16$, $SE = .03$, $z = -5.52$, $p < .001$. Error rates were higher following related primes (.066) than following unrelated primes (.051). There was also a trend toward there being a three-way interaction between Relatedness, Prime Type, and Prime Letter, $\beta = -.05$, $SE = .03$, $z = -1.89$, $p = .059$, reflecting a numerical tendency for the effect of Relatedness to vary among Prime Type and Prime Letter conditions. Specifically, error rates were statistically equivalent following related primes (.062) and following unrelated primes (.052) for zjudge-type primes when the initial letter was a consonant (unlike in the other conditions, in which error rates were always significantly higher following related primes than following unrelated primes). No other effects were significant (all ps $> .15$).

Experiment 1c, "Same" Trials

Latency. There were significant main effects of Relatedness, $\beta = -15.88$, $SE = .92$, $z = -17.20$, $p < .001$, and Prime Type, $\beta = -7.90$, $SE = .94$, $z = -8.45$, $p < .001$. These effects reflected shorter latencies following related primes and following zudge-type primes, respectively. There was also a trend toward there being a main effect of Prime Letter, $\beta = -6.13$, $SE = 3.53$, $z = -1.74$, $p = .082$, reflecting the fact that overall latencies were slightly shorter when the initial (added/substituted) letter was a consonant than when it was a vowel. None of the interactions, including the Relatedness by Prime Type interaction, was significant (all ps $> .35$).

Errors. The only significant effect was that of Relatedness, $\beta = .22$, $SE = .04$, $z = 5.78$, $p < .001$, reflecting the fact that error rates were lower following related primes. No other effects were significant (all ps $> .25$).

Experiment 3, "Different" Trials

Latency. There were significant main effects of Relatedness, $\beta = 5.89$, $SE = 1.00$, $z = 5.87$, $p < .001$, and Prime Letter, $\beta = -6.81$, $SE = 2.00$, $z = -3.40$, $p < .001$. These effects reflected shorter latencies following unrelated primes and when the initial (added/substituted) letter was a consonant, respectively. There was also a trend toward there being a Relatedness by Prime Type interaction, $\beta = -1.86$, $SE = 1.02$, $z = -1.82$, $p = .069$, reflecting the numerically larger (inhibitory) priming for zjudge-type primes than for zudge-type primes. No other effects were significant (all ps $> .10$).

Errors. There was a main effect of Relatedness, $\beta = -.13$, $SE = .05$, $z = -2.63$, $p = .008$, reflecting the fact that error rates were higher following related primes. No other effects were significant (all ps $> .20$).

Discussion

The basic empirical question examined in these experiments was whether primes like zjudge, that is, primes that involve the addition of a letter to the beginning of the target, are better primes than those like zudge, that is, primes in which the first letter of the target is replaced. That specific result cannot only be predicted from an analysis of the impact of flankers (see Chanceaux & Grainger, 2012; Chanceaux, Mathôt, & Grainger, 2013 – see also Lupker et al., 2015, for a discussion of this issue) but, more importantly, is predicted by most models of orthographic coding, as discussed above. The results of Experiments 1a, 1b, and 1c give a very clear answer to that question. Primes like zjudge are not better primes than primes like zudge. The only hint that zjudge-type primes might be better primes was in Experiment 1c on the "different" trials, where there was a numerical (but not significant) tendency in that direction. In virtually every other situation, the priming effect for zudge-type primes was numerically larger than that for zjudge-type primes and, in fact, the only relevant interaction that was significant was in Experiment 1b, in which there was a small, but significant, priming advantage for zudge-type primes. Further, the conclusion that zjudge-type primes are not better primes than zudge-type primes is nicely supported by the results in Adelman et al.'s (2014) megastudy, with those data showing a small numerical advantage for zudge-type primes. Finally, it should be noted that the pattern of essentially equivalent priming for the two prime types obtained regardless of whether the added/substitution letter was a consonant or a vowel.

One possible question that could be raised concerning our experiments is whether they were powerful enough to detect the zjudge priming advantage that most models of orthographic coding predict. To answer that question, we ran a post hoc power analysis based on the data for Experiments 1a and 1b, experiments for which one of those models, Davis's (2010) Spatial-coding model, provides predicted effect sizes in ms. Specifically, it predicts a 16-ms zjudge priming advantage in the conventional masked priming task (Experiment 1a) and a 9-ms zjudge priming advantage in the sandwich priming task (Experiment 1b) when the end-letter marking assumption is maintained and advantages that increase to 22 ms and 13 ms, respectively, when that assumption is dropped (see Table 1).

