An Examination of Models of Reading Multi-morphemic and Pseudo Multi-morphemic Words Using Sandwich Priming

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Running Head: Reading Multi-morphemic Words

Word Count:

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Abstract

Rastle et al. (2004) reported that true (e.g., walker) and pseudo (e.g., corner) multi-morphemic words prime their stem words more than form controls do (e.g., brothel priming BROTH) in a masked priming lexical decision task. This data pattern has led a number of models to propose that both of the former word types are "decomposed" into their stem (e.g., walk, corn) and affix (e.g., -er) early in the reading process. The present experiments were designed to examine the models proposed to explain Rastle et al.'s effect, including models not assuming a decomposition process, using a more sensitive priming technique, sandwich priming (Lupker & Davis, 2009). Experiment 1, using the conventional masked priming procedure, replicated Rastle et al.'s results. Experiments 2 and 3, involving sandwich priming procedures, showed a clear dissociation between priming effects for true versus pseudo multi-morphemic words, results that are not easily explained by any of the current models. Nonetheless, the overall data pattern does appear to be most consistent with there being a decomposition process when reading real and pseudo multi-morphemic words, a process that involves activating (and inhibiting) lexical-level representations including a representation for the affix (e.g., -er), with the ultimate lexical decision being based on the process of resolving the pattern created by the activated representational units.

Keywords: morphological decomposition, masked priming, sandwich priming

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The past half century has seen a considerable amount of research into the issues relating to how one reads multi-morphemic words (i.e., processes and representations). Taft and Forster (1975) is regarded by many as the paper representing the seminal work on these issues. In that paper, the authors proposed that the way one reads a prefixed word is to initially separate the stem and prefix (a process that has been referred to as "affix stripping"), to next attempt to access the lexical representation for the stem and, if successful, to then attempt to put the two components back together in order to understand the word. In the subsequent literature, this type of account has been altered by assuming that the "affix stripping" process is not an active process but rather a "morpho-orthographic decomposition" process in which the affix and stem of a multi-morphemic word activate separate memorial representations early in processing (e.g., Grainger & Beyersmann, 2017; Marslen-Wilson et al., 2008; Taft et al., 2019; Taft & Nguyen-Hoan, 2010).

More recently, many of the empirical contributions to this discussion have come from the use of the masked priming lexical decision task (Forster & Davis, 1984). In that task, a prime is briefly presented prior to a target requiring a lexical decision (hereafter, this task will be referred to as the "conventional" task). In the masked priming literature, the presumed impact of the word prime is that, although it is typically not available to consciousness, it activates its own memorial representations, potentially including its semantic representations, as well as those relevant to orthographically similar words. A nonword prime, having no memorial representation, would only activate the memorial representations relevant to orthographically similar words. If the representations activated by the prime are helpful to target processing because, for example, the prime and target are orthographically similar (Adelman et al., 2014), responding will be facilitated. If those representations are harmful to target processing (e.g., Davis & Lupker, 2006), responding will be inhibited. In all cases, the baseline condition involves the same targets following a prime that is unrelated orthographically, phonologically, semantically and morphologically to its target. (As will be discussed subsequently, however, not all models of the processes being investigated here are based on activation processes, a fact that will have implications for how well those models can account for the priming effects observed in the present experiments.)

What is often taken as the classic masked priming result in the morphological processing literature was reported by Rastle et al. (2004) (see also Longtin et al. (2003) for a parallel demonstration in French). The crucial conditions in these types of experiments are, typically, the following: a) a condition in which there is a true morphological relationship between the prime and target words (walker-WALK – the “transparent” condition), b) a condition in which the prime and target words have an apparent morphological relationship but actually do not (i.e., the prime is a pseudo multi-morphemic word – corner-CORN – the “opaque” condition) and c) a condition in which the prime word contains the target word but the additional letters in the prime are not themselves a morphological unit (brothel-BROTH – the “form” condition). Although results can vary, Rastle et al.’s result pattern, which is the most typical pattern, is for the transparent condition to produce a slightly, but not necessarily significantly, larger priming effect than the opaque condition and for the opaque condition to produce a significantly larger priming effect than the form condition (e.g., Lavric et al., 2007; Longtin et al., 2003; Marslen-Wilson et al., 2008; Rastle & Davis, 2008; although see Milin et al., 2017). In fact, the form condition often produces no significant priming. (Throughout this paper, primes will be written in lower case, targets will be written in upper case and words/affixes being used as examples in the text will be written in italics.)

For present purposes, it is important to note that both of these contrasts are relevant. The difference between the opaque and form conditions provides evidence that the letters in the prime that represent an affix impact the priming process even if those letters only form a pseudo affix. That is, it is taken as evidence that the priming in the opaque condition is not due simply to prime-target orthographic similarity but instead is due to the pseudo affix (i.e., the *-er* in *corner*) allowing activation of memorial representations that are not activated by nonaffixes (i.e., the *-el* in *brothel*). The typically small difference between the transparent and opaque conditions provides evidence that the process by which the prime's pseudo affix contributes to the priming effect is driven to a reasonable degree by orthographic factors and is essentially accomplished automatically.

With respect to the transparent-opaque difference, it is also important to note that there has been considerable controversy about this contrast. In response, Rastle and Davis (2008) analyzed all the relevant experiments at that point in time in which the transparent-opaque contrast had been examined in Indo-European languages. Those authors concluded that there was virtually no evidence of a difference when the prime duration was less than 60 ms. More recent results (e.g., Andrews & Lo, 2013; Diependaele et al., 2011; Feldman & Martin, 2022; Feldman et al., 2009; 2015; Jared et al., 2017; Morris et al., 2011), however, suggest that Rastle and Davis's conclusion is too strong. Those results, which showed a significant transparent priming advantage and, in some cases, little priming in the opaque condition, have been taken as an indication that the situation is somewhat more complicated that Rastle et al.'s data (and Rastle and Davis's analysis) would suggest.

In an attempt to deal with these data inconsistencies, it has been suggested (e.g., Baayen et al., 2011; Marelli et al., 2015; Marelli & Baroni, 2015) that whenever the opaque condition produces a large priming effect, as it did in Rastle et al.'s (2004) experiment, it is due to a number of opaque prime-target pairs being semantically related (e.g., archer-ARCH; fruitless-FRUIT). Hence, any advantage for the opaque condition over the form condition is actually due to semantic relatedness among the pairs in the opaque condition. In response, Beyersmann et al. (2016) have provided a demonstration that Rastle et al.'s pattern can be obtained even when the semantic similarity of the primes and targets in the opaque condition is, seemingly, well controlled. For present purposes, however, the point to make is that the degree to which one should consider words like *archer* and *arch* to be semantically related is somewhat arbitrary, as it depends on how one constructs their model of semantics. Therefore, in an effort to avoid this controversy, in the present experiments we used Rastle et al.'s stimuli, expecting to replicate their data pattern in the conventional task, and, when evaluating models for which semantics is key, we allowed those models to assume that any priming in the opaque condition was based on uncontrolled semantic relatedness.

Regardless of how one wants to explain the priming in the opaque condition, or masked priming in general, it is important to note that the fact that Rastle et al.'s (2004) pattern emerges in masked priming experiments clearly indicates that it reflects the impact of very early (prime) processing on target representations (as opposed to experiments in which the primes are unmasked and their impact on target representations can be presumed to reflect later processes as well). Therefore, all attempts to model that pattern must include assumptions about how early prime processing interacts with target-relevant representations, specifically, what target representations are being affected by the prime as well as how those representations are being affected. In that context, the motivation for the present research was to investigate Rastle et al.'s pattern using a more sensitive priming technique, with a view toward evaluating how the various models of the relevant processes and representations might explain/predict the results. In order to do so, we start with descriptions of the various models, both in terms of representational assumptions and how those representations are presumed to be affected by a masked prime.

Localist models that assume morpho-orthographic decomposition

These types of models are based on the common assumption that the masked prime creates an orthographic code that codes both letter identities and positions (Grainger, 2008). That code, referred to as "input" in the models in Figures 1 and 2, then activates representations of the lexical and sublexical units assumed by the model. As mentioned above, the interactions among those units (which can be inhibitory) during the prime's exposure set the stage for target processing.

More detailed accounts of how decomposition process might work are represented in Taft and Nguyen-Hoan’s (2010) and Grainger and Beyersmann’s (2017) models, reproduced in Figures 1 and 2, respectively. These models, described in some detail below, have a number of assumptions, most of which are shared.

Figure 1 – A representation of Taft and Nguyen-Hoan's (2010) model[1]

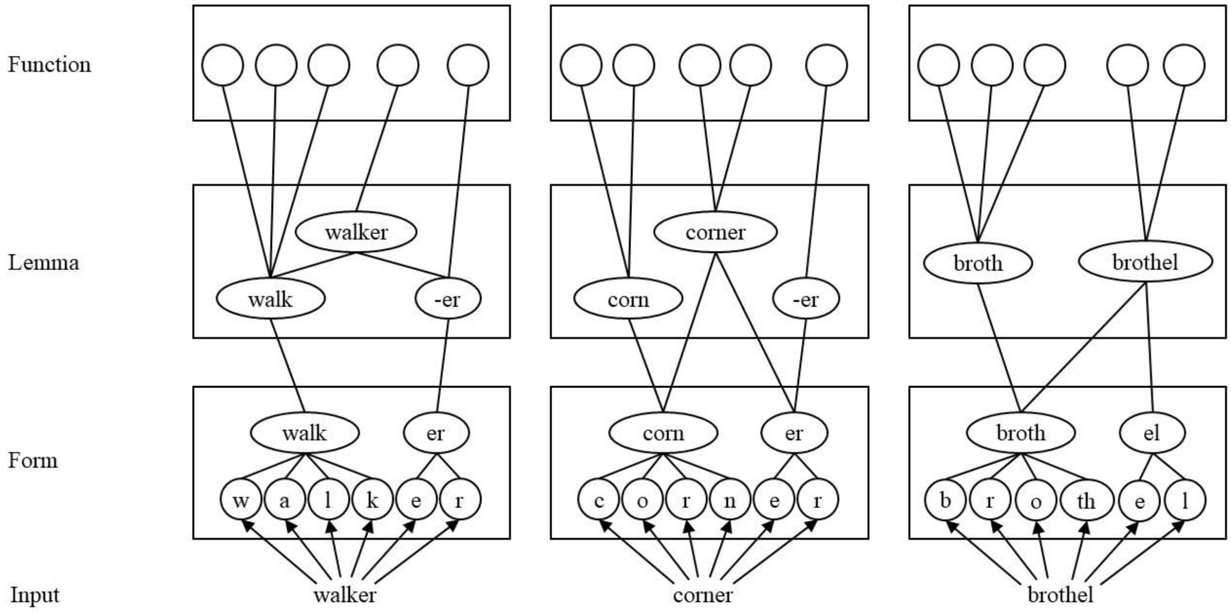
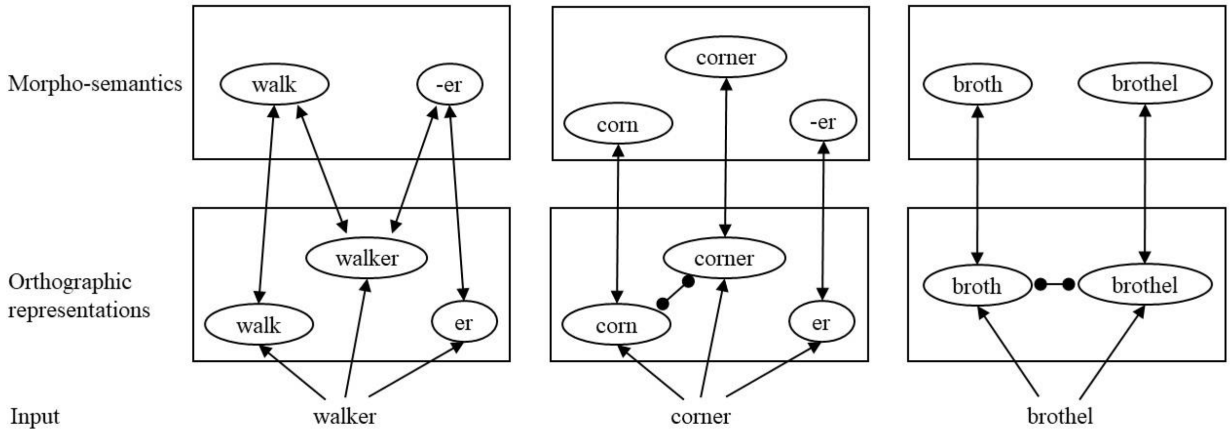


