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Identifying the contributions of letter identity and relative letter position to orthographic priming

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Identifying the contributions of letter identity and relative letter position to orthographic priming

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ABSTRACT

Still and Morris (2008) discovered that nonword anagram primes interfere with word target processing when the letters in the prime appear in reverse order of the letters in the target (e.g., *yruf* - *FURY*). This finding was unexpected as facilitation is typically found when a word target is preceded by an orthographically similar nonword prime (e.g., Grainger & Jacobs, 1999). The present study was designed to replicate and extend Still and Morris' finding of anagram interference. Results across three experiments indicate that anagram interference is modulated by target word frequency, stimulus length, prime exposure duration, and whether or not the anagram prime and target share letters in the same *relative* positions (e.g., *enorht* vs. *oetnrh* vs. *htoren* for the target *THRONE*). In addition to replicating the finding of anagram interference, these results show that the anagram interference is robust and is not limited to a specific set of stimuli. Current models of word recognition are unable to account for the finding of anagram interference.

CHAPTER 1. INTRODUCTION

Much of the research in visual word recognition has focused on two related topics: 1) the representations involved in word recognition and 2) the process by which these representations are accessed. Recently, these topics have been addressed in studies investigating the way in which letter position is coded during word recognition. In these studies, the underlying representations and processes involved in word recognition are inferred from the effects of letter position manipulations on participant responses. A task commonly used in these investigations is masked orthographic priming, where one masked and briefly displayed item (prime) is followed by a second item (target) to which the participant responds. It is assumed in many theories of word recognition that presentation of a prime will lead to the activation of all word representations that are similar to the prime (Davis & Lupker, 2006). Preactivation of a representation by a similar prime affects the speed and accuracy of participant responses to the target. For example, the prime *juhge* is assumed to activate the representation for the target *JUDGE*; in this case, participants will respond faster because target processing has a "head-start" in comparison to a target that has not been preactivated.

When masked orthographic priming is used to study letter position it is assumed that a prime will more strongly preactivate a target representation when there is a better "match" between their respective letter positions. A measure of how well the representations "match" is obtained by comparing responses to a target when it has been primed by an item that is dissimilar to the target (usually a prime that shares no letters with the target) to responses when a prime is similar to the target. The difference in response time yields a measure of the target representation's preactivation in the orthographically similar condition – a measure of the orthographic priming effect. By comparing priming effects across several conditions, hypotheses can be formed about the representations involved in masked orthographic priming and, potentially, word recognition.

There is now an abundance of data suggesting that the representations involved in orthographic priming do not code letters in their absolute positions; instead, letter positions are coarsely coded (e.g., Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Perea & Lupker, 2003; Peressotti & Grainger, 1999). The "coarseness" of letter position coding is constrained by the finding that facilitation is observed only when the letters shared between the prime and target appear in the same relative positions (i.e., in the same left-to-right order). This characteristic of the orthographic priming effect comes primarily from experiments using partial-word primes (e.g., *FLCN– FALCON*; Peressotti & Grainger, 1999). Facilitation is obtained only when relative letter position is preserved; no facilitation is obtained when the letters in the prime appear in a different left-to-right order than those in the target (e.g., *FCLN – FALCON;* Grainger et al., 2006; Peressotti & Grainger, 1999).

Although data from several studies suggest that some preservation of letter position is necessary to access any given word representation, this assertion has not been adequately tested, because in the majority of studies, letter position is only partially disrupted between the prime and target. For example, it is common for a proportion of the letters in the prime and target to appear in the same absolute position, or for at least some of the letters in the prime and target to appear in the same relative positions (e.g., the *F* and *N* in *FCLN*; Peressotti & Grainger, 1999). There are few, if any, experimental investigations of conditions where the prime and target share letters, but those letters do not appear in the same absolute *or* relative positions. This gap in the literature leaves little opportunity to falsify the assumption that letters must appear in the correct relative position to activate a word representation. The importance of this oversight was recently revealed when Still and Morris (2008) found interference (slower response times) when all letters were shared between the prime and target, but none of those letters appeared in the same absolute position or in the same relative positions (e.g., *yruf – FURY*). This interference is not easily explained by existing models of word recognition. The purpose of this study is to further investigate the origins of Still and Morris' anagram interference finding as it suggests that modifications must be made to current assumptions about word representations and the way in which those representations are selected.

The Interactive Activation Model

One of the first models to formally implement a system for coding letter position was the Interactive Activation (IA) model (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Even though the IA model was proposed over twenty years ago, many subsequent models have adopted the IA framework (e.g., Dual-Route Cascaded model, Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Multiple Read-Out model, Grainger & Jacobs, 1996) or have adopted IA assumptions. For example, one assumption adopted by several researchers is that inhibitory connections exist between word representations (e.g., Open-Bigram model, Grainger & van Heuven, 2004; Self-Organizing Lexical Acquisition and Recognition [SOLAR] model, Davis, 1999). In addition, most studies investigating letter position coding test the assumptions of the IA model. Therefore, it is important to understand how the IA model works.

The IA model has three levels of representation that are used in word recognition: feature, letter, and word. Bidirectional excitatory and inhibitory connections exist between each level and inhibitory connections exist between items within a level (e.g., between two word nodes). Because the original IA model was implemented using four-letter words, the model contains four "slots" – one slot for each letter. Each slot has its own feature detectors and letter representations. When a letter string is presented to the model, feature detectors are activated for the features present in each individual letter of the stimulus. For example, when presented with the word *head*, feature detectors in the first slot would become active for features found in the letter *h* (e.g., long vertical line on the left, short vertical line on the right, short horizontal connector). In addition, features not found in the letter *h* would be suppressed. Each of the activated feature nodes then spreads activation to the letter level; those letter nodes having excitatory connections with the activated feature node (i.e., letters containing that feature) become activated while those having inhibitory connections with the activated feature node (i.e., letters without the feature) are inhibited. If the letter *h* is activated in the first slot, all other letters will be inhibited (the IA model does not misidentify letters because the inhibitory connections from the feature to letter level are stronger than the excitatory connections between the levels). Letter and feature node activation occurs independently and simultaneously for each slot.

Once a letter node is activated, it spreads activation to the word level. Specifically, all word nodes containing that letter in that specific slot are activated via excitatory connections. Words not containing the letter in that slot are inhibited. For example, the letter *h* in the first slot will activate *head* but will inhibit *shin*. In addition to the connections between the letter and word levels, inhibitory connections exist between nodes in the word level. Once a word node becomes activated it inhibits other word nodes, with the amount of inhibition being relative to the node's activation level; thus, a word node with a high activation level will strongly inhibit other word nodes, while a node with a lower activation level will weakly inhibit other nodes. Lexical inhibition allows the model to "settle" on a solution more quickly.