Our power analysis was conducted using the simR package, Version 1.0.5 (Green & MacLeod, 2016; see also Brysbaert & Stevens, 2018) in R. For both experiments, we ran a linear mixed-effects model with Relatedness and Prime Type as the fixed effects, subjects and items as random effects, and raw RTs as the dependent variable.[11] We then modified the estimate for the interaction between Relatedness and Prime Type to reflect the priming advantage predicted by the Spatial-coding model. For Experiment 1a, we used an estimate of $\beta = 4.00$ for the interaction, a change that made the priming effect for zjudge primes, $\beta = -30.72$, 16 ms larger than the priming effect for zudge primes, $\beta = -14.72$, in the estimated marginal means. For Experiment 1b, we used an estimate of $\beta = 2.25$ for the interaction, a change that made the priming effect for zjudge primes, $\beta = -44.27$, 9 ms larger than the priming effect for zudge primes, $\beta = -35.27$, in the estimated marginal means (to be conservative, we used the zjudge priming advantages predicted for the two experiments by the Spatial-coding model with the end-letter marking assumption, advantages that are smaller than those predicted by the model without that assumption).

The power analysis was conducted by comparing the model with the (modified) interaction with the model without the interaction with a likelihood ratio test and performing 1,000 simulations for this comparison. The results indicated that Experiment 1a would have had a power of .945, 95% CI [.929, .958], to detect a 16-ms zjudge priming advantage, whereas Experiment 1b would have had a power of .712, 95% CI [.683, .740], to detect a 9-ms zjudge priming advantage. Considering that, as noted, these analyses were based on the Spatial-coding model with the end-letter marking assumption, the version of the model which predicted the smallest zjudge priming advantage, it would seem that our experiments were sufficiently powered to detect that advantage.[12] Note also that, although the power to detect the predicted zjudge priming advantage was a bit short of the commonly accepted .80 threshold for Experiment 1b, there was no hint for such an advantage in the actual data of that experiment. Indeed, Experiment 1b was the one experiment where we found a significant zjudge priming *dis*advantage.

There were two additional results that arose in our experiments that should be noted. The first was that there was a Prime Type effect, specifically, shorter (i.e., zudge-type) primes tended to produce shorter overall latencies. An examination of the data from Experiments 1a and 1b, however, clearly suggests that this effect was not only quite small (approximately 4 ms in both experiments) but also that it essentially only arose when the primes were related to the target. This result (and the fact that there was no Prime Type effect for nonword targets) suggests that the Prime Type effect was not a length effect (i.e., longer primes, per se, do not slow decision latencies) but rather, it reflects the likelihood that zudge is actually a slightly better prime for JUDGE than zjudge is, at least in lexical decision experiments.

The situation in Experiment 1c was slightly different. In that experiment, the Prime Type effect was a bit larger and it was not restricted to the related conditions. It was, however, restricted to the "same" trials. Although the source of this effect is far from clear, one possibility is that a prime that is longer than the reference stimulus might have had the effect of biasing participants away from a "same" response owing to the fact that stimuli that are different lengths cannot, by definition, be the same stimulus. That

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[11] We ran a linear mixed-effects model, instead of the GLMM used for the analyses reported in the Results section, because evaluating the latter was impossible with the simR package. For the same reason, we dropped the fixed effect of Prime Letter in these analyses. Further, we used raw RTs instead of transformed RTs as the dependent variable because producing a difference in priming effects expressed in ms, the measure provided by the Spatial-coding model, is easier, and more easily interpretable, with raw RTs than with transformed RTs. Note, finally, that these linear mixed-effects models produced the same pattern of results as reported for the GLMMs. In particular, priming effects were equivalent for zjudge and zudge primes in Experiment 1a, whereas there was a significant zjudge priming *dis*advantage in Experiment 1b.

[12] We also conducted another set of power analyses to determine the smallest zjudge priming advantage that was detectable with a power of .80 for each of our experiments (including Experiment 1c). We used the same procedure described above, except that we parametrically increased the estimate of the interaction to evaluate power for every 1-ms increase in the zjudge priming advantage (starting from a hypothesized 8-ms zjudge priming advantage). The results indicated that the smallest zjudge priming advantage detectable with a power of .80 was 14 ms for Experiment 1a (actual power = .882, 95% CI [.860, .901]), 11 ms for Experiment 1b (actual power = .854, 95% CI [.831, .875]), and 13 ms for Experiment 1c (actual power = .803, 95% CI [.777, .827]). All power analyses can be found at https://osf.io/2ds5h/.

hypothesis would, however, seem to lead to the expectation that primes longer than the targets would produce shorter overall latencies on "different" trials, a result that did not obtain.