Figure 2 – A representation of Grainger and Beyersmann's (2017) model



Note. Connections ending in arrows and circles represent excitation and inhibition, respectively.

One shared assumption is that a presented (prime) word will activate representations of words that have the same initial letter combination. The motivation for this assumption comes from the finding (Beyersmann et al., 2016; Taft et al., 2019, see also Lupker et al., 2022b) that primes sharing their initial letters with their targets inevitably produce priming unless the entire prime is a word (e.g., brothic and brothap will prime BROTH even though brothel will not).

A second shared assumption, the assumption that makes the models “decomposition” models, is that representations for legitimate affixes (e.g., -*er*) exist and, if the presented (prime) word contains such a letter unit (in the appropriate position in the word – Crepaldi et al., 2010b; 2015), the affix’s representational unit is activated as well. As will be discussed below, the models assume that it is the activation of that unit that allows the opaque condition to produce nearly the same amount of priming as the transparent condition.

A third shared assumption is that the basic representational unit for the multi-morphemic prime exists in all conditions, although, as can be seen in the figures, the models do make slightly different assumptions as to how that unit is activated and where in the system it resides. The fourth shared assumption is that, in the opaque and form conditions, those activated word representations produce competition with the target’s representation (e.g., Davis & Lupker, 2006; Drews & Zwitserlood, 1995; Segui & Grainger, 1990), explicitly represented in Figure 2 in

Grainger and Beyersmann’s (2017) model by the connections ending in filled circles. It is these two assumptions which explain why brothel does not prime BROTH.

The fifth (and final) shared assumption is the models’ key assumption as it is what allows the models to explain the priming effect observed in the opaque condition. That assumption is that the competition between the representations for *corner* and *corn* is retarded due to the activation of the representation for the affix. In Taft and Nguyen-Hoan’s (2010) model, essentially, the lemma for *–er* inhibits the activation of the lemma for *corner* making it a less effective competitor. This inhibitory process emerges because the activation of the lemma representations for *corner*, *corn*, and *–er* (when the prime corner is presented) suggests that the representation of *corn* might be relevant to understanding the word *corner* and, hence, the representation of *corn* should not be inhibited, at least not initially, allowing a priming effect to emerge.

In Grainger and Beyersmann’s (2017) model, the mechanism for how the affix’s representation might retard the inhibition process is not specified but Grainger and Beyersmann have proposed the principle of “full decomposition” as an explanation for why that would happen. According to this principle, “at some point during the processing of a complex word or pseudoword, it is known that the string of letters being processed can be completely divided into a set of component morphemes, independently of the semantic or syntactic compatibility of these morphemes" (p. 296). The realization that the complex word can be fully decomposed without any letters remaining unaccounted for diminishes the level of inhibition between representations for primes and targets in the opaque condition.

In both cases, based on these sets of assumptions, the models provide an account of Rastle et al.'s (2004) pattern. Note that neither model specifically predicts that there will be equivalent priming in the opaque and transparent conditions, merely that there will be more priming in the opaque condition than in the form condition due to the diminished competition. It is also important to point out that an additional assumption that both models would make is that the impact of the activated representation for the affix is time limited. As such, when corner is presented for a longer duration, making it a visible prime, the system can determine that the representation for *corn* is not relevant to the processing of *corner* and, hence, the representation of *corner* would start to suppress any activation that its presentation may have produced in the representation of *corn*. As a result, there is no priming in the opaque condition in that situation (Rastle et al., 2000).

One difference between these two models is in how they assume the representations for transparent primes affect the representations of their targets. Grainger and Beyersmann's (2017) model assumes that the representations of transparent primes activate “morpho-semantic” representations of their targets with those representations then feeding activation back to the orthographic representation of those targets. Taft and Nguyen-Hoan’s (2010) model assumes that the interaction between representations of the transparent primes and targets takes place in a more direct fashion, at the lexical level (compare Figures 1 and 2) and, hence, is not semantically based.

Alternatives to localist decomposition models

There are, of course, models of the relevant processes that their creators argue would explain Rastle et al.’s (2004) pattern that are not decomposition models (e.g., Baayen et al., 2011; Diependaele et al., 2013; Marelli & Baroni, 2015; Plaut & Gonnerman, 2000; Rueckl & Aicher, 2008; Rueckl et al., 1997; Seidenberg & Gonnerman, 2000). These types of models, which are based on distributed representation assumptions, are of two types with, for present purposes, a crucial distinction between them being how the models conceptualize masked priming.

Both types of these models assume that masked priming effects are essentially due to the semantic similarity of the prime and target. One type (Baayen et al., 2011; Marelli & Baroni, 2015) is not based on activation principles. Rather, this type of model is based on the idea that the prime and target create semantic vectors and the size of the priming effect is a direct function of the similarity of those vectors (the implicit assumption being that the similarity of the prime and target vectors in an unrelated condition is essentially zero). The ability of these types of models to explain Rastle et al.'s (2004) data, documented in both papers, comes from the claim, noted above, that, based on the models' assumptions about how semantic similarity is best calculated, the primes and targets in Rastle et al.'s opaque condition were semantically similar. (The question of whether these models could account for a difference between the opaque and form conditions was not addressed in the papers.) In some ways, these models, although based on distributed, rather than localist, representational principles, are similar to the decomposition models described above in the sense that they assume that affixes themselves can play an important role in word recognition. However, unlike those models, these models do not assume the existence of localist representational units for affixes, nor do they assume the existence of representational (e.g., lexical) units for morphologically complex words (e.g., *walker*).

The other type of distributed representation models are activation based. Models of this sort (e.g., Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000) assume that morphological priming effects are due to an interaction of orthographic, phonological and semantic representations in a connectionist system. Specifically, according to Jared et al. (2017), priming effects "arise from patterns of coactivation in the mappings between form and meaning" (p. 23). That is, the ability of walker to prime WALK reflects the fact that the prime walker produces a pattern of activation that is similar to that produced by WALK across a linked set of orthographic, phonological and semantic units. As a result, the system will successfully process WALK more rapidly.

One challenge faced by both of these types of models is that, as yet, they have no obvious way of explaining many of the classic orthographic priming effects (e.g., jugde for the target JUDGE or femce for the target FENCE, see Adelman et al., 2014), effects that, presumably, do not involve either semantic vectors being generated by prime processing or coactivation of links between orthographic and semantic units activated by prime processing. This challenge is one that was noted by Stevens and Plaut (2022). (Readers should refer to Stevens and Plaut (2022) for a discussion of challenges posed to both types of models by other word recognition phenomena.) The activation-based distributed representation models could, however, explain such effects if they assumed that priming was at least partially due to the activation of shared orthographic units, an assumption not at all inconsistent with the basic structure of those models.

The other major challenge for activation-based distributed representation models had been that they would predict that opaque prime-target pairs (e.g., corner-CORN) would produce little priming because opaque prime-target pairs are purposely selected not to be semantically related. That challenge can be addressed by the claim (noted above) that, in many evaluations of opaque priming, the selection process was less than successful in that the opaque pairs used actually were semantically related and, therefore, shared linkages between orthographic and semantic units (Baayen et al., 2011; Marelli et al., 2013, 2015; Marelli & Baroni, 2015).[2]

The present research

In the present experiments, these issues/models were examined by using (in Experiments 2 and 3) another masked priming procedure, one which is quite sensitive to the processing/activation of lower level memory representations, the representations assumed, by activation-based models, to be responsible for producing Rastle et al.’s (2004) pattern. That procedure is the sandwich priming procedure (Lupker & Davis, 2009). The expectation was that, because target activation levels, as well as the activation levels of other components (see Experiment 3), are being more directly manipulated in this task, our results would provide a closer examination of Rastle et al.’s pattern allowing a more complete analysis of its implication for the models.

In sandwich priming, each trial involves a conventional masked priming lexical decision sequence. However, prior to the prime’s presentation, there is a brief masked presentation of the target in both the related and unrelated conditions (e.g., a trial in the transparent related condition would involve the presentation of the sequence: walk-walker-WALK) which should initially activate the representations relevant to target processing on both related and unrelated trials.

Importantly, on related trials, according to Davis’s (2010) Spatial-coding model, there are two impacts on subsequent processing. The major and, for present purposes, more important, impact is that once the target’s representations have been activated by the initial prime (i.e., the target itself) the ability of those representations to maintain/increase their activation is a function of the interactions between those target representations and the early processing of the second prime (the “prime of interest”), the processing that the models being examined here are attempting to describe.

The typical result in sandwich priming experiments is that there is a much larger priming effect from primes of interest that are orthographically similar to their targets than one discovers in conventional masked priming tasks. Indeed, a number of studies (Comesaña et al., 2016; Davis & Lupker, 2017; Lupker & Davis, 2009; Perea et al., 2014; Stinchcombe et al., 2012; Trifonova & Adelman, 2018) have shown that this paradigm can actually produce sizeable priming effects for some prime-target pairs that fail to produce any priming in the conventional task. For present purposes, however, the most important point is that, if this analysis is correct, the priming effects produced by the primes of interest using this procedure should provide a more sensitive evaluation of the nature of the impact of prime processing than the conventional task does. The presumed impact on the model specific mechanisms will be discussed further in the Introduction to Experiment 2.