The processing of a letter string from feature-to-letter-to-word levels represents only a subset of the processes in the IA model; the connections between the levels are bidirectional, thus there are top-down influences in the model as well. Top-down influences are modeled in such a way that if a node at the letter or word level becomes activated, it sends recurrent activation (inhibition or excitation) back down to the nodes feeding into it.[1] For example, when the word representation for *head* becomes activated, additional excitatory activation is sent to the *h* in slot 1, the *e* in slot 2, the *a* in slot 3, and the *d* in slot 4. In addition to increasing the activation levels for each letter node, this recurrent activation results in more bottom-up activation from each letter node being passed on to the word level. Recurrent activation decreases the time needed for a word representation to be selected in the model.

As previously mentioned, the majority of studies have used masked priming paradigms to test predictions about the way in which letter positions are coded in word representations. The IA model by itself cannot be used to make predictions about the outcome of masked priming experiments because the model only processes one stimulus at a time. Additional assumptions must be made about the way the prime and target interact in the IA model. Those assumptions are addressed in the following section – "Masked Orthographic Priming". A second consideration is how well the IA model accounts for letter

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[1] Parameters control the amount of inhibition and excitation between nodes within the same levels and nodes in different levels. This means that ten parameters control inhibition and excitation and they can vary widely in their settings. For example, in the original instantiation of the IA model there was no letter–to–letter inhibition, but word–to–word inhibition was high.

position effects obtained in masked priming experiments. In the "Evidence for Relative Position Coding" section, recent studies demonstrating the shortcomings of the IA model letter coding scheme are discussed. These studies motivated the development of several new models of word recognition that use alternative coding schemes; they are discussed in "Models of Word Recognition that Account for Relative Position Priming". Even with new letter position coding schemes, recent models of word recognition cannot account for Still and Morris' (2008) interference findings (e.g., *elba* interferes with lexical decisions to *ABLE*). These findings are presented in the "Determining the Contributions of Letters and Bigrams to Orthographic Priming" section.

Masked Orthographic Priming

One experimental method has come to dominate the field of word recognition research – the masked priming paradigm (Grainger, 2008). Forster and Davis (1984) were the first to popularize this procedure in conjunction with the lexical decision task. "Three-field" masked priming paradigms are characterized by the presentation of a mask, then a briefly displayed prime that is followed by a target.[2] The type of response required of the participant (e.g., lexical decision, naming, semantic categorization) can be varied. Target presentation also can be varied. For example, in most lexical decision tasks the target is displayed until the participant responds, but in perceptual identification tasks the target is briefly displayed and masked. Masked orthographic priming has become a preferred method of investigation for two primary reasons. First, the prime is briefly displayed, limiting participant awareness of the prime and reducing strategic effects (Forster, 1998). Second, priming paradigms allow

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[2] Forster and Davis (1984) used a word that was dissimilar from the prime and target as the forward mask. In subsequent experiments it has become more common to use symbol strings as the mask.

researchers to use within-item manipulations so that participant responses to any given target (e.g., *ABLE*) can be compared across conditions (e.g., *axle-ABLE* vs. *host-ABLE*; Davis, 2003). For non-priming tasks in which participants respond to the presentation of a single word, researchers must compare responses to different items; for example, when investigating the effects of word frequency, one might compare report of *AXLE*, a low-frequency word, to report of *ABLE*, a high-frequency word.[3] The problem is that these words do not differ only in word frequency; for instance, *AXLE* has higher imageability than *ABLE*. If differences are found in responses to these words, should they be attributed to word frequency or imageability? In short, when comparisons are made between items, it is more difficult to know what variables are responsible for the differences. By comparing responses to the same target, as can be done in the priming paradigm, this problem is reduced (Forster, 1998).

Interpretation of data obtained in the priming paradigm depends on the assumption that the representation of a target can be preactivated by an orthographically similar prime. In the IA model this is simulated by limiting the number of cycles that the prime is presented so that the model does not “settle” on one solution (it is important that the model does not settle on one solution because that would results in a reset of letter level activation). Brief display of the prime results in the partial activation of candidate word representations that share letters in the same position with the prime. The target is then presented to the model; processing of the target begins from the state it was in when the prime was replaced with the target. Therefore, the IA model treats the prime and target as one event. Preactivation of

[3] Word frequency is usually obtained from a database. It is calculated by counting the number of times a word appears in print from a corpus of documents.

word representations by the prime has two possible outcomes: facilitation (faster or more accurate responding or both) or interference (slower or less accurate responding or both).[4] Facilitation is thought to occur when the prime preactivates the word representation of the target but does not strongly activate other word representations. Interference is thought to occur when the prime preactivates the word representation of the target *and* strongly activates at least one other word representation; the interference occurs because the target cannot be recognized until the other activated word representations have been inhibited.

In the masked priming literature, several variables influence the orthographic priming effect, including prime lexicality and relative prime – target word frequency. Models that share basic assumptions with the IA model can account for masked priming data with a few exceptions, as will be described. The lexical status of the prime is one variable that contributes to whether orthographic priming – preactivation of the word representation – results in facilitation or interference. In particular, nonword primes tend to lead to facilitation while word primes tend to lead to interference; this is referred to as the lexicality effect (Grainger & Jacobs, 1999). The lexicality effect is explained by the assumption that nonword primes do not strongly activate any word representations, thus the processing of the target is facilitated from the "head start" provided by the prime. In contrast, when a word prime is presented, it activates its own word representation which will inhibit other similar word representations (selective lexical inhibition, Davis & Lupker, 2006). Before the target can be recognized, it must overcome the inhibition from the prime; this results in interference. An exception to the lexicality effect occurs when the word prime and target are identical and,

[4] In this dissertation *inhibition* refers to the theoretical construct suggesting that one node can suppress another. In contrast, the term *interference* describes behavioral outcomes, e.g., slower response times or increased error rates or both.

therefore, activate the same word representation (e.g., Forster & Davis, 1984; Perea & Lupker, 2003). In this case no competing word representations are activated and facilitation is observed. It should be noted that although the lexicality effect is typically found, a few experiments have yielded contradictory results. For example, facilitation has been found for word primes and targets that are orthographic neighbors (e.g., *irrigate – IRRITATE*; Forster, 1987) – orthographic neighbors are items that share all their letters in the same positions except for one. In addition, Still and Morris (2008) obtained interference for word targets preceded by anagram nonword primes. There are two reasons why this finding is not predicted by current models of word recognition. First, the only inhibitory effects that can lead to interference in participant responses come from the inhibitory connections between word representations. Second, nonwords do not have word representations, thus they cannot inhibit word representations. Models of word recognition that assume lexical inhibition is the only source of interference have difficulty reconciling these findings.