A second additional result that appeared in these experiments is that there was a Prime Letter effect in some analyses, that is, an overall difference, both in error rate and latency between the primes starting with consonants and the primes starting with vowels (although, as reported, this difference did not interact with any of the other factors in the word trial data). At least one of these effects arose in all three experiments.

In Experiment 1a, the individuals for whom the initial (added/substituted) letter in the primes was a consonant were slower and more error prone with both word and nonword targets (i.e., they showed a consonant disadvantage in all four contrasts). That pattern did not hold up in Experiments 1b and 1c, however. Of the eight analyses in those two experiments, there were six null effects of Prime Letter, one significant effect showing a consonant advantage and one significant effect showing a consonant disadvantage. Therefore, although the data from Experiment 1a would suggest that it is harder to process a prime when it begins with a consonant, the data from Experiments 1b and 1c do not. Thus, the more likely hypothesis concerning any Prime Letter effect would seem to be that the participants in the vowel condition in Experiment 1a were simply better readers (of the target stimuli) and, hence, faster and more accurate responders, than those in the consonant condition.

General Discussion

The goal of the present research was to contrast the effectiveness of masked primes that added a letter to the beginning of their targets (e.g., zjudge-JUDGE) against the effectiveness of masked primes that replaced the first letter of their targets with that same letter (e.g., zudge-JUDGE). Most models of orthographic coding predict that the former type of primes would be more orthographically similar to their targets than the latter because the former primes contain all the letters of the target in their correct order. Hence, zjudge-type primes should be better primes. Nonetheless, a larger priming effect for zjudge-type primes was not obtained in Adelman et al.'s (2014) megastudy. Unfortunately, as noted, the unrelated conditions used in the megastudy were less than perfect for evaluating the priming effect for zjudge-type primes because the unrelated primes had one less letter than was contained in the (related) zjudge-type primes.

The present experiments directly contrasted the two prime types using unrelated primes of the same length as the parallel related primes in three different masked priming paradigms, the conventional task, the sandwich priming task (Lupker & Davis, 2009), and the masked priming same-different task (Duñabeitia et al., 2011; Kinoshita & Norris, 2009; Norris & Kinoshita, 2008, 2012). The results of all three experiments were quite consistent with those from Adelman et al.'s (2014) megastudy in that zjudge-type primes were not more effective primes than zudge-type primes and, in fact, in the sandwich priming task a small but significant priming advantage was observed for the zudge-type primes. The lack of a zjudge-type prime advantage appears to present a serious challenge for most current models of orthographic coding.

Open-Bigram Models

The reason for the inability of the various open-bigram models to explain the present data is clear. Primes like zjudge activate all the relevant open bigrams in the word JUDGE. Essentially, the prediction these models make is that, because zjudge-type primes have this ability, they should be virtually as effective as an identity prime (i.e., the orthographic similarity score for zjudge and JUDGE is essentially 1.00). The exception, of course, is SERIOL, which would not regard zjudge as a particularly effective prime for JUDGE because the two letter strings differ in their initial letter position. Nonetheless, like the other open-bigram models, SERIOL still predicts a zjudge-type prime advantage, a result that did not obtain.

One way to attempt to address this issue might be for the modelers to enhance the inhibition processes contained in their models. The models already assume that inconsistent bigrams (i.e., the ZJ bigram is inconsistent with the lexical representation for JUDGE) do provide some inhibition to the lexical representations that those bigrams are inconsistent with. Increasing the size of the inhibition effect certainly would cause these models to predict smaller priming effects for zjudge than they do now (as can be seen by examining SERIOL's predictions).

Alternatively, as suggested by Welvaert et al. (2008), one could add a mechanism to the models that creates inhibition in the target as a result of the existence of any letters in the prime that are not in the target. In fact, based on their own results as well as those reported by Van Assche and Grainger (2006), Welvaert et al. have suggested that each discrepant letter added to a prime containing the target (e.g., the z in zjudge) reduces the priming effect by approximately 11 ms from the priming produced by a repetition prime (i.e., judge-JUDGE). Ktori et al. (2015) have offered a similar idea with their results suggesting that the impact of adding a letter to the prime may be somewhat larger than 11 ms, at least in a sandwich priming experiment.

The key point to realize, however, is that none of these fixes, either increasing the inhibition effects that are already in the model or adding a mechanism affected by the existence of discrepant letters, would appear likely to solve the problem created by the present data. The reason is that any inhibition effect created by the existence of the "z" in zjudge (for whatever reason) would also be created by the existence of the "z" in zudge (consider, e.g., the contrast between SERIOL's predictions and the predictions of the other open-bigram models). Therefore, the models would likely still predict that zjudge would be a better prime than zudge because zjudge has more of the JUDGE-relevant open bigrams than zudge does.