In Experiments 1 and 2 the impact of sandwich priming was contrasted with that of conventional masked priming using the same conditions as examined by Rastle et al. (2004). Experiment 1 was a replication of Rastle et al.'s experiment, although only a subset of their stimuli was used. That is, unfortunately, some of Rastle et al.'s stimuli seemed to be a bit too British for our Canadian participant population. After removing stimuli of that sort and then removing others so that the three conditions were balanced on all the relevant factors, 36 (of the original 50) targets remained in each of the three conditions. In Rastle et al.'s data, the priming effects for their sets of 50 targets were 27 ms in the transparent condition, 22 ms in the opaque condition and 4 ms in the form condition. Based on the latencies reported in Rastle et al.'s Appendix, the respective priming effects for the (36 × 3 = 108) stimuli used in the present experiments were 26 ms, 26 ms and 5 ms, respectively. The expectation, therefore, was that the typical priming pattern would be replicated in Experiment 1, with a reasonably large opaque-form difference and little evidence of a transparent-opaque difference.[3] Experiment 2 involved those same stimuli in a sandwich priming lexical decision experiment.

Experiment 1

Method

Participants. The participants were 124 University of Western Ontario undergraduate students who participated for course credit. All had normal or corrected-to-normal vision and were native speakers of English. Note that, for this experiment and for Experiment 2, the sample sizes were considerably larger than the sample size in Rastle et al.'s (2004) experiment (*N* = 62) in order to ensure that we would be able to detect the interaction between priming and prime-target relationship that masked morphological priming lexical decision tasks typically produce.

Materials. From the stimuli used by Rastle et al. (2004), 36 targets and their associated primes (both related and unrelated) were selected from the 50 targets in each of the transparent, opaque and form conditions. The targets were selected so that they were essentially equated on length (4.9, 4.8 and 4.6 letters, respectively), CELEX frequency (30.6, 28.2 and 21.2 occurrences per million (opm), respectively) and Coltheart et al.'s (1977) N (2.1, 2.0, 2.1, respectively). Lengths were also equated for the related primes (7.1, 7.2 and 7.0 letters, respectively) and the unrelated primes (7.1, 7.2 and 7.0 letters, respectively) as were CELEX frequencies (for the related primes, 13.2, 23.8 and 14.0 opm, respectively; for the unrelated primes, 19.2, 27.6, 19.9 opm, respectively) and N values (for the related primes, .6, .8 and 1.0, respectively, for unrelated primes, 1.5, 1.0 and .8, respectively). From the stimuli used by Rastle et al. (2004), 108 nonword targets and their associated word primes (all suffixed words unrelated to the nonwords) were also selected. The nonword targets had similar average lengths (4.9 letters) and N values (2.0) as the word targets. A list of the stimuli for the word trials is contained in Appendix A and a list of the stimuli for the nonword trials is contained in Appendix B.

In order to counterbalance the conditions, the word targets in each of the conditions were divided into two sets of size 18 with one set being presented with related primes (to half the participants) and the other set with unrelated primes (to that same half of the participants). The prime-target relationships were reversed for the other half of the participants.

Procedure. Participants were tested individually. Participants were told that following a string of hash marks (i.e., #########), they would see a letter string on the computer screen. Their task was to indicate whether the letter string was an English word or not by pressing the right shift-key if it was a word and the left shift-key if it was a nonword.

Each trial consisted of the presentation of three stimuli in the same location in the middle of the computer screen, a 17 inch PC monitor. First, a row of ten hash marks (##########) was presented for 550 ms to serve as a fixation mark, followed by the prime (in lowercase) for 50 ms, followed by the target (in uppercase) for 3 s or until a response was made. Response times (RTs) were measured from the target's onset until the participant's response.

The primes were displayed in lowercase in size 14 New Courier font, whereas the targets were displayed in uppercase in size 17 New Courier font. The targets were also flanked by two arrow symbols, "<" and ">", displayed immediately to the left and to right of the target, respectively. The reason that the targets were in a larger font than the primes and were flanked by the arrow symbols (which participants were told to ignore) was because, in this manipulation, the targets are shorter than the primes. That fact may potentially reduce the targets' effectiveness as backward masks for the primes unless the appearance of the targets is modified so that their physical length on the screen matches or exceeds that of their primes, as the modifications that we applied were intended to do. (Note that this particular precaution was not taken by Rastle et al., 2004.) The specific order of presentation of the targets within each list was randomized for each participant using Forster and Forster's (2003) DMDX software.

When the participant responded to a trial, the target disappeared from the screen and the next trial began. All participants received 8 practice trials involving a novel set of stimuli prior to the 216 experimental trials. No participants mentioned any awareness of the primes. The entire experiment lasted approximately 10 minutes. This and the other experiments reported here were approved by the University of Western Ontario REB (Protocol # 104255).

Results

Response times faster than 250 ms or slower than 1600 ms were removed as outliers (2.4% and 4.0 %, respectively, for the “word” and “nonword” trials). Data from two word targets (i.e., “glut” from the opaque condition and “squaw” from the form condition) were also removed due to error rates above 45%. The remainder of the correct responses and the error rates for the word trials were analyzed using a generalized linear mixed-effects model (GLMM) in which subjects and items (the target stimuli) were random effects, and Prime-Target Relationship (Transparent vs. Opaque vs. Form, within-subject and between-item) and Relatedness (Related vs. Unrelated, within-subject and within-item) were fixed effects.

In this and the following experiments, in the latency analyses, a GLMM was used instead of a linear mixed-effects model, the type of model that is more commonly used for latencies, because linear models, unlike generalized linear models, assume normally distributed residuals. Because the typically positively skewed distribution of raw RTs fails to accommodate that assumption, the common practice in linear model analyses is to normalize raw RTs with a reciprocal transformation (e.g., invRT = -1000/RT). Unfortunately, nonlinear transformations such as a reciprocal transformation 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 et al., 2013). For that reason, consistent with more recent practices (e.g., Cohen-Shikora et al., 2019; Lo & Andrews, 2015; Yang et al., 2019), we used a GLMM because generalized linear models, unlike linear models, do not assume normally distributed residuals and can, therefore, better accommodate the distribution of raw RT data without requiring a transformation of those data.

A Gamma distribution was used to fit the raw RTs, with an identity link between fixed effects and the dependent variable (Lo & Andrews, 2015). For the error rate analysis, a binomial distribution was used with a logit link between fixed effects and the dependent variable. Because, in the current version of lme4 (the R package used for running the GLMMs), convergence failures for GLMMs are frequent (although many of those failures reflect false positives: Bolker, 2022), in order to limit the occurrence of failures, we kept the random structure of the model as simple as possible by using only random intercepts for subjects and items. For the same reason, the model was run increasing the maximum number of iterations to one million and using the BOBYQA optimizer, an optimizer that typically returns estimates that are equivalent to those returned by lme4's default optimizer, but produces fewer convergence failures (see, e.g., Colombo et al., 2020; Lupker et al., 2020a, 2020b).[4]

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, 2019). The model was fit by maximum likelihood with the Laplace approximation technique. The lme4 package, version 1.1-23-1 (Bates et al., 2015), was used to run the GLMM. The function Anova in the car package, version 3.0-7 (Fox & Weisberg, 2016), was used to obtain estimates and probability values for the fixed effects specifying Type III Sums of Squares. Pairwise comparisons for the levels of the Prime-Target Relationship factor, when necessary, were conducted using the emmeans package, version 1.4.6 (Lenth, 2018), with Tukey's HSD adjustment for multiple comparisons. All analyses were conducted in R version 3.6.3 (R Core Team, 2020). Mean response latencies and error rates for each condition for the word trials based on the subject means are reported in Table 1 as are the mean latency and error rate for the nonword trials. For this and the following experiments, the raw data and R files used for the analyses are publicly available at https://osf.io/5uge6/. Any information concerning the experimental materials that is not contained in the two Appendices is available upon request. None of these experiments was preregistered.

Table 1 – Mean latencies and error rates for the word trials in Experiment 1.

	Prime-Target Relationship		
Relatedness	Transparent	Opaque	Form
Related	629 (1.6%)	678 (7.3%)	697 (8.8%)
Unrelated	656 (2.3%)	705 (8.1%)	708 (9.8%)
Priming Effect	27 (0.7%)	27 (0.8%)	11 (-1.0%)

(Note: The mean latency for the nonwords was 790 ms and the mean error rate was 5.7%.)

Word trials

Latencies. Relatedness was significant, $\chi^2 = 75.97$, $p < .001$, as related primes produced faster latencies than unrelated primes overall. The Prime-Target Relationship effect was also significant, $\chi^2 = 187.95$, $p < .001$, as the transparent condition was overall faster than both the opaque condition, $\beta = 58.3$, $SE = 5.14$, $z = 11.32$, $p < .001$, and the form condition, $\beta = 71.8$, $SE = 5.25$, $z = 13.69$, $p < .001$, and the opaque condition was overall faster than the form condition, $\beta = 13.6$, $SE = 3.33$, $z = 4.08$, $p < .001$. Importantly, the interaction between Relatedness and Prime-Target Relationship was also significant, $\chi^2 = 12.99$, $p = .002$. This interaction reflected the fact that the Relatedness effect in the form condition was significantly smaller than that in both the transparent, $\beta = -17.44$, $SE = 5.53$, $z = -3.15$, $p = .002$, and opaque conditions, $\beta = -15.28$, $SE = 5.04$, $z = -3.03$, $p = .002$ (the Relatedness effect was not different in the transparent and opaque conditions, $\beta = -2.16$, $SE = 5.43$, $z = -.40$, $p = .691$). When analyzed separately, the smaller Relatedness effect in the form condition was significant (11 ms; $\beta = 9.4$, $SE = 3.91$, $z = 2.41$, $p = .016$), as were the Relatedness effects in the transparent (27 ms; $\beta = 26.8$, $SE = 3.79$, $z = 7.08$, $p < .001$) and opaque conditions (27 ms; $\beta = 24.7$, $SE = 3.89$, $z = 6.34$, $p < .001$).