Orthographic priming effects are also modulated by word frequency. According to the IA model, high-frequency words have a higher level of resting activation than low-frequency words (McClelland & Rumelhart, 1981). This higher level of activation allows the model to settle on high-frequency words faster and with fewer errors than low-frequency words. In the masked priming paradigm when word primes and targets are used, the relative word frequency of the prime and target affects the amount of interference obtained. In particular, interference is greater when the prime is higher-frequency than the target (e.g., Davis, 2003; Davis & Lupker, 2006; Segui & Grainger, 1990). This finding is easily accounted for by the IA model (McClelland & Rumelhart, 1981). In masked priming experiments the higher-frequency prime inhibits the word representation of the lower-frequency target more than a lower-frequency prime inhibits a higher-frequency target.

But, the generalizability of relative prime – target word frequency findings has recently come into question. Nakayama, Sears, and Lupker (2008) conducted a series of experiments in which they manipulated relative prime-target frequency and neighborhood size (a word with many orthographic neighbors is described as being from a high-density neighborhood, while a word with few neighbors is from a low-density neighborhood). Primes and targets were words, so interference was expected and greater interference was expected when the prime was higher-frequency than the target. Nakayama et al. demonstrated that when the word stimuli were from high-density neighborhoods, no relative prime-target frequency effect was found; that is, high-frequency targets preceded by low-frequency primes resulted in interference that was statistically indistinguishable from the interference obtained when low-frequency targets were preceded by high-frequency primes. When stimuli from low-density neighborhoods were used, more interference was obtained when targets were lower-frequency than the primes compared to when targets were higher-frequency than the primes as is consistent with previous research (e.g., Segui & Grainger, 1990). The IA model does not predict this pattern of results. Instead, it predicts that relative prime-target frequency should yield the same amount of interference no matter the neighborhood density (e.g., Davis, 2003).

In contrast to the relative prime-target frequency effects obtained with word primes, the IA model predicts that target word frequency “has a negligible effect” on the facilitation obtained when nonword primes are used (Davis & Lupker, 2006, p.674). In the model, nonword primes preactivate word target representations via excitatory connections between the letter and word levels. That "bottom up" activation does not vary for low- vs. high-frequency word representations. Therefore, low- and high-frequency targets should benefit equally from preactivation by orthographically similar nonword primes.

Despite this prediction, there are reasons to hypothesize that target word frequency could have some effect on the amount of facilitation obtained in masked priming experiments. First, although the difference in facilitation only approached significance, Davis and Lupker (2006) found that facilitation for low-frequency targets was numerically greater than that for high-frequency targets. Thus, it is possible that target frequency is related to the amount of facilitation obtained, but those differences are small. Second, it is possible that the average speed with which a participant can respond to low- vs. high-frequency targets modulates the amount of facilitation that is observed. It is well known that high-frequency targets are responded to faster and more accurately than low-frequency targets and that there is a limit to how fast and accurate responding can be. When participant responses are already fast and accurate, there is less opportunity for improvement. By extension, when high-frequency targets are preactivated by an orthographically similar nonword, there is less opportunity for improvement than when low-frequency targets are used. In other words, if there is any effect of target word frequency it should emerge as greater facilitation for low-frequency targets than for high-frequency targets (much like the trend observed by Davis and Lupker).

An Alternative Conceptualization of Masked Priming

The IA model was originally developed to account for findings associated with the word superiority effect whereby a single letter string is briefly presented and participants indicate which of two letters was displayed in a specified position in the letter string (e.g., McClelland & Rumelhart, 1981). In order to use the IA model to make predictions about the outcome of masked priming studies, where two items rather than one are presented, some assumptions must be made. The fundamental assumption is that activation from the prime and target is integrated; that is, the prime and target are treated as if only one item was presented. But should two events – the prime and target – be treated as one? The Competition Model (Morris, Still, & Caldwell-Harris, 2009) was designed specifically to account for the interactions between identical or orthographically similar items presented in close temporal proximity. According to the tenets of this model, even though participants often are unaware of the prime, it still competes as a separate event for access to awareness.[5] The competition model operates under four primary assumptions: 1) items presented in close temporal proximity compete with one another for access to awareness (Dehaene & Naccache, 2001); 2) competition is based on the total activation of each item; 3) the activation of each item is composed of activation of its own representation and persisting activation from the item(s) presented before it (i.e., forward masking; Breitmeyer, 1984; Desimone, 1996); and 4) repetition of letters, or orthographic similarity, between two items leads to an increased signal-to-noise ratio for the second item along with lower overall activation levels (e.g., Desimone, 1996; Ringo, 1996). The implications of these assumptions and how they relate to masked orthographic priming follow.

As mentioned, in the competition model the prime and target are treated as two separate events competing for access to awareness. Competitiveness of an item depends on several variables including prime lexicality, word frequency, exposure duration,

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[5] An exception would be if two physically identical stimuli were presented successively with no break between them. In this case, the two stimuli would appear to be one continuous stimulus. This situation is uncommon as computerized experiments tend to have a refresh cycle between presentation of the prime and target.

neighborhood density and orthographic similarity (e.g., Morris & Still, 2008; Still & Morris, 2007). To determine the way in which word frequency, lexicality, exposure duration, and neighborhood density affect the competition, a general heuristic can be used: If a stimulus characteristic leads to increased identification, then that characteristic usually indicates increased competitiveness for that item. For example, items with longer exposure durations outperform items with shorter exposure durations, items from high-density neighborhoods outperform those from low-density neighborhoods, words outperform nonwords, and high-frequency words outperform low-frequency words. In the competition model, each of these stimulus characteristics is modeled as higher activation levels for items containing these characteristics. What is assumed here is that these stimulus characteristics influence the speed and accuracy with which an item is processed or encoded.

According to the competition model, *each* event in the masked priming paradigm (mask, prime, and target) competes with temporally adjacent items for access to awareness. The briefly-displayed prime often fails to access awareness because its activation is exceeded by that of both the mask and the target. In contrast, the target always accesses awareness because it is displayed until the participant responds; what varies is how quickly the target's activation exceeds that of the prime. The question is whether an orthographically similar prime facilitates recognition of the target or hinders it. As mentioned, orthographic similarity between prime and target leads to an increased signal-to-noise ratio for the target, which in turn increases the speed of target identification; however, the presence of an orthographically similar prime also can decrease the overall activation associated with the target, reducing its ability to compete with the prime (the latter effect occurs because of the decrease in noise associated with the similar target). The encoding characteristics of the prime also influence the outcome of the competition; primes that are poorly encoded (e.g., short prime exposure durations, nonword primes) compete minimally with the target while primes that are better encoded (e.g., longer prime exposure durations, word primes) compete more with the target. Thus, the outcome depends on whether or not the increase in the signal-to-noise ratio is outweighed by the decrease in the target's total activation. Nonword primes tend to produce facilitation because they decrease the target's activation only minimally, whereas word primes tend to produce interference (the lexicality effect).