Davis's (2010) Spatial-Coding Model

In terms of predicting the overall effect sizes, this model did a reasonable job, predicting an overall effect size of 20 ms under the default end-letter marking assumption and 26 ms without that assumption in Experiment 1a and 44 ms under the end-letter marking assumption and 52 ms without that assumption in Experiment 1b. The overall effect sizes were 22 ms and 39 ms in the two experiments, respectively. However, like the open-bigram models, the Spatial-coding model predicted a zjudge-type prime advantage in all three experiments, an effect that did not obtain.

As suggested above, one way to try to address this issue in general would be to set the model assumptions in a way that would increase the (inhibitory) impact of a mismatching letter. That is, the existence of the "z" in zjudge might be assumed to have a strong impact on the orthographic similarity of zjudge and JUDGE, allowing the model to predict a smaller priming effect from zjudge than it now does. However, as also noted above when discussing the open-bigram models, it's unlikely that an approach like that would solve the problem because zudge contains the same mismatching letter as zjudge does and, hence, the model would also then predict a smaller priming effect from zudge (i.e., the predicted zjudge-zudge difference would likely maintain).

An alternative approach might be to focus on the existence of the bigram "zj" in zjudge, an illegal combination of letters in English. For example, such combinations could provide inhibition to activated lexical representations. That approach, however, is unlikely to work either because there were no real differences in terms of priming between primes in which the added/substituted letters were consonants (e.g., zjudge, zudge) and those in which the added/substituted letters were vowels (ojudge, oudge). The latter types of primes would create few, if any illegal orthographic combinations. Therefore, at present, it does not appear that the Spatial-coding model has an obvious way of explaining why primes containing the entire target (e.g., zjudge) are not better primes than primes containing only a subset of that target (e.g., zudge).

The LTRS Model

Of all the models examined, the LTRS model (Adelman, 2011) was the one model that did not predict a zjudge prime advantage. The LTRS model's success in this realm is based on how it conceptualizes the lexical activation process. Lexical representations consistent with the available orthographic information are activated once any information of that sort has arrived. What is important to note, however, is that the activation levels of those representations do not increase strictly as a function of the *amount* of consistent input available, as is the case in most models of orthographic coding/word recognition. Rather, activation levels increase as a function of the *time* the lexical representations are receiving activation (i.e., the amount of time that they are consistent with all the arriving information). Once a piece of inconsistent information arrives (either identity information like the existence of the "z" or precise position information like the fact that the "j" in zjudge has a letter to its left), the activation process stops, with the obtained activation level being maintained for at least a short period of time (i.e., decay has not started prior to the target arriving in a typical masked priming situation). Any positive information arriving after this point in time is, therefore, of no relevance to the activation process. Because precise position information tends to arrive later (precise position information is only relevant once at least some identity information has become available), on most trials, the trigger for the activation process to end for both zjudge and zudge would likely be the discovery of the "z." Hence, the two prime types would tend to allow the lexical representation for JUDGE to receive activation for essentially the same amount of time, leading to equal size priming effects.

The ability of the LTRS model to explain the present data is based, therefore, on its distinction between the activation level that is created by the prime being a function of the duration of the prime's activation of the target (before inconsistent information is detected) rather than being a function of some sort of orthographic similarity calculation for the prime and target. The primes zjudge and zudge for the target JUDGE barely differ on the former, whereas, according to most models of word recognition, they differ substantially on the latter. A reasonable implication is that the duration of activation until inconsistent information is detected may very well be an aspect of the orthographic coding/priming process that needs to be incorporated into other models.

What also needs to be noted, however, is that, although the LTRS did a good job of accounting for the main contrast investigated here, there are a number of aspects of the model that will need to be developed before it could be regarded as a model of the word recognition process (as opposed to a model of the priming process). For example, it has, at present, no obvious means of explaining why priming effect sizes in the conventional task are affected by certain lexical factors (e.g., word frequency, prime lexicality, prime neighborhood size/density) because it makes no assumptions about the structure of the lexicon. It also has no obvious means of predicting the increases in priming observed in the sandwich priming task (Experiment 1b) or in the masked priming same-different task (Experiment 1c). As a result, it makes essentially the same predictions in Experiments 1b and 1c as it does in Experiment 1a because the priming mechanism is essentially the same in all tasks. As noted above, however, there would appear to be a number of ways that these issues could be addressed. That is, there certainly are model parameters that can be altered or new mechanisms that can be added to allow the model to predict larger priming effects in the sandwich priming task and it is likely the case that actions of this sort can be done to address the other issues as well. What the impact of altering those parameters will be on the model's ability to predict results in the conventional task and the same-different task or to predict the various interactions between priming effects and lexical factors are issues for future research.