Errors. Relatedness was not significant overall, $\chi^2 = 2.68$, $p = .101$. Prime-Target Relationship was significant, however, $\chi^2 = 17.02$, $p < .001$, as the transparent condition was overall more accurate than both the opaque condition, $\beta = -1.10$, $SE = .39$, $z = -2.79$, $p = .015$, and the form condition, $\beta = -1.58$, $SE = .39$, $z = -4.05$, $p < .001$ (the opaque and form conditions did not differ from one another, $\beta = -.48$, $SE = .38$, $z = -1.26$, $p = .419$). The interaction between Relatedness and Prime-Target Relationship was also significant, $\chi^2 = 7.04$, $p = .030$. This interaction reflected the fact that the (negative) Relatedness effect in the form condition was significantly different from the (positive) Relatedness effect in the transparent condition, $\beta = .57$, $SE = .24$, $z = 2.40$, $p = .017$, although only numerically different from the (positive) Relatedness effect in the opaque condition, $\beta = .32$, $SE = .17$, $z = 1.85$, $p = .064$ (the Relatedness effect was not significantly different for the transparent and opaque conditions, $\beta = .25$, $SE = .25$, $z = 1.02$, $p = .308$). However, when analyzed separately, the Relatedness effect in the transparent condition was statistically significant (.7%; $\beta = -.43$, $SE = .21$, $z = -2.03$, $p = .042$), whereas the Relatedness effects in the opaque (.8%; $\beta = -.18$, $SE = .13$, $z = -1.33$, $p = .184$) and form conditions (-1%; $\beta = .15$, $SE = .12$, $z = 1.27$, $p = .205$) were not.

Discussion

The pattern produced by our subset of Rastle et al.'s (2004) stimuli (i.e., equivalent priming in the transparent and opaque conditions and little priming in the form condition) was quite similar to that reported in their parallel experiment both overall and when only considering their data from the subset of stimuli we used. This pattern is quite consistent with the decomposition models. Additionally, in terms of Grainger and Beyersmann's (2017) model, the implication is that feedback from morpho-semantic representations must have been minimal in Experiment 1 as it did not provide the transparent condition any advantage over the opaque condition.

This pattern is also consistent with the distributed representation models if the assumption is made that these opaque primes were essentially as semantically related to their targets as the transparent primes were to theirs. That is, in terms of the activation-based distributed representation models, the opaque primes were as effective as the transparent primes were at producing "patterns of coactivation in the mappings between form and meaning" (Jared, et al., 2017, p. 23), the presumed source of the priming according to those models. In terms of the similarity-based distributed representation models, the prime-target similarity values must have been essentially equal in the transparent and opaque conditions. These stimuli were the stimuli used in the sandwich priming task in Experiment 2.

Before continuing, however, two issues with respect to Experiment 1 need to be addressed. First, the fact that we followed Rastle et al.’s (2004) procedure meant that none of the nonword targets were primed by orthographically similar primes (as noted in footnote 3). Thus, one could argue that if participants had been able to detect both the fact that there was an orthographic relationship between any masked primes and targets and the fact that those relationships only exist for word targets, they could use that information strategically in order to produce more rapid responding in the related conditions (Feldman et al., 2009).

While there are no data in Experiment 1 that could be used to clearly rule out this possibility, two points should be noted. First, there is very little evidence that participants are even aware of the existence of 50 ms primes, much less that participants have the ability to use them strategically (e.g., Kinoshita et al., 2011). Second, and more importantly, because the orthographic similarity between the related primes and targets was identical in all three conditions (i.e., the target was a subset of the prime), this type of strategy would have affected the three conditions equally. Hence, it would not explain the interaction of Prime-Target Relationship and Relatedness.

The other issue that needs to be addressed concerns the fact that the latencies following unrelated primes in the transparent condition were significantly faster than those in the other two conditions, a result also reported by Rastle et al. (2004).

This type of result is not uncommon and likely has a fairly straightforward explanation (for a discussion, see Marelli et al., 2015; see also Xu & Taft, 2015). The relevant issue here is that, because of this difference, one could argue that the priming effect in the transparent condition was artificially restricted. Again, Experiment 1 contains no data that could rule out that possibility. The point needs to be made, however, that, for decomposition models, the prediction is not that there will always be an identical amount of priming in the transparent and opaque conditions. The priming in the two conditions derive from slightly different sources. The priming in the opaque condition is a function of the extent to which the activation of the representation of the affix prevents the prime's representation from inhibiting the target's representation. That type of inhibition process plays no role in the transparent condition. What is the core prediction is that priming in the opaque condition is, typically significantly, larger than that in the form condition, as was the case in Experiment 1 even though unrelated condition latencies were essentially equivalent in those two conditions. This result indicates that the opaque priming effect was not simply based on orthographic similarity, the key point for decomposition models.

Experiment 2

As noted, in the sandwich priming procedure, the assumed impact of the initial prime (i.e., the target itself) is to activate the memory representation(s) of the target prior to the conventional priming sequence beginning on both related and unrelated trials. On unrelated trials, the heightened activation in the target's representation will start to decay when the initial prime is removed and the (unrelated) prime of interest is presented. On related trials, however, that activation will be maintained to some degree and/or enhanced by the processing of any prime that activates those same representations. What is the expected data pattern in a sandwich priming task according to the various models discussed above?

According to the decomposition models, both of which are activation-based models, the heightened activation created in the representations relevant to target processing as a result of presenting the target as the initial prime should be maintained/increased by a related prime of interest. In contrast, unrelated primes of interest will allow that activation to decay. In line with prior results in sandwich priming experiments, there should, therefore, be an increase in the sizes of the priming effects observed in Experiment 1, at least in the transparent and opaque conditions, as the addition of the initial prime should not change any other aspect of the target activation process in those conditions. That is, there are no inhibitory processes involved in the transparent condition and, with respect to the opaque condition, there should be little, if any, competition from the representation of the prime of interest because in both Taft and Nguyen's (2010) model and Grainger and Beyersmann’s (2017) model, mechanisms, arising from the activation of the affix’s representation, are in place to prevent competition from playing a major role.

In addition, according to Grainger and Beyersmann’s (2017) model, there is the potential that priming in the transparent condition might be enhanced further by activation from the linkage between the morpho-semantic representation and the orthographic representation of the target (see Figure 2). That is, the processing of the two primes, the first of which is the target itself, may allow the target’s morpho-semantic representation to be activated sufficiently to produce some measurable additional feedback activation in the target’s orthographic representation. Essentially, therefore, according to both models, the overall impact of the initial prime should be to produce a larger priming effect in the transparent and opaque conditions in Experiment 2 than in Experiment 1, the typical result in sandwich priming experiments.

The form condition would work slightly differently. In that condition, there will be substantially less opportunity for increased priming due to the competition/inhibition between the representations of the prime of interest and the target. As in the other conditions, the two primes will both produce activation in both representations. Hence, although the target’s representation will have additional activation, the prime of interest’s representation will be a much stronger competitor. Potentially, due to the fact that the target is presented first (as an initial prime) its representation may gain a bit of an advantage over that for the prime of interest, leading to a slight increase in priming in Experiment 2. That increase, however, would be expected to be much smaller than the increase observed in the other two conditions.

For activation-based distributed representation models (e.g., Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000), the initial prime (i.e., the target) will activate the orthographic, phonological and semantic units (and, more importantly, their mappings) for the target's representation. When a related prime of interest is presented, it will help maintain that activation, depending on the condition. Based on the fact that the transparent and opaque conditions produced equivalent priming in Experiment 1, the most reasonable model-based assumption concerning our stimuli is that the mapping relationships between the primes of interest and their targets must be equally strong in the two conditions. Therefore, once those mappings are activated by the initial prime, the primes of interest in both conditions should be able to maintain that activation, producing increased and equivalent priming effects.

Such is, again, not necessarily the case in the form condition as the orthographic units of those primes of interest are not linked to the semantic units of their targets. Therefore, activation of the relevant mappings would decay in this condition during the presentation of the related prime of interest in the same way as it would decay during the presentation of an unrelated prime. There may be some additional priming in the form condition in Experiment 2 if the activation of shared orthographic units contributes to the priming effect (as the small priming effect in the form condition in Experiment 1 would suggest). However, the impact of priming at the orthographic level appears to be small for these stimuli. Therefore, any increased priming in the form condition should be minimal.

The models discussed above seem to predict similar patterns, increased priming in the transparent and opaque conditions but not in the form condition with the equivalence in priming in the former two conditions being maintained. This same pattern of predictions does not seem to hold for the other type of distributed representation models, essentially because of how the models explain the priming process (i.e., it is not an activation process).

Consider first Baayen et al.’s (2011) model. This model bases its explanation of priming in Rastle et al.’s (2004) paradigm on Ratcliff and McKoon’s (1992) compound cue theory. According to this idea, prime and target associations to items in memory (e.g., meanings) are combined to form a cue that produces a familiarity value. The prime and target do not contribute equally to the calculation of that value with the model assumption being that the weight on the target information is .95 and the weight on prime information is .05 in the model equations. Latencies on any trial are an inverse function of the familiarity value of the compound cue. The reason that priming is observed is that, to the extent that the prime and target are associated with the same items in memory, that cue will have a higher familiarity value than a cue formed from unrelated primes and targets.

In sandwich priming, a second prime is added, the target itself. If that second prime has any effect at all, it would have to do so by contributing to the compound cue. That is, it would have to be given some weight so that its linkages to items in memory would be integrated into the familiarity equation on both related and unrelated trials. Those linkages, however, are the same as those of the target. Therefore, giving the initial prime weight by taking weight from the target would essentially be the same mathematically as not changing the familiarity equations at all. Therefore, no change in the priming effect would be predicted. For any change in predicted priming to occur, weight given to the initial prime would have to be taken from the prime of interest (which would, presumably, be the case in both the related and unrelated conditions).

What then are the implications of taking weight from the prime of interest and giving it to the target? The result would be to diminish the impact of the prime of interest. That is, if, for example, .02 were taken from the prime of interest, making its weight .03, and that weight were given to the initial prime (i.e., the target), that would mean that the target’s weight would increase to .97. The result, in both the related and unrelated conditions, would be that the responses would be based more exclusively on target processing. Because the target is the same in the related and unrelated conditions, the latencies in those two conditions would start to merge. Therefore, the prediction would be that there would be less priming in a sandwich priming task than in a conventional task rather than the increased priming effect typically observed in sandwich priming experiments. Equally importantly for present purposes, whatever impact the initial prime would have should not affect the three conditions differentially.

Marelli and Baroni’s (2015) model has a similar problem. According to that model, semantic vectors are produced for the prime and target. The predicted priming effect is a direct function of the cosine of the angle between the two vectors (with the implicit assumption being that the cosine of the angle between the prime and target vectors in the unrelated condition is essentially 0). For the initial prime to have any impact, its vector must be integrated into this similarity calculation. Because the initial prime is the target, if it were integrated by having its vector added to the target vector, the direction of the target vector would be unchanged. Therefore, the cosine of the angle between this composite target vector and the prime of interest’s vector would also be unchanged (in both the related and unrelated conditions), meaning that the priming effect in the sandwich priming task should be the same as that in the conventional task.