Encoding of the prime and target largely contributes to whether or not orthographic similarity will result in facilitation or interference. Figure 1 provides a summary of the effects of encoding. The function in Figure 1 represents the difference between the outcome of the competition for an orthographically similar prime and target and a control prime and target. When a point on the function is greater than zero, facilitation is observed; when a point on the function is less than zero, interference is observed. The x-axis represents a general continuum for encoding with poor encoding on the left and better encoding on the right. When encoding is poor, facilitation is more likely to occur; when encoding is better, interference is more likely to occur. This function will be used as an aid for describing how the variables investigated in the present experiments could be conceptualized as encoding effects within the competition model.

One drawback to using the competition model to predict masked priming results is that it was not designed to investigate letter position coding. The original implementation of the competition model used a position independent coding scheme such that the model could not distinguish between items like *stop* and *otps*. What this means is that the competition

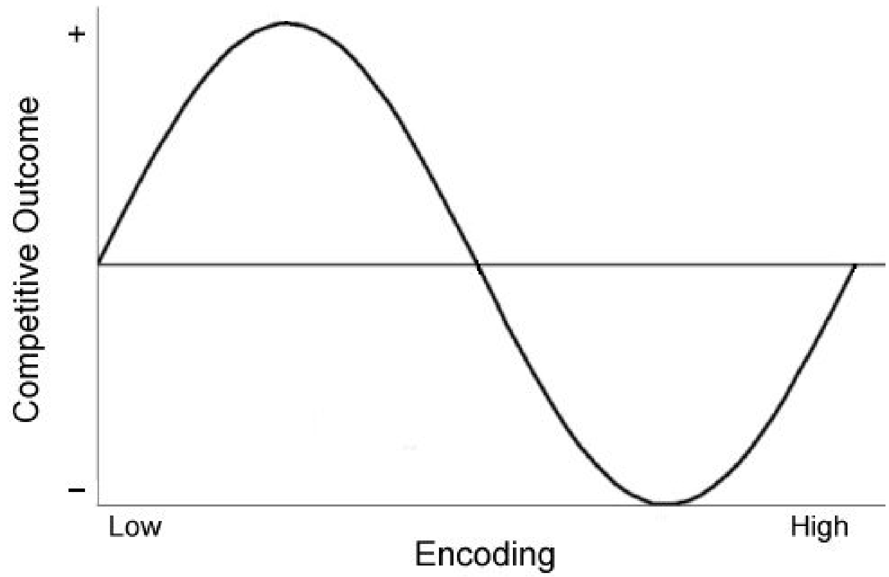

Figure 1. General function depicting the influence of encoding on competitive outcomes for the target. The function itself represents the difference between orthographically similar and control conditions as predicted by the competition model. Competitive outcomes greater than zero reflect facilitation while competitive interactions less than zero reflect interference. Encoding is a continuous variable that is related to the signal-to-noise ratio of a representation in the competition model.

model, in its original form, cannot account for why presentation of the prime *stop* facilitates recognition of the target *STOP*, but presentation of the prime *pots* does not. Therefore, although the original version of the competition model provides some insight as to how encoding variables affect the interaction between the prime and target, it cannot generate precise predictions concerning letter position coding.

Evidence for Relative Position Coding

Like that of the competition model, the letter coding scheme of the IA model is inadequate. The IA model's slot-position coding scheme has been tested extensively in recent years using the masked orthographic priming paradigm. These examinations have been conducted primarily by manipulating the positions of the letters shared between the prime and target. For example, Perea and Lupker (2003) found that facilitation obtained from a word primed by itself (identity priming; *judge* – *JUDGE*) was indistinguishable from the amount of facilitation obtained when a word was primed by a transposition neighbor – a word that shares all letters with the target, but two letters are transposed (*jugde* – *JUDGE*). In comparison, Perea, Duñabeitia, and Carreiras (2008) demonstrated that transpositions of nonadjacent letters (*caniso* – *CASINO*) result in less facilitation than transpositions of adjacent letters. Together, these findings are used as evidence that word representations are insensitive to small disruptions in letter position, but sensitive to larger disruptions in letter position under data-limited conditions. Transposed-letter priming is problematic for the IA model coding scheme; according to the model, the primes *jugde* and *juhpe* are equally similar to the target *JUDGE* because both primes share three letters in the same position with the target. Contrary to those predictions, the prime *jugde* led to more facilitation than the prime *juhpe*.

Another method of testing the IA model letter coding scheme is by preserving the relative positions (same left to right order) of some of the letters between the prime and the target, but manipulating the absolute positions in which those letters appear. Peressotti and Grainger (1999) investigated this by comparing conditions where primes and targets shared letters in the same absolute positions to conditions where primes shared letters in the same relative positions with targets. In their Experiment 4, primes were presented that contained the first, third, fourth, and sixth letters of the six-letter target (partial-word primes), but the absolute position of the letters was varied. In one condition letters in the prime appeared in the same relative position (e.g., *FLCN* – *FALCON*). In two additional conditions the letters in the prime appeared in the same absolute position as the target but symbols were inserted in place of letters two and five (e.g., *F–LC–N* – *FALCON* and *F%LC%N* – *FALCON*). The final prime condition contained no letters, just symbols (e.g., *%%%%%% - FALCON*). Participants made a lexical decision to the target. Priming was measured by the difference between response times to the target in the symbol condition and response times to targets in the partial-word prime conditions. With 33-ms and 50-ms prime exposure durations, statistically indistinguishable amounts of priming were found in all three partial-word prime conditions. This finding was taken as evidence that letters do not have to appear in the same absolute position in primes and targets in order to activate the target's word representation; preserved relative position was sufficient.

Peressotti and Grainger (Experiment 3; 1999) further investigated the precision of relative position coding by using partial-word primes in which relative letter position was preserved or partially disrupted. For example, for the target *FALCON*, participants were presented with a prime preserving relative position, *FLCN*, or with a prime in which relative position was disrupted such as *NLCF* or *FCLN*. Each condition was contrasted with a control condition in which none of the letters was shared between the prime and target. Results indicated significant facilitation for target words that were preceded by primes preserving relative position (e.g., *FLCN*), but there was no discernable effect when relative letter position was not preserved in the prime (e.g., *NLCF* or *FCLN*). Partial-word priming effects are robust and have also been demonstrated in seven- and nine-letter words using both four- and five-letter partial-word primes (Grainger et al., 2006). There are two primary implications from transposition and partial-word priming research: 1) letters do not have to appear in the correct absolute position to activate word representations; 2) relative letter positions must be preserved in partial-word primes in order for the prime to preactivate the representation of the target word.