The Comparison With the zjudge Prime Effects in Lupker et al. (2015)

As noted, Lupker et al. (2015) have previously examined priming from zjudge-type primes. Those priming effects were contrasted against the priming effects produced by middle-letter replacement primes (e.g., juzge) and, as well, end letter superset primes (e.g., judgez). The methodologies used in the three experiments reported by Lupker et al. were the same as those used in the present investigation. The specific goal of Lupker et al.'s experiments was to contrast the predictions of open-bigram models against those of the noisy position models, in particular Davis's (2010) Spatial-coding model.

Consistent with the above discussion, the open-bigram model predictions were that the two primes involving letter additions (i.e., zjudge and judgez) should be better primes than middle-letter replacement primes because the letter addition primes should activate all of the open-bigrams involved in target processing. In contrast, the primes and targets in those experiments were selected specifically so that Davis's (2010) Spatial-coding model would not predict any differences in priming among the three prime types. The data did not support the prediction of better priming for the letter addition primes. In fact, as noted above, in Lupker et al.'s sandwich priming experiment and in their same-different task experiment, the zjudge-type primes produced significantly less priming than juzge-type primes (which produced the same amount of priming as judgez-type primes).

Although the stimuli used in the present investigation are somewhat different than those used by Lupker et al. (2015), in particular, the targets used by Lupker et al. were somewhat longer and less frequent than the present targets (and only consonants were used as the added/replacement letters), a comparison of the impact of zjudge-type priming effects in the two situations may be of some interest. The priming effects (for the consonant letter primes) in the sandwich priming experiments in the two articles were quite similar, 31 ms in Lupker et al. and 34 ms in the present Experiment 1b. The parallel comparison between same-different task experiments showed identical priming effects (33 ms) on "same" trials in the two situations, although there was a difference between the effect sizes on "different" trials, 0 ms in Lupker et al., −13 ms in the present Experiment 1c.

It was in the conventional tasks where there was a noticeable difference between experiments, with there being a 15-ms priming effect in the present investigation versus a 40-ms priming effect in Lupker et al. (2015). (That 40-ms priming effect was, however, statistically equivalent to the priming effects for the other two prime types, consistent with Davis's (2010) Spatial-coding model but not with the open-bigram models.) What is also relevant here is that, (a) as noted previously, in Adelman et al.'s (2014) megastudy, in which only the conventional task was used, the priming effect for zjudge-type primes was 22 ms, and (b) for the vowel letter primes in the present Experiment 1a, the priming effect was 21 ms. Therefore, although an argument can be made that the 15-ms effect for consonant letter primes in the present Experiment 1a may underestimate the actual impact of zjudge-type primes, it would be extremely difficult to make an argument that the priming effect for zjudge-type primes in the present Experiment 1a should have been large enough to support the model prediction that zjudge-type primes are better primes than zudge-type primes in the conventional task. What seems considerably more likely is that the 40-ms priming effect from zjudge-type primes observed by Lupker et al. was somewhat of an overestimate of those primes' effectiveness.

Conclusions

Primes involving the addition of a letter to the front of the target (e.g., zjudge) are regarded as more orthographically similar to their base word (i.e., JUDGE) than primes in which the target's initial letter is replaced (e.g., zudge) by most models of orthographic coding/word recognition because zjudge-type primes contain all the letters contained in the target word in their correct order. Hence, as shown in the present simulations, those models make the clear prediction that zjudge-type primes should be better primes than zudge-type primes. Consistent with the findings of Adelman et al. (2014), however, what the present results show is that such is not the case in any of the three masked priming tasks investigated here with there being no obvious way for most current models to explain the obtained pattern.

The one model that did have some success predicting this pattern, the LTRS model (Adelman, 2011), has a somewhat different basis than other word recognition models. Specifically, the word recognition process is strongly affected by the emergence of inconsistent information (e.g., the perception of the z in both zjudge and zudge is regarded as being diagnostic of the fact that the prime is not the word JUDGE) and the degree of priming obtained is a function of how long it takes for the system to discover inconsistent information. Although it's unclear whether this particular model can be extended to account for the full pattern of data reported here, particularly the typical finding that priming effects are larger in sandwich priming and same-different tasks than in the conventional masked priming lexical-decision task, its relative success suggests that many of the current models may need to allow inconsistent information to play a larger role in how they conceptualize the orthographic coding/word recognition process.

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