If, instead, the initial prime's vector were combined with the prime of interest's vector, the resultant composite prime vector would be somewhere (e.g., half way) between the two prime vectors. The result would be that the angle between the composite prime vector and the target vector would be reduced in both the related and unrelated conditions. However, that reduction in angle (and corresponding increase in cosine) would be much greater in the unrelated condition than in the related condition because the angle in the unrelated condition was much larger to begin with. Therefore, the prediction would be that the priming effect would be smaller in the sandwich priming task than in the conventional task. The main point here is simply that, without changing model assumptions concerning how priming takes place, the similarity-based distributed representation models predict that, in Experiment 2, there will be either no increase in priming or reduced priming in all three conditions.

Method

Participants. The participants were 98 University of Western Ontario undergraduate students who participated for course credit. None had participated in the previous experiment. All had normal or corrected-to-normal vision and were native speakers of English.

Materials. The materials were the same as in Experiment 1.

Procedure. The basic procedure was the same as that of Experiment 1. Note, in particular, that the stimulus onset asynchrony for the prime of interest and the target was the same as in Experiment 1. The only difference between experiments was that a 33 ms lowercase presentation of the target in size 14 New Courier font was inserted between the forward mask and the prime of interest on all trials.

Results

Response times faster than 250 ms or slower than 1600 ms were removed as outliers (2.4% and 3.8%, respectively, for the word and nonword trials). Data from two word targets (i.e., “glut” from the opaque condition and “squaw” from the form condition) were also removed due to error rates above 45%. The remainder of the correct responses and the error rates for the word trials were analyzed in the same way as in Experiment 1. That is, GLMM analyses were used in which subjects and items (the target stimuli) were random effects, and Prime-Target Relationship (Transparent vs. Opaque vs. Form, within-subject and between-item) and Relatedness (Related vs. Unrelated, within-subject and within-item) were fixed effects. Mean response latencies and error rates for each condition for word trials based on the subject means are reported in Table 2 as are the mean latency and error rate for the nonword trials.

Table 2 – Mean latencies and error rates for the word trials in Experiment 2.

	Prime-Target Relationship		
Relatedness	Transparent	Opaque	Form
Related	615 (2.0%)	671 (7.2%)	698 (9.7%)
Unrelated	660 (2.7%)	694 (8.4%)	703 (8.5%)
Priming Effect	45 (0.7%)	23 (1.2%)	5 (-1.2%)

(Note: The mean latency for the nonwords was 786 ms and the mean error rate was 5.8%.)

Word trials

Latencies. Relatedness was significant, $\chi^2 = 53.79$, $p < .001$, as related primes produced faster latencies than unrelated primes overall. The Prime-Target Relationship effect was also significant, $\chi^2 = 50.53$, $p < .001$, an effect that derived from the fact that the transparent condition was overall faster than the form condition, $\beta = 71.7$, $SE = 17.3$, $z = 4.15$, $p < .001$. Although the transparent condition was numerically faster than the opaque condition as well, the two conditions did not differ statistically, $\beta = 58.3$, $SE = 34.9$, $z = 1.67$, $p = .216$, nor did the opaque and form conditions, $\beta = 13.4$, $SE = 20.0$, $z = .67$, $p = .780$. The interaction between Relatedness and Prime-Target Relationship was also significant, $\chi^2 = 32.02$, $p < .001$. This interaction reflects the fact that the Relatedness effect differed across the prime-target relationship types. Specifically, the Relatedness effect in the form condition was significantly smaller than those in both the transparent, $\beta = -39.9$, $SE = 7.08$, $z = -5.63$, $p < .001$, and opaque conditions, $\beta = -19.9$, $SE = 7.09$, $z = -2.81$, $p = .005$, and the Relatedness effect in the opaque condition was significantly smaller than that in the transparent condition, $\beta = -20.0$, $SE = 6.54$, $z = -3.06$, $p = .002$. Further, when analyzed separately, the Relatedness effect was significant in both the transparent (45 ms; $\beta = 45.5$, $SE = 5.29$, $z = 8.60$, $p < .001$) and opaque conditions (23 ms; $\beta = 25.5$, $SE =$

5.40, $z = 4.73$, $p < .001$), but not in the form condition (5 ms; $\beta = 5.6$, $SE = 5.20$, $z = 1.08$, $p = .279$).

Errors. Relatedness was not significant overall, $\chi^2 = 1.18$, $p = .276$. Prime-Target Relationship was significant, $\chi^2 = 16.71$, $p < .001$, as the transparent condition was overall more accurate than both the opaque condition, $\beta = -1.09$, $SE = .37$, $z = -2.95$, $p = .009$, and the form condition, $\beta = -1.45$, $SE = .37$, $z = -3.96$, $p < .001$ (the opaque and form conditions did not differ from one another, $\beta = -.36$, $SE = .36$, $z = -1.01$, $p = .573$). The interaction between Relatedness and Prime-Target Relationship was also significant, $\chi^2 = 6.30$, $p = .043$. This interaction reflected the fact that the (negative) Relatedness effect in the form condition was significantly different from the (positive) Relatedness effect in the transparent condition, $\beta = .55$, $SE = .26$, $z = 2.15$, $p = .032$, although only marginally different from the (positive) Relatedness effect in the opaque condition, $\beta = .37$, $SE = .19$, $z = 1.95$, $p = .051$. The Relatedness effect did not differ between the transparent and opaque conditions, $\beta = .17$, $SE = .26$, $z = .67$, $p = .505$. When analyzed separately, the Relatedness effect was not significant in any condition: the transparent condition (.7%; $\beta = -.35$, $SE = .22$, $z = -1.58$, $p = .113$), the opaque condition (1.2%; $\beta = -.17$, $SE = .14$, $z = -1.21$, $p = .225$), the form condition (-1.2%; $\beta = .20$, $SE = .13$, $z = 1.53$, $p = .125$).

Combined Analyses of Experiments 1 and 2

To examine the impact of the sandwich priming procedure, for each prime-target condition, we contrasted the priming effects in Experiments 1 (conventional masked priming) and 2 (sandwich priming) in a pairwise fashion. In these combined analyses, the latencies of the correct responses and the error rates for the word trials in each condition were analyzed using GLMMs in which subjects and items were random effects, and Relatedness and Experiment were fixed effects.

Latencies. The GLMM for the form condition failed to converge initially, but managed to converge once it was restarted from the apparent optimum as per the recommended troubleshooting procedure (see “convergence” help page in R). For that condition, we report the results from the restarted model. All three conditions showed a main effect of Relatedness (related faster than unrelated; transparent: $\chi^2 = 154.40$, $p < .001$; opaque: $\chi^2 = 50.96$, $p < .001$; form: $\chi^2 = 4.91$, $p = .027$), and no main effect of Experiment (transparent: $\chi^2 = .24$, $p = .625$; opaque: $\chi^2 = 1.41$, $p = .236$; form: $\chi^2 = .16$, $p = .687$). Only the transparent condition, however, showed a change in the size of the priming effect across experiments, $\chi^2 = 10.70$, $p = .001$ (opaque: $\chi^2 < .01$, $p = .949$; form: $\chi^2 = .28$, $p = .596$). This result was due to the fact that, in the transparent condition, the priming effect was larger in sandwich priming (i.e., Experiment 2, 45 ms) than in conventional masked priming (i.e., Experiment 1, 27 ms).

Errors. The transparent condition showed a significant main effect of Relatedness (related more accurate than unrelated), $\chi^2 = 5.59$, $p = .018$, whereas this effect was marginal for both the opaque, $\chi^2 = 3.01$, $p = .083$, and form conditions (with the numerical tendency in the form condition being for a negative priming effect – related less accurate than unrelated), $\chi^2 = 3.42$, $p = .064$. None of the three conditions showed a main effect of Experiment (transparent: $\chi^2 = .94$, $p = .332$; opaque: $\chi^2 < .01$, $p = .982$; form: $\chi^2 = .04$, $p = .839$), nor a change in the size of the priming effect across experiments (transparent: $\chi^2 = .05$, $p = .826$; opaque: $\chi^2 = .02$, $p = .898$; form: $\chi^2 = .03$, $p = .861$).

Discussion

The results of Experiment 2 were different in only one respect from those of Experiment 1. The priming effect in the transparent condition (45 ms) increased significantly from its size in Experiment 1 (27 ms) and was significantly larger than that in the opaque condition (in spite of the fact that the latency following unrelated primes was considerably shorter in the transparent condition than in the opaque condition). In contrast, the priming effect sizes in the opaque and form conditions were virtually unaffected by the change to the sandwich priming technique.

The increased priming in the transparent condition is consistent with both of the decomposition models (Grainger & Beyersmann, 2017; Taft & Nguyen-Hoan, 2010) as well as with the activation-based distributed representation models (in which the priming effect is assumed to be due to the activation of mappings between units). In contrast, the similarity-based distributed representation models do not appear to predict the core finding of an increase in the transparent condition priming effect as a result of adding the initial prime.

As described previously, the lack of increased priming in the form condition is also relatively consistent with all models. The challenge for the models that predicted the increase in priming in the transparent condition is how, in that context, they can handle the lack of an increase in priming in the opaque condition. With respect to the two decomposition models, the initial presentation of the target should have activated its representations prior to the presentation of the opaque prime of interest. The prime of interest would then add to/maintain that activation. Importantly, the activation of the affix by that prime should prevent that prime's representation from inhibiting the representation of the target until processing of the prime of interest had reached a considerable level. Based on the results in the conventional task, the assumption is that processing only reaches that level so late in prime processing that inhibition can only play a small role in the opaque condition, allowing that condition to show nearly the same level of priming as the transparent condition. As such, if there is increased priming in the transparent condition there should have been increased priming in the opaque condition as well. It would appear that the only way for these models to explain the lack of an increase in the opaque condition would be by making the ad hoc assumption that because the representation of the prime of interest receives activation from all three presented stimuli, its activation level is so high that the representation of the affix can no longer stop it from competing with the target's representation.

Note, however, that Grainger and Beyersmann's (2017) model can explain why the transparent and opaque conditions might have produced different levels of priming in Experiment 2. The reason is that the transparent condition in that experiment could have benefited from an additional source of priming. That is, the model assumes that the morpho-semantic representation for the target feeds activation back to the target's orthographic representation in the transparent condition. Although that process appeared to have had no impact in Experiment 1 (as evidenced by the equivalent priming in the transparent and opaque conditions) it might have played a role in Experiment 2. That is, the target itself, presented as the initial prime, may have activated the target's morpho-semantic unit early in processing, giving the feedback process more time to unfold and, hence, allowing transparent targets to show more priming than opaque targets. What's important to note, however, is that, although this idea would account for a difference between the transparent and opaque conditions, it alone would not explain why there was no increase in the opaque priming effect in Experiment 2.

With respect to the distributed representation models in which priming is assumed to be driven by the patterns of coactivation in the mappings between form and meaning, the data from Experiment 1 need to be explained by assuming that our primes of interest are equally effective at activating those mappings in the transparent and opaque conditions. In Experiment 2, the presentation of the initial prime (i.e., the target) should also activate those mappings for the target in the two conditions. Therefore, one would expect that those conditions would behave in a parallel fashion in Experiment 2, producing increased priming effects in both conditions. The lack of increased priming in the opaque condition in Experiment 2, in the face of increased priming in the transparent condition, would, therefore, seem to pose a challenge for these models, just as it does for the decomposition models.