Models of Word Recognition that Account for Relative Position Priming

Several models have been developed that can account for relative position priming effects. Although each model is unique, they can be classified into two groups: those that use *individual letters* as the basis for activating word representations and those that use *bigrams* (ordered contiguous and noncontiguous letter pairs). There are two prominent models that use individual letters for lexical access: the Overlap model (Gomez, Ratcliff, & Perea, 2008) and the SOLAR model (Self-Organizing Lexical Acquisition and Recognition; Davis, 1999). In its current state, the Overlap model codes letter position and can calculate the match between two letter strings. Therefore, it only specifies how letter representations are activated and the way those letter representations might be used to activate appropriate word representations. It does not contain a word representation layer or output mechanism, thus this model cannot account for relative prime-target frequency effects, the lexicality effect, how one word representation comes to be output over another, or any top-down influences in word recognition.

The primary tenet of the Overlap model is that letters are coded in their approximate positions. Unlike the IA model where a letter representation is activated for the one position in which it appears, the Overlap model suggests that a letter representation has the highest activation level for the position in which it appears, but that the letter representation is also activated to a lesser degree in nearby positions. For example, a letter appearing in the third position will activate its letter representation most strongly at the third position, but will also activate its letter representation in positions two and four to a lesser degree and positions one and five to an even lesser degree. The amount of activation and the number of positions activated are determined by parameters in the model. The letter distributions for each position are compared to word representations stored in memory; the word representation with the best match is the word that is selected (for equations and parameters see Gomez et al., 2008). With this method of letter coding, the Overlap model is able to account for the finding that word representations are activated even when there are minor disruptions in letter order. Gomez et al. have suggested that the Overlap model could be added on as the "front-end" of other models of word recognition; for example, it could replace slot position coding in the IA model.

Unlike the IA and Overlap models, the letter level in the SOLAR model (Davis, 1999) is position independent. In the model, letters in a word are processed serially from left-to-right. As each subsequent letter is processed its letter representation is activated and each letter becomes associated with a specific level of activation. The activation gradient is characterized by a monotonically decreasing function whereby the first letter is associated with the highest activation level and the final letter is associated with the lowest activation level. In this model, orthographically similar words like *salt* and *slat* can be distinguished because the *l* and *a* in each word are associated with different activation levels. But the model also accounts for transposition priming; *salt* will activate the word *slat* under data-limited conditions because the letters are the same and the activation levels associated with them are similar.

Bigram models are characterized by their use of letter pairs – bigrams – instead of individual letters to activate word representations. The most prominent bigram models are the Open-Bigram (Grainger & van Heuven, 2003; Schoonbaert & Grainger, 2004) and SERIOL models (Sequential Encoding Regulated by Inputs of Oscillations within Letter units; Whitney, 2001). Both models use open bigrams, meaning that bigrams are composed of contiguous and noncontiguous letter pairs (e.g., in the word *farm*, both *fa* and *fr* are bigrams). Even though access to word representations is based on bigram activation in both models, the characteristics of the bigrams differ.

The Open-Bigram model (Grainger & van Heuven, 2003; Schoonbaert & Grainger, 2004) consists of three levels – letter detectors, bigrams, and word representations (also called the alphabetic array, the relative position map, and O-words for orthographic word forms, respectively) – with bidirectional excitatory and inhibitory connections between the bigram and word representation levels and unidirectional feedforward connections from the letter detectors to the bigram representations. In the model, the letters in a word are processed in parallel with bigrams created for every two-letter combination that appears in the word in left-to-right order. These open bigrams are constrained in that they are formed only for letter pairs that are separated by two or fewer intervening letters. For example, in the word *house* there are nine bigrams – *ho*, *hu*, *hs*, *ou*, *os*, *oe*, *us*, *ue*, *se*. There are no bigrams for *oh* because the letters are not in the correct left-to-right order and there is no bigram for *he* because the letters are separated by more than two letters. Bigrams have equal weights in the word representation, so every bigram contributes to word recognition equally.

The SERIOL model (Whitney, 2001) differs in several ways from the Open-Bigram model, but discussion here is limited to those differences pertaining to bigram formation and bigram characteristics. The SERIOL model contains five layers (edge, feature, letter, bigram, and word). Letter nodes in the letter layer "fire" in left-to-right order for languages that read from left to right. Bigram nodes are activated when their constituent letters fire in the correct order. For the word *house*, for example, the bigram *hu* would be activated only when the letter *u* fired after the letter *h*. Bigrams are weighted so that some bigrams activate word representations more strongly than others. The weight varies based on the temporal proximity of the two constituent letters and based on the position of the constituent letters in the word. Bigrams consisting of letters firing in immediate temporal succession have the highest weights; as the temporal “distance” between the letters increases, bigram weight decreases. Bigrams containing the first or last letter of a word have higher weight than bigrams containing interior letters. There are two additional differences between the bigrams used in the SERIOL model and those used in the Open-Bigram model. First, in the SERIOL model the bigrams are truly open in that there is no limit to the number of letters that can intervene between two constituent letters. Second, word boundaries – blank spaces before and after the word – are included in the bigrams (e.g., Whitney & Cornelissen, 2008). For example, the word *house* contains twelve bigrams including those with word boundaries (denoted by an *) – **h*, *ho*, *hu*, *hs*, *he, ou*, *os*, *oe*, *us*, *ue*, *se, e**.

Bigram models account for transposed letter findings because the transposed letter prime shares more bigrams with the target than the control condition and the transposed letter prime shares nearly as many bigrams with the target as identical stimuli. They also easily accommodate relative position priming findings. For example, according to the Open-Bigram model the presence of the bigram *CN* in *FALCON* is the same as the *CN* in *FLCN*. In sum, models using bigrams to code letter positions as well as models using individual letters can account for transposed letter and relative position priming results.

Because the most recent models of word recognition can account for relative-position priming, some researchers have conducted more fine-grained investigations by using each model’s letter position coding scheme to make predictions about how strongly a prime should preactivate a target. A similarity score, or “match” value, can be generated for each model based on its assumptions about the way letter order is coded.[6] For example, in the IA model *jugde* and *JUDGE* share three out of five letters, producing a match value of .60; this is the same match value as *juhpe* and *JUDGE,* so these primes should produce equal amounts of facilitation. Based on the fact that the match value predictions for the IA model do not correspond with empirical evidence, some would suggest that the letter coding scheme used in the IA model has been falsified. Match values have been used this way in several recent investigations (e.g., Davis & Bowers, 2006; Guerrera & Forster, 2008; Kinoshita & Norris, 2009) and will be used to make general predictions in the present experiments.