Experiment 3

As none of the models discussed above can readily explain the contrast between the transparent and opaque conditions in Experiment 2, the goal of

Experiment 3 was to focus more directly on what separates the models that can predict the increased priming in the transparent condition from one another, that is, their assumptions concerning the role of the affix in the priming process.

The decomposition models are based on the idea that affixes have representations that are activated essentially automatically when words containing those letters in the appropriate positions are read. The affix representations then play a key role in producing Rastle et al.'s (2004) pattern, in particular, the priming observed in the opaque condition, by preventing the representation of the prime from inhibiting the representation of the target, in contrast to what those models assume happens in the form condition.

One additional point to be made is that, in both decomposition models, affix representations are linked to target representations in the transparent condition. As such, the activation of the affix's representations would lead to activation of transparent target representations. Note as well that the affix's and target's representations are more directly linked in Taft and Nguyen-Hoan's (2010) model (i.e., at the lemma level) than in Grainger and Beyersmann's (2017) model (across levels – see Figures 1 and 2).

In an attempt to examine these ideas, Experiment 3 involved a modified version of the sandwich priming task. In this task, the initial prime was not the target word but the affix or the nonaffix in the form condition (e.g., the priming sequence in the related transparent condition was: er-walker-WALK). According to decomposition models, the presentation of the affix should activate its representations, potentially providing activation to the target's representation in the transparent condition. Its impact should also be felt in the opaque condition as activating the affix's representation in that fashion should make it very effective at preventing the representation of the opaque prime from inhibiting the representation of the target, potentially allowing the opaque condition to show a larger priming effect in Experiment 3 than in Experiment 1. Finally, neither model would predict an impact of the task change in the form condition in Experiment 3 since neither model assumes that there are representations for the nonaffixes that were presented as initial primes.

With respect to the other models, as the affixes (and nonaffixes) actually bear no relationship to the targets, those models would predict that the initial prime should have no effect on the nature of the priming effects observed in this experiment (i.e., the results of Experiment 3 should mimic those of Experiment 1).

Method

<u>Participants</u>. The participants were 56 University of Western Ontario undergraduate students who participated for partial course credit. None had

participated in the previous experiments. All had normal or corrected-to-normal vision and were native speakers of English. Although a larger sample would have been desirable, a power analysis conducted with the powerSim function in the simR package, version 1.0.5 (Green & MacLeod, 2016; see also Brysbaert & Stevens, 2018) in R suggested that 34 participants would be sufficient to detect an interaction as large as the interaction between Relatedness and Prime-Target Relationship reported in Experiment 2 with a power of at least .80.[5]

Materials. The materials were the same as those in Experiment 1.

Procedure. The procedure was the same as that in Experiment 2 except that the initial prime was the letters of the suffix or nonsuffix contained in the related prime of interest for both the word and nonword targets. Further, because this initial prime was inevitably much shorter than the subsequent prime, in order to enhance the effectiveness of the initial prime as a forward mask for the prime of interest, the initial prime was flanked by six arrow symbols, “<<<” and “>>>”, displayed immediately to the left and to right of the initial prime.[6]

Results

Response times faster than 250 ms or slower than 1600 ms were removed as outliers (2.1% and 3.9%, respectively, for the word and nonword trials). Data from four word targets (i.e., “facet”, “glut”, and “helm” from the opaque condition and “squaw” from the form condition) were also removed due to error rates above 45%. The remainder of the correct responses and the error rates for the word trials were analyzed in the same way as in Experiments 1 and 2. Mean response latencies and error rates for each condition for word trials based on the subject means are reported in Table 3.

Table 3 – Mean latencies and error rates for the word trials in Experiment 3.

	Prime-Target Relationship		
Relatedness	Transparent	Opaque	Form
Related	642 (1.6%)	692 (7.3%)	718 (11.6%)
Unrelated	684 (3.7%)	705 (8.7%)	726 (10.9%)
Priming Effect	42 (2.1%)	13 (1.4%)	8 (-.7%)

(Note: The mean latency for the nonwords was 791 ms and the mean error rate was 5.5%.)

Word trials

Latencies. There was a main effect of Relatedness, $\chi^2 = 34.75$, $p < .001$, with faster latencies following related than unrelated primes overall. There was also a main effect of Prime-Target Relationship, $\chi^2 = 39.89$, $p < .001$, as the transparent condition was overall faster than both the opaque, $\beta = 43.4$, $SE = 13.9$, $z = 3.11$, $p = .005$, and form conditions, $\beta = 73.0$, $SE = 11.7$, $z = 6.26$, $p < .001$, and the opaque condition was overall faster than the form condition, $\beta = 29.6$, $SE = 11.6$, $z = 2.57$, $p = .028$. The interaction between Relatedness and Prime-Target Relationship was also significant, $\chi^2 = 18.93$, $p < .001$. This interaction reflected the fact that the Relatedness effect in the transparent condition was significantly larger than that in both the opaque, $\beta = -30.23$, $SE = 8.7$, $z = -3.48$, $p < .001$, and form conditions, $\beta = -35.34$, $SE = 8.7$, $z = -4.05$, $p < .001$ (the Relatedness effects were not significantly different in the opaque and form conditions, $\beta = -5.11$, $SE = 8.5$, $z = -.60$, $p = .548$). Further, when analyzed separately, the Relatedness effect was significant in the transparent condition (42 ms; $\beta = 43.90$, $SE = 5.93$, $z = 7.40$, $p < .001$) and in the opaque condition (13 ms; $\beta = 13.67$, $SE = 6.38$, $z = 2.14$, $p = .032$) although it was not significant in the form condition (8 ms; $\beta = 8.56$, $SE = 6.38$, $z = 1.34$, $p = .180$).

Errors. The main effect of Relatedness was significant, $\chi^2 = 7.12$, $p = .008$, as related primes produced fewer errors overall than unrelated primes. The main effect of Prime-Target Relationship was also significant, $\chi^2 = 17.21$, $p < .001$, as the transparent condition produced fewer errors than both the opaque, $\beta = -1.15$, $SE = .48$, $z = -2.39$, $p = .044$, and form conditions, $\beta = -1.93$, $SE = .47$, $z = -4.15$, $p < .001$ (the opaque and form conditions did not differ from one another, $\beta = -.78$, $SE = .45$, $z = -1.75$, $p = .188$). The interaction between Relatedness and Prime-Target Relationship was significant as well, $\chi^2 = 8.52$, $p = .014$. This interaction reflected the fact that the Relatedness effect in the transparent condition was significantly larger than that in the form condition, $\beta = 1.05$, $SE = .36$, $z = 2.90$, $p = .004$, and marginally larger than that in the opaque condition, $\beta = .74$, $SE = .38$, $z = 1.95$, $p = .051$ (the Relatedness effects were not significantly different in the opaque and form conditions, $\beta = .31$, $SE = .26$, $z = 1.19$, $p = .235$). Further, when analyzed separately, the Relatedness effect was significant in the transparent condition (2.1%; $\beta = -.97$, $SE = .33$, $z = -2.99$, $p = .003$) but it was not significant in either the opaque (1.4%; $\beta = -.23$, $SE = .20$, $z = -1.15$, $p = .251$) or form condition (-.7%; $\beta = .08$, $SE = .17$, $z = .46$, $p = .643$).

Combined Analyses of Experiments 1 and 3

To determine whether the modified sandwich priming procedure used in Experiment 3 had a different impact on priming effects than the conventional priming procedure used in Experiment 1 did, we contrasted the priming effects in the two experiments for each condition in pairwise fashion. In these combined analyses, the latencies of the correct responses and the error rates for the word trials in each condition were analyzed using a GLMM in which subjects and items were random effects, and Relatedness and Experiment were fixed effects.

Latencies. All conditions showed significant main effects of Relatedness (related faster than unrelated; transparent: $\chi^2 = 110.14$, $p < .001$; opaque: $\chi^2 = 24.76$, $p < .001$; form: $\chi^2 = 4.21$, $p = .040$). The form condition also showed a significant main effect of Experiment, $\chi^2 = 4.24$, $p = .039$, indicating faster latencies overall in conventional priming (i.e., Experiment 1) than in modified sandwich priming (i.e., Experiment 3), with the opaque condition showing a marginal tendency in the same direction, $\chi^2 = 3.28$, $p = .070$ (in the transparent condition, $\chi^2 = .97$, $p = .325$). Most importantly, only the transparent condition showed a significant interaction between Relatedness and Experiment, $\chi^2 = 6.41$, $p = .011$ (opaque: $\chi^2 = 1.63$, $p = .201$; form: $\chi^2 < .01$, $p = .953$). This interaction in the transparent condition reflected a larger priming effect in modified sandwich priming (i.e., Experiment 3, 42 ms) than in conventional priming (i.e., Experiment 1, 27 ms).

Errors. The only effect that reached significance was the main effect of Relatedness (related more accurate than unrelated) in the transparent condition, $\chi^2 = 12.04$, $p < .001$ (which was marginal in the opaque condition: $\chi^2 = 3.13$, $p = .077$; form: $\chi^2 = .84$, $p = .358$). The main effect of Experiment was marginal in the opaque condition, $\chi^2 = 3.36$, $p = .067$, and in the form condition, $\chi^2 = 3.55$, $p = .059$, reflecting overall higher accuracy in conventional priming (i.e., Experiment 1) than in modified sandwich priming (i.e., Experiment 3) in those conditions (transparent: $\chi^2 = .40$, $p = .527$). Finally, there was no significant interaction between Relatedness and Experiment in any condition (transparent: $\chi^2 = 1.73$, $p = .188$; opaque: $\chi^2 = .03$, $p = .866$; form: $\chi^2 = .31$, $p = .579$).

Discussion

The pattern in Experiment 3 was quite similar to that in Experiment 2. The only difference was that the priming effect in the opaque condition was somewhat smaller in Experiment 3 and was no longer significantly different from that in the form condition (although the opaque priming effect in Experiment 3 was statistically significant itself, which the effect in the form condition was not, and the opaque priming effect was not significantly different from the opaque priming effect observed in Experiment 1, as reported in the combined analyses presented above, or the opaque priming effect observed in Experiment 2, $\chi^2 = 1.89$, $p = .169$). Essentially, what the results of Experiments 2 and 3 imply is that providing either the target or the suffix as an initial prime aids target processing in the transparent condition but not in the other two conditions.