There are caveats to consider when using match values. The influences of some components (e.g., inhibitory connections between word representations, top-down influences) of the models are not considered in the calculations (e.g., Guerrera & Forster, 2008). For example, match values do not indicate whether increased activation of a word representation will result in facilitation or interference because they do not consider the lexical status of the prime and match values do not consider the influence of relative prime-target frequency in orthographic priming. But, because the present experiments use only nonword primes, the match values provide a reasonable estimate of the pattern of facilitation that should be observed according to the SOLAR, SERIOL, and Open-Bigram models.

Determining the Contributions of Letters and Bigrams to Orthographic Priming

A point has been reached in relative position priming research where several models can account for the majority of the data. When this occurs researchers often look for

[6] Most match values can be calculated using Colin Davis' MatchCalculator program which is available at his website, http://www.pc.rhul.ac.uk/staff/c.davis/Utilities/MatchCalc/index.htm. Match values consist of normalized values of orthographic similarity where zero represents no similarity whereas one represents a perfect orthographic match. Values for the Overlap model are not available via the MatchCalculator, but the equations used in the model are available in Gomez et al. (2008).

parsimony; models that can account for the data with fewer assumptions are preferred. In this case, all four of the aforementioned models contain a letter level, but only two contain the additional bigram level. If both bigram and non-bigram models can account for the same data, perhaps bigrams are not needed to explain relative position priming. Two studies contain manipulations that uniquely tested the contributions of bigrams to orthographic priming; they did this by varying the number of bigrams shared between the prime and target (e.g., Guerrera & Forster, 2008; Still & Morris, 2008).

In both the SERIOL and Open-Bigram models, bigrams are the only sublexical units that activate word representations; therefore, when a prime and target share no bigrams, no facilitation or interference should be observed. Both Guerrera and Forster (2008) and Still and Morris (2008) have found evidence against this prediction. In addition, if bigrams are the only representations that directly activate word representations, comparable amounts of facilitation or interference should be observed when two different primes share approximately the same number of bigrams with the target. Evidence exists that is contrary to this prediction as well (e.g., Davis & Bowers, 2006; Guerrera & Forster, 2008; Still & Morris, 2008).

Guerrera and Forster's (2008) Experiment 3 included three critical prime manipulations in which the number of bigrams shared between the prime and target was varied. To elucidate description of the letter positions used for the primes, letter position is reported according to the letters' original positions in the target; this coding scheme has been used extensively by Grainger and colleagues. For example, the prime *ohuse* and target *HOUSE* would be represented by the numbers 21345 and 12345 respectively. The first of Guerrara and Forster's conditions included an internal transposition condition in which the prime and target shared the first and last letters in the same position, but the six internal letters were transposed (e.g., 13254768 – 12345678 for *anbroaml – ABNORMAL*). The second condition was the all-transposed, or extreme transposition, condition in which every pair of letters was transposed (21436587; *baonmrla*). The third condition – reversed halves – was created by splitting the target in half and then reversing the letter order of each half (43218765; *onbalamr*). Based on the letter coding scheme implemented in the Open-Bigram model, primes and targets in the internal transposition and extreme transposition conditions share approximately the same number of bigrams while primes and targets in the reversed halves conditions share no bigrams.[7] Using 40-ms masked prime exposure durations and a lexical decision task, Guerrera and Forster found significant facilitation in the internal transposition condition, but no facilitation or interference was found in the extreme transposition or in the reversed halves conditions. These results do not follow the pattern of priming predicted by the match values for the SERIOL or Open-Bigram models. The implication of this finding is that bigrams may not be the only units involved in activating word representations.

Still and Morris (2008) used similar manipulations to those of Guerrera and Forster (2008), but included a novel condition – the mirror anagram condition – in which neither the SERIOL nor the Open-Bigram model predict any facilitation or interference. In the mirror anagram condition, the letters in the prime appeared in the exact opposite order of the letters in the target (e.g., *elba – ABLE*). Because no letters appeared in the same relative order, no bigrams were shared between the prime and target. In addition to the mirror anagram

[7] Some words contained repeated letters. In these cases bigrams may have been shared between the prime and target in the reversed halves condition.

condition, Still and Morris included a bigram anagram condition that preserved some bigrams (3/6 or 4/6 bigrams) between the prime and target, (e.g., *bael* – *ABLE*) and included an orthographic neighbor condition in which the prime and target shared all letters in the same position except for one letter that was replaced (e.g., *ible* – *ABLE*, 3/6 shared bigrams).[8] The first results of interest are that significant facilitation was found for neighbor primes and targets but not for primes and targets in the bigram anagram condition even though both primes shared approximately the same number of bigrams with the target. Like Guerrera and Forster's (2008) findings, these are problematic for bigram models of word recognition.

The second result of interest was that interference was obtained in the mirror anagram condition. Accounting for this finding is difficult for models of word recognition. Most models posit that interference emerges when more than one word representation has been activated by the prime. The problem is that the mirror anagrams in the experiment were nonwords and were unlikely to activate many word representations that would compete with the target for recognition. For example, within current models of word recognition it is difficult to make the argument that mirror anagram nonwords like *eulc*, *htom*, *mreg*, *lruh*, *fehc*, and *hgis* should activate multiple word representations. Thus each of the current models of word recognition predicts that nonword anagram primes should not interfere with target processing, but they may facilitate target processing when some letters appear in the same relative positions in the prime and target. Because the match value predictions produced by the SOLAR, SERIOL, and Open-Bigram models for the anagram conditions are similar, for

[8] Five-letter words were included in the experiment, but are not discussed here. In the mirror anagram condition the primes and targets share no bigrams, but the third letter in the prime was in the same absolute position as the third letter in the target (e.g., *hcrep* – *PERCH*). This stimulus characteristic makes interpretation of the data from the five-letter mirror anagram condition more complex.

the remainder of this dissertation they will be presented as general word recognition model predictions (e.g., see Figure 2).

Although models of word recognition may eventually be modified to account for these findings, it would likely come at a cost to primary assumptions of the models. For example, the IA model could be modified so that letter representations activate every word representation containing that letter, regardless of letter position. The result would be that anagram primes activate many words that then compete with the target for recognition. Additional assumptions would be needed to explain why anagram primes produce interference in comparison to control primes that share no letters with the target; perhaps an assumption stating that word representations only have inhibitory connections to other word representations that contain the same letters. Then, an additional assumption would be needed to account for the fact that letter position does contribute to word recognition at some stage because one can differentiate between the words *stop* and *post* and *pots*. These would constitute major modifications to current IA model assumptions.

As an alternative, Still and Morris (2008) proposed that their results may be explained by assuming that both individual letters, regardless of position, *and* letters in their relative positions (e.g., bigrams) contribute to the activation and selection of word representations. There are several possible ways to implement the separate influences of letters and bigrams. Therefore, the purpose of the present experiments is to constrain the possible implementations by examining the robustness of mirror anagram interference and by further investigating the interaction between letters and bigrams through additional bigram manipulations.

Present Experiments

Several questions that were raised by Still and Morris' (2008) findings are addressed. First, how robust is interference for mirror anagrams? Interference for mirror anagrams has been shown only with four-letter words; it is possible that the effect is restricted to short words. Results from some studies do suggest that orthographic priming effects are affected by word length. For example, in a masked orthographic priming paradigm, significant interference has been found for four- and five-letter word targets when they were preceded by higher-frequency, orthographically similar word primes (Davis & Lupker, 2006). But, Davis and Lupker reported that in a similar experiment using seven-letter targets, interference was not obtained; instead, there was a trend toward facilitation.

Second, what are the contributions of letters and bigrams to orthographic priming effects? The results obtained by Still and Morris (2008) could be explained if one assumes that letters and bigrams shared between the prime and target influence the outcome in the orthographic priming paradigm in qualitatively different ways. Specifically, when the same letters appear in the prime and target, but those letters appear in different positions, the prime will inhibit the target. In contrast, when bigrams are shared between the prime and target, the prime will facilitate target processing. This set of assumptions will be referred to as the *Lexical Access by Bigrams and Letters (LABL) hypothesis*. Based on this hypothesis, interference is found for mirror anagrams because there is interference from the letters that appear in the wrong position. For neighbor primes and targets, facilitation is obtained because several bigrams are shared between the prime and target. In the bigram anagram condition no facilitation or interference is observed because the interference from letters appearing in the wrong position offsets the facilitation obtained from the bigrams that are shared between the prime and target. The LABL hypothesis could be tested by using bigram anagrams in which the number of bigrams shared between the prime and target is varied. Facilitation should be observed if the number of bigrams shared between prime and target is increased; interference should be observed if the number of shared bigrams is decreased (see Figure 2 for an illustration of these predictions).

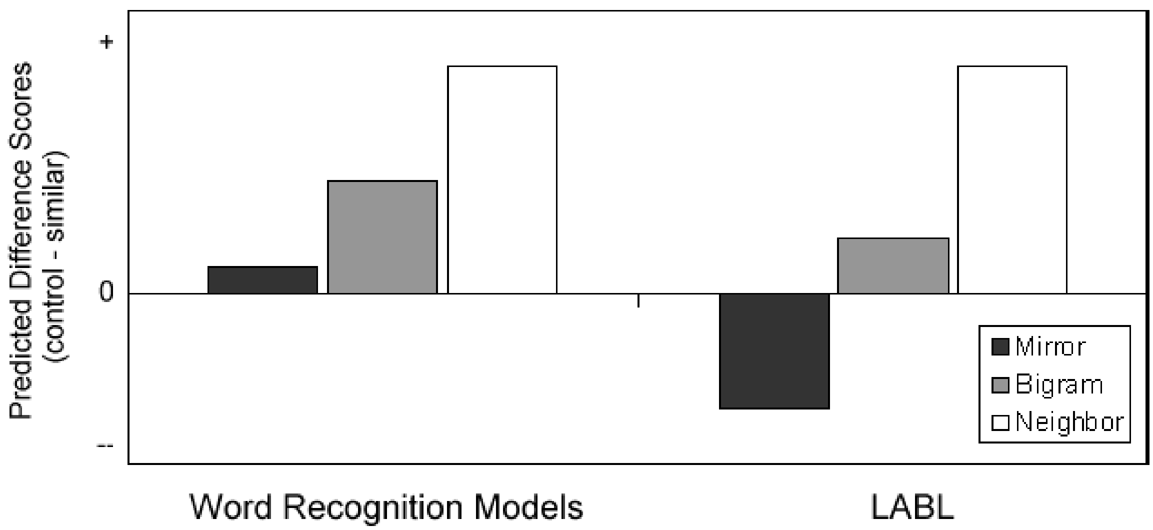

Figure 2. General predictions made by word recognition models and the LABL hypothesis for the conditions tested by Still and Morris (2008). Of note is that word recognition models do not predict any interference when a word target is preceded by a nonword anagram prime.

Third, do the contributions of letters and bigrams change over time? There is evidence that orthographic priming effects change as prime exposure duration is varied. For example, in their Experiment 6, Grainger et al. (2006) investigated the time course of word recognition by studying the time course of orthographic priming effects. In their experiment, primes were displayed for 33 or 83 ms and were followed immediately by a seven-letter target to which participants made a lexical decision. The finding of interest for the present investigation is that facilitation was obtained from partial-word primes (e.g., the prime *flcn* for the target *FALCON*) in the 33-ms condition, but no facilitation was found when primes were displayed for 83 ms.[9] This change in orthographic priming effects is assumed to reflect different points of progress in the word recognition process (e.g., Grainger et al, 2006; Guerrera & Forster, 2008). In relation to letter position processing, researchers have proposed that the earliest stages of word recognition are less sensitive to absolute letter position, but as more information is made available, letter position becomes more important (e.g., Kinoshita & Norris, 2009; Grainger et al., 2006). If this is the case, one might expect that the relative contributions of letters and bigrams to orthographic priming would change as prime exposure durations are manipulated.

The present experiments address the three aforementioned issues. They test the robustness of the mirror anagram finding by examining whether or not interference is limited to shorter words (like the four-letter words used by Still and Morris) by using longer (six-letter) word targets. In addition, Experiments 1 and 2 used six-letter primes which allowed for the inclusion of more bigram anagram manipulations. Specifically, *two* bigram anagram conditions were included along with the mirror anagram and neighbor conditions. These manipulations were used to test the hypothesis that letters and bigrams have unique contributions to orthographic priming; the primes in one bigram anagram condition shared four bigrams with the target, while primes in the other condition shared eight bigrams with the target.

The present experiments also examined the effects of prime exposure duration. Experiment 1 used 35-ms prime exposure durations as in Still and Morris (2008), while Experiments 2 and 3 used 70-ms prime exposure durations. A final variable examined was

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[9] Primes in this experiment were unmasked. In Experiment 5, Grainger et al. (2006) used 33-ms prime exposure durations and either presented a mask before the prime or not. Facilitation was not found for seven- and nine-letter targets in any of the masked conditions but facilitation was found in the unmasked conditions.

prime length; six-letter primes were used in Experiments 1 and 2, while five-letter primes were used in Experiment 3. The prime length manipulation was important for two reasons. First, it allowed a further test of the robustness of anagram interference. Second, there was the question of why anagram interference had not been reported previously; many investigations have used "scrambled" primes (e.g., Grainger et al., 2006; Kinoshita & Norris, 2009; Peressotti & Grainger, 1999). Although there are several reasons why this may be the case, one possibility was tested in Experiment 3. Perhaps anagram interference emerges only when all letters are shared between the prime and the target. If so, it is no surprise that partial-word priming studies (e.g., Grainger et al., 2006; Peressotti & Grainger, 1999) have not previously reported an anagram interference finding. Third, the partial-word primes used in Experiment 3 also afforded the opportunity to investigate more anagram bigram conditions – anagram primes shared zero, two, or four bigrams with targets. Thus, the partial-word prime manipulation provided a strong test of the LABL hypothesis (Still & Morris, 2008).