The increased priming in the transparent condition of Experiment 3 would seem to be inconsistent with the activation-based distributed representation models. In those models, whatever form-meaning mappings exist for affixes, those mappings have no overlap at either the orthographic or meaning level with those of the targets. Hence, presenting the affix as an initial prime should have no impact on the observed priming effect in any condition. The increased priming in the transparent condition in Experiment 3 would also seem to be inconsistent with the similarity-based distributed representation models. Adding a component (i.e., the affix) that is unrelated to the target to the familiarity equation in either Baayen et al.’s (2011) model or Marelli and Baroni’s (2015) model should either have no impact on the size of the priming effect or reduce it, depending on how that prime is assumed to be integrated into the familiarity calculation.

The increased priming effect in the transparent condition is somewhat less problematic for the decomposition models. Presenting the affix as the initial prime would presumably raise the activation of the affix’s representational unit. That action should have had some impact on the activation in the representational units of the target in the transparent condition in the two models, seemingly more so in Taft and Nguyen-Hoan’s (2010) model than in Grainger and Beyersmann’s (2017) model, due to linkages between the affix's representation and the target's representation. However, it should also be said that, given the indirectness of those representations, even in the former model, it may seem somewhat surprising that the impact of presenting the affix as the initial prime could be as large as that of presenting the target itself as the initial prime.

As noted, in both decomposition models, the activation of the representation of the affix is also assumed to play an important role in the opaque condition. That is, it allows the system to retard the competition between the representations of the prime of interest and target. The lack of an increased priming effect in that condition in Experiment 2 raises the possibility that there could have been inhibitory effects at work in that experiment, potentially due to there being an exceptionally high level of activation in the representation of the prime of interest. The presentation of the affix as an initial prime in Experiment 3 should have completely killed any inhibition between the primes and targets in that condition, maximizing the impact of the opaque prime on target processing. As the priming effect in the opaque condition in Experiment 3 was, if anything, slightly smaller than in the prior experiments, the decomposition models would have to assume that the impact of the affix in terms of retarding the competition between the representations of the prime of interest and target was already maximized in the priming manipulation used in the conventional task (i.e., in Experiment 1).

General Discussion

In the present research, a set of items in the three basic conditions in Rastle et al.'s (2004) morphological priming experiment was used in a conventional masked priming experiment (Experiment 1), a sandwich priming experiment (Experiment 2) and a modified sandwich priming experiment (Experiment 3), one in which the first prime was the affix, pseudo affix or nonaffix contained in the prime of interest. Experiment 1 provided a nice replication of Rastle et al.'s pattern, significant and equivalent priming in the transparent and opaque conditions and minimal priming in the form condition. The two sandwich priming experiments produced two basic results: 1) the priming effects in the opaque and form conditions were not increased by either sandwich priming manipulation and 2) priming in the transparent condition was increased, essentially to the same degree, by both sandwich priming manipulations.

The models

Three types of models of the representations and processes involved in morphological masked priming were examined in terms of how well they could explain what is taken to be the classic data pattern (i.e., Rastle et al., 2004) in these types of experiments. One of those model types is the similarity-based distributed representation models (e.g., Baayen et al., 2011; Marelli & Baroni, 2015). Those types of models explain masked priming effects in terms of how semantically similar the prime and target are. As similarity values calculated in the fashion proscribed by those models are fairly similar for the transparent and opaque conditions but, apparently, somewhat lower for the form condition, they are able to explain the results of the present Experiment 1. The data of Experiments 2 and 3 would, however, seem to present the models with two challenges.

The first challenge is that, if prime-target similarity is the driving force for priming effects in masked priming lexical decision tasks, the obvious prediction would be that the equivalent priming effects produced in the transparent and opaque conditions in Experiment 1 should remain equivalent in Experiments 2 and 3. That is, there is no obvious reason why presenting a brief (33 ms) prime prior to the prime of interest, regardless of whether the initial prime is directly relevant to target processing (Experiment 2) or virtually irrelevant to target processing (Experiment 3) should change the prime-target similarity relationships in those two conditions.

The second and, seemingly larger, challenge is that these models have no obvious way of explaining the typical pattern of increased priming in sandwich priming experiments (Davis & Lupker, 2017; Guerrera & Forster, 2008; Lupker & Davis, 2009; Trifonova & Adelman, 2018). In fact, depending on the precise assumptions made about how a second prime would be integrated into the priming process, the models predict either no change or a decrease in priming. In general, this problem seems likely to stem from the fact that the models assume that all masked priming effects are semantically based, an assumption that is unlikely to be correct. The masked priming literature provides many examples of orthographic priming (e.g., Adelman et al., 2014), including examples of how those effects can, in certain circumstances, be inhibitory (e.g., Davis & Lupker, 2006; Segui & Grainger, 1992) as well as a number of examples of how small or nonexistent orthographic priming effects can become significant if a sandwich priming procedure is used (Comesaña et al., 2016; Davis & Lupker, 2017; Lupker & Davis, 2009; Perea et al., 2014; Stinchcombe et al., 2012; Trifonova & Adelman, 2018). At the same time, evidence of more standard types of semantic priming (e.g., horse-DOG) in masked priming lexical decision experiments is actually quite sparse (see de Wit & Kinoshita, 2015; see also Taikh & Lupker, 2020). These types of results would seem to call for both a more activation-based account of masked priming effects and a reconsideration of the factors that the models assume are responsible for producing those effects.

A second type of model is the activation-based distributed representation models (e.g., Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000). These modes assume that priming is due to activation of mappings between orthographic and semantic units (Jared et al., 2017). Under the further assumption that those mappings are essentially equally strong for the transparent and opaque prime-target pairs, the models can explain the equivalent priming effect sizes in the two conditions in Experiment 1. These types of models are also challenged by the results of Experiments 2 and 3 in two ways. The first challenge is the same as that for the similarity-based distributed representation models. If the activation of mappings for the transparent and opaque pairs was equivalent in strength in Experiment 1, the two conditions should also have also produced equivalent priming effects in Experiments 2 and 3. The second challenge is somewhat related. That challenge is explaining how any priming increase in Experiment 3 could have been due to the use of the affix as an initial prime, as the models maintain that affixes do not play a role in the processing of an unaffixed stem word.

These challenges seem to underline one of the conclusions that our analysis of the similarity-based distributed representational models point to: The priming in masked priming experiments is more complicated than the distributed representation models being examined here assume. Again, the masked priming literature is replete with demonstrations of orthographic priming and, therefore, there is no reason to assume that such processes would not be at work in our experiments. The present results, particularly the fact that –er as an initial prime helps the processing of WALK, seem to point to a further conclusion, that true affixes do have an impact in masked priming experiments and, therefore, that those units must have some special status in the orthographic/lexical processing sequence.

The other type of models examined (Grainger & Beyersmann, 2017; Taft & Nguyen-Hoan, 2010), the decomposition models, assume that there is a representation for both of the morphemes in two-morpheme words (e.g., affix and stem) and that, when an apparently affix plus stem word is read, both representations are activated. Also activated, according to both models, is the representation of the real or pseudo two-morpheme word, although the models make somewhat different assumptions concerning how that activation arises. The further assumption is that there are interactions among the activated representations. The specific pattern of those interactions produces Rastle et al.'s (2004) pattern and, therefore, allows the models to predict the results of Experiment 1.

These models also find challenges in the results of Experiments 2 and 3. Like the activation-based distributed representation models, the models have no obvious explanation for why there was no increased priming in the opaque condition in Experiment 2 although an explanation could be created by assuming that the activation in the representation of the prime of interest was simply too high, as a result of presenting the initial prime, to prevent it from inhibiting the activation of the target’s representation. Note again that Grainger and Beyersmann’s (2017) model can explain why there was more priming in the transparent condition than in the opaque condition in that experiment (feedback from the morpho-semantic representation of the target).

Both models do have mechanisms for explaining the increased priming in the transparent condition in Experiment 3, however, the path to priming in Grainger and Beyersmann’s (2017) model is quite weak, involving activation spreading across three links as well as across two levels of representation. In Taft and Nguyen-Hoan’s (2010) model, the linkage between the affix’s representation and the target’s representation is much more direct, involving only lemma level representations. Hence, it would seem to be the model that is more compatible with Experiment 3’s results.

A potential (partial) resolution

Although none of the models successfully accounts for all the present data, it appears that the decomposition models do a somewhat better job. The implication is that something like the core representational assumptions of these types of models (i.e., that representations exist for the stem, the word used as the prime and the affix) and the basic assumption that priming is an activation process appear to be necessary in order to explain not only the present results but also the pervasive finding of more priming in the opaque condition than in the form condition. (The assumption that priming is an activation process would also, of course, be necessary to explain the now extensive masked orthographic/lexical priming literature.)

Equally necessary is the assumption that there are memory representations for multi-morphemic words, at least the common ones (e.g., *walker*) as well as, of course, for monomorphemic words (e.g., *walk*, *corn*, *corner*). And, finally, the fact that primes sharing their initial letters with their targets inevitably produce priming unless the entire prime is a word that does not appear to be multi-morphemic (Beyersmann et al., 2016; Taft et al., 2019) supports the assumption that *walker* and *walk* activate each other's representations as do *corner* and *corn* (see Marslen-Wilson et al., 2008). The task, then, is modeling the interactions among the activated representations when those words are read. Indeed, in normal reading, it would seem that one of the lexical system's main jobs is to evaluate such interactions in order to determine which of the activated representations is appropriate for the word being read.

Where the present proposal differs from the ideas incorporated in the decomposition models (as well as the other models) is that, while, in general, the activation pattern created by related, seemingly multi-morphemic primes helps processing of monomorphemic target words like WALK and CORN (in comparison to when the prime is an unrelated word), responding is not based entirely on activation levels. The degree of priming is also a reflection of the degree of compatibility of the activated representations (i.e., the two initial primes walk (Experiment 2) and –er (Experiment 3) would be compatible with *walker* while the two initial primes corn (Experiment 2) and –er (Experiment 3) would not be compatible with *corner*).

When the degree of compatibility is not high, as in the case of the opaque condition, presenting either the stem/target (Experiment 2) or the affix (Experiment 3) as an initial prime would produce no priming enhancement because the initial prime would not contribute to resolving the competition between the three units (i.e., *corn*, *corner*, and -*er*). However, what also seems to be the case is that because of the existence of a representation for -*er*, not only does the prime corner activate the representation for *corn* but also the competition among the units is not as intense as the competition created between *brothel* and *broth* in the form condition (consistent with the decomposition models' assumptions).

Along these lines, note that, unlike in Experiments 1 and 2, although the priming effect in the opaque condition in Experiment 3 was significant, it did not differ significantly from that in the form condition. If this difference between experiments is real, it fits reasonably well with the ideas expressed just above. That is, by presenting –er as an initial prime in a sandwich priming task

(Experiment 3), the activation of the *–er* unit would be increased. As a result, the resolution of the competition between *corner*, *-er* and *corn* may not only receive no benefit from that initial prime, but it may even become more difficult. That is, the lexical unit for *corn* would then be competing with two active units, neither of which is supportive of any representation of the concept *corn*, potentially leading to the slightly smaller priming effect observed in Experiment 3.

One additional point should be noted. This proposal in no way denies the potential impact of semantics in either the activation or resolution process. As noted, there are a number of studies in the literature (e.g., Feldman et al., 2004; 2009; Jared et al., 2017) suggesting that the degree of semantic similarity between the prime and target in morphological priming experiments can matter. There are also a number of studies showing that morphologically related words that differ because of a letter change rather than an affix addition (e.g., fell-FALL) do produce priming in comparison to appropriate orthographic controls (e.g., full-FALL) (Crepaldi et al., 2010a; Feldman et al., 2010; Forster et al., 1987; Pastizzo & Feldman, 2002). While the general point of the decomposition debate has concerned what these result patterns imply about the nature of the decomposition process (which is being viewed now as an activation process), there is no reason to assume either than semantics is irrelevant, per se, or that the locus of any semantically-based priming effects is the decomposition process. Rather, if semantics does matter in these types of experiments, it may matter after activation of stem and affix representations and their associated semantic representations has taken place, during what we are referring to as the resolution process. Such an idea, seemingly, is also compatible with there being a role for Grainger and Beyersmann's (2017) morpho-semantic representations in that process (see also Meunier and Longtin (2007) for a similar idea, albeit one based on data from a somewhat different paradigm).

Conclusion

Rastle et al.'s (2004) results have given birth to a number of models of how readers represent and process multi-morphemic words. The present experiments involved two versions of a newly developed masked priming technique, sandwich priming, in an attempt to provide a more sensitive look at the relevant processes. None of the present models of reading multi-morphemic words can provide a full account of the complete data pattern, that is, the fact that the procedure led to increased priming in the transparent condition but not in the form condition or, most importantly, the opaque condition, a condition that, in most of those models, is assumed to involve quite similar processing and representations as those in the transparent condition when considering Rastle et al.'s (2004) stimulus set. A tentative way of (potentially) resolving the relevant issues, while maintaining some of the assumptions of decomposition frameworks, is offered. Clearly, understanding the nature of representations and processing of multi-morphemic (and pseudo multi-morphemic) words is a challenge that will continue to attract research interest well into the future.

Footnotes

[1] In Figure 4 in Taft and Nguyen-Hoan (2010), for *corner*, the affix *-er* at the form level was represented as being activated directly from the input (i.e., the word *corner*) rather than from the graphemes *e* and *r*, graphemes which were not represented in that figure. In contrast, in their Figure 1 for *hunter* (analogous to *walker* in the present Figure 1), the affix *-er* at the form level was represented as being activated from the graphemes *e* and *r* rather than directly from the input (i.e., the word *hunter*). Because the model does not assume that the decomposition process works differently for truly suffixed vs. pseudo suffixed words at the form level, we did not reproduce this discrepancy in the present figure. Instead *-er* is assumed to be activated by the graphemes *e* and *r* in both cases. Marcus Taft (personal communication; January 7, 2023) has indicated that the present Figure 1 appears to be a slightly clearer way to depict this model.

[2] Plaut and Gonnermann (2000) have shown that in a morphologically rich language like Hebrew, connections can be created for truly opaque pairs, allowing them to potentially show priming effects. However, as English is not a particularly morphologically rich language, a distributed representation account would still have considerable difficulty explaining the reasonably large opaque-form priming effect difference typically found in English unless the opaque prime-target pairs were semantically related.

[3] As the goal of Experiment 1 was to establish that the reduced stimulus sets we used would replicate Rastle et al.'s (2004) pattern, allowing our results to be explained by all the models under consideration (with the appropriate assumptions), we attempted to replicate Rastle et al.'s procedure as closely as we felt we could. Therefore, we also used a subset of the nonword targets Rastle et al. used and, as is typical in these types of experiments, we did not pair any of them with orthographically similar primes. In order to allow for appropriate comparisons, the same basic procedure was used in Experiments 2 and 3.

[4] When using the default optimizer in the present experiments, the results were virtually identical, although that optimizer did fail to converge a number of times.

[5] The power analysis was conducted on the latency data by comparing a linear mixed-effects model with the interaction term and a similar model without that term using a likelihood-ratio test and performing 1000 simulations for the comparison (see also Yang et al., 2021).

[6] As Crepaldi et al. (2015) have demonstrated, suffixes do not prime when they are presented at the beginning of the prime letter string (e.g., ersheet does not prime TEACHER), presumably because they are not recognized as suffixes. Therefore, it was possible that our suffix primes, surrounded by "<<<" and ">>>", would not be recognized as suffixes and, hence, would have no impact on target processing. The results of Experiment 3 indicate that such was not the case.

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Author Notes

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Appendix A.

Targets, related primes and unrelated primes for word trials in Experiments 1, 2 and 3.

Form condition stimuli

Targets	Related primes	Unrelated primes
APPEND	appendix	believer
BROTH	brothel	warfare
BUTT	button	prayer
CANDID	candidacy	epileptic
COLON	colonel	ability
COMMA	command	equally
DEMON	demonstrate	instruction
DIAL	dialog	lately
ELECT	electron	suburban
EXTRA	extract	justify
FREE	freeze	golden
FUSE	fuselage	citation
GALA	galaxy	keeper
GLAD	glade	cuffs
HEAVE	heaven	firmly
PARENT	parenthesis	lectureship
PHONE	phonetic	dreadful
PLAIN	plaintiff	absurdity
PLUS	plush	filmy
PULP	pulpit	gifted
QUART	quartz	roller
RABBI	rabbit	weekly
SALMON	salmonella	petulantly
SHOVE	shovel	tricky
SIGH	sight	happy
SMUG	smuggle	twelfth
SQUAW	squawk	oddity
STAMP	stampede	defector
STIR	stirrup	buoyant
STUD	studio	gently

STUN	stunt	misty
SURF	surface	medical
SURGE	surgeon	novelty
TWIN	twinkle	cheaply
TWIT	twitch	lesser
VILLA	villain	grossly

Opaque condition stimuli

Targets	Related primes	Unrelated primes
AMP	ample	widen
ARCH	archer	feudal
AUDIT	audition	selfless
BOARD	boarder	factual
BRAND	brandy	safely
BUZZ	buzzard	loyally
COAST	coaster	muffler
COURT	courteous	developer
CRAFT	crafty	vainly
CROOK	crooked	pottery
CRYPT	cryptic	dweller
DEPART	department	production
DISC	discern	starter
FACET	facetious	distantly
FLEET	fleeting	simplify
FLICK	flicker	adviser
FRUIT	fruitless	alcoholic
GLOSS	glossary	sufferer
GLUT	gluten	bridal
GRUEL	grueling	existent
HELM	helmet	brutal
INVENT	inventory	murderous
IRON	irony	sandy
LIQUID	liquidate	extremism
PLAN	planet	editor
QUEST	question	actually
RATION	rational	steadily
SECRET	secretary	obviously
SIGN	signet	frosty

SNIP	sniper	hourly
STILT	stilted	gaseous
THICK	thicket	scruffy
TREAT	treaty	angler
TROLL	trolley	naughty
TRUMP	trumpet	chatter
UNIT	united	others

Transparent condition stimuli

Targets	Related primes	Unrelated primes
ACID	acidic	yearly
ADOPT	adopted	kingdom
AGREE	agreement	equipment
ALARM	alarming	composer
ANGEL	angelic	watcher
ARTIST	artistry	calmness
BEARD	bearded	thinker
BOMB	bomber	lessen
BULB	bulbous	leftist
CHILL	chilly	finely
CLOUD	cloudless	enactment
CREAM	creamy	watery
DREAM	dreamer	masonry
DRUNK	drunkard	feathery
EMPLOY	employer	addition
ERUPT	eruption	vicarage
FILTH	filthy	harden
FLESH	fleshy	lovers
GLOOM	gloomy	miller
GOLF	golfer	thinly
GUILT	guilty	formal
INHIBIT	inhibitory	amateurish
LEGEND	legendary	anxiously
MARSH	marshy	thorny
MOURN	mourner	tripper
NORTH	northern	friendly
POET	poetry	dealer
REACT	reaction	physical

RENEW	renewable	exemption
RISK	risky	downs
SOFT	soften	heroic
TEACH	teacher	finally
TOAST	toaster	wishful
TRAIN	trainee	cookery
VIEW	viewer	ranger
WIDOW	widowed	beastly

Appendix B.

Targets and primes for the nonword trials in Experiments 1, 2 and 3.

Targets	Primes
ACLID	rover
ACRIRE	windy
ACRODE	tenth
AMOAK	raider
ANARP	boxer
AVINE	nothing
BARROD	kiddie
BENOW	taxable
BLICK	airliner
BREAP	swampy
BROBE	wealthy
BUKE	booster
CAGLE	coarsely
CALC	piggy
CANTILE	oddly
CAPLE	weakling
CHEG	priority
CHIDEL	ruler
CHISK	stately
CIFF	minded
CLARP	badly
CLETT	witty
CLICE	validate
CLINSE	bulky
CLODE	quickly
CRABON	bushy
CREMP	theirs
CRINT	milky
CRITEN	merely
CRONG	tester
CYPE	waxen
DARF	fasten
DASSER	nearly
DAWTH	worker
DESIG	lofty

DOTHER	poacher
DRELL	homely
DRIGGER	jacket
DRINE	groggy
EMPERT	nimbly
ENVID	sagely
FANLE	baker
FERB	fatty
FIDY	sixty
FLINSE	math
FOAP	leader
FOUCH	atomic
FOVEN	rusty
FRECK	neatly
GARR	layer
GLISON	buyer
GLYNCH	hairy
GRISH	tension
GROUGH	scrubby
GUBE	batty
HIZZLE	slowly
INLUM	rocky
ISK	needful
IZED	plunger
JISP	growth
JITHER	meaty
JONDLE	simply
LELVE	removal
MUND	fewer
MURF	deeply
NEEN	dolly
NUCE	mummy
NULP	awful
OBE	armor
PERP	rider
PHECKS	daddy
PHEEM	comer
PHIM	penalty
PICTLE	voter
PIMB	outer

PLAPED	likely
PLEX	maker
PRAIR	lover
PROIL	rainy
RESH	sexless
REVEN	shaver
RIGO	upper
RIPENT	felony
SAPAY	steeply
SARVE	funny
SCREAL	firstly
SHEG	health
SIFY	blankly
SKERN	hooker
SLAFE	barker
SLAST	newly
SMIRCH	fairly
SNIB	gusty
STIB	miner
STON	noisy
STURPY	likes
SWEEL	fuzzy
THIC	dimly
TREBE	salty
TRELL	always
TRODE	bearer
USH	lucky
VAPSE	grimy
VOZE	dirty
WEFF	owner
YEBB	dusty
YURK	lanky
ZOZE	candor