CHAPTER 2. EXPERIMENT 1

Experiment 1 was designed to replicate and extend the findings of Still and Morris (2008). A primary objective of Experiment 1 was to replicate the mirror anagram interference finding as it has only been demonstrated in one study. It was also important to show that interference is not restricted to the specific set of stimuli used by Still and Morris. A second objective of Experiment 1 was to test the hypothesis that interference occurs when a prime and target have the same letters, but those letters appear in different positions, and that facilitation occurs when a prime and target share bigrams (the LABL hypothesis).

To meet these objectives, six-letter stimuli were used in Experiment 1; this allowed more bigram anagram manipulations. Four orthographic conditions were created. Two conditions, the 0-bigram anagram (letters in reverse order in the prime and target) and neighbor (prime and targets were orthographic neighbors), were similar to those used by Still and Morris (2008). The other two conditions were "bigram" anagram conditions: primes and targets in the 4-bigram anagram condition shared four bigrams while those in the 8-bigram anagram condition shared eight bigrams. With these additional conditions, the LABL hypothesis could be tested. Specifically, if shared individual letters in the wrong position lead to interference and shared bigrams lead to facilitation, a particular pattern of data should be observed: interference for 0-bigram anagrams, interference or a null effect for 4-bigram anagrams, a null effect or facilitation for 8-bigram anagrams, and facilitation for neighbors. General predictions from word recognition models and the LABL hypothesis are presented in Figure 3 for each of the experimental conditions. Models of word recognition generally predict that the most facilitation should be found in the neighbor condition with less facilitation in the 8-bigram anagram condition, less in the 4-bigram anagram condition, and little or no facilitation in the 0-bigram anagram condition. One exception is that the Open-Bigram model predicts approximately the same amount of facilitation in the 8-bigram anagram and neighbor conditions while the other models predict much less facilitation in the 8-bigram anagram condition. The LABL hypothesis predicts facilitation in the neighbor condition and less facilitation in the 8-bigram anagram condition; interference is predicted in the 0-bigram anagram and less interference in the 4-bigram anagram condition.

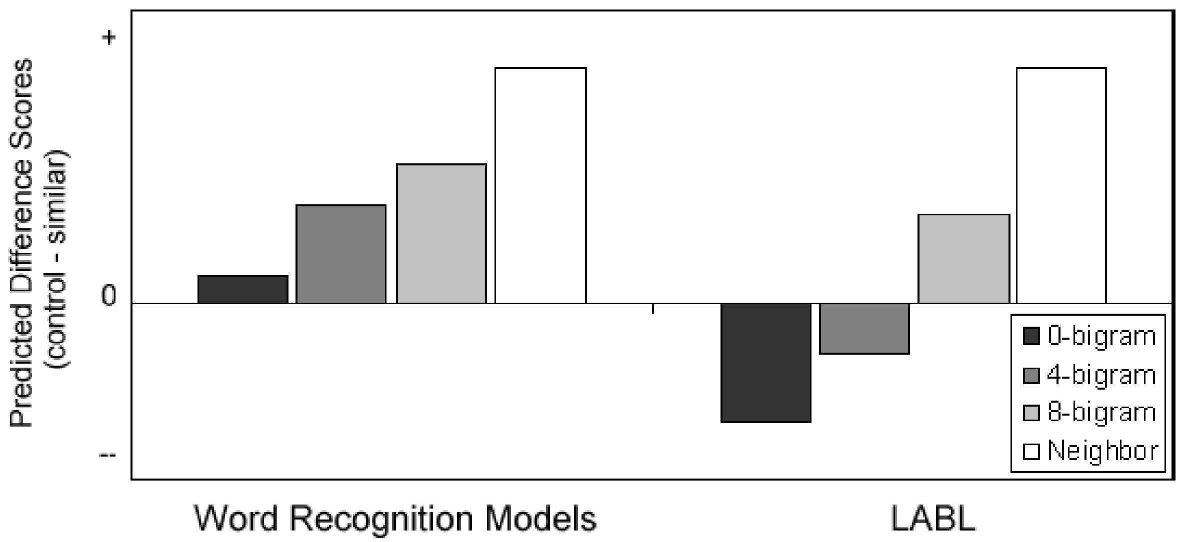

Figure 3. General predictions made by word recognition models and the LABL hypothesis for the orthographically similar conditions tested in Experiments 1 and 2.

Target word frequency was manipulated in addition to orthographic similarity. Although the results of some studies (e.g., Davis & Lupker, 2006, Experiment 1) suggest that target word frequency plays a minor role in the amount of facilitation obtained, Still and Morris' (2008) anagram interference was highly dependent on target word frequency. They used both low- and high-frequency word targets in order to maximize the chances of finding significant effects as it was the first investigation to use these anagram conditions. In their study, Still and Morris also investigated two different prime exposure durations: 35 ms and

100 ms. When 35-ms prime exposure durations were used, significant interference for mirror anagrams was found only for high-frequency targets. In contrast, when 100-ms prime exposure durations were used, significant interference for mirror anagrams was found only for low-frequency targets with a trend toward interference for high-frequency targets. Because it could not be known in advance how the anagram orthographic priming effects would change when longer stimuli were used, both low- and high-frequency words were used in the present experiments.

One additional stimulus constraint was that only words and nonwords with no repeated letters were selected. Because the main manipulations in these experiments involved creating anagrams that do not share letters in the same absolute positions and creating anagrams that do not share letters in the same relative positions, items with repeated letters are problematic. For example, there are few anagram combinations that can be made for the word *research* that satisfy the aforementioned conditions; the relative letter orders *re* and *er* in *research* make it impossible to create an anagram that does not preserve at least one of the two letter orders. In addition, repeated letters are potentially problematic because they could result in repeated bigrams (e.g., in *research* there are two *re* and two *ea* bigrams). Schoonbaert and Grainger (2004) suggested that only one of the repeated bigrams would be used during word recognition (duplicates of a bigram are not created), but questions remain as to how repeated bigrams would ultimately be output in the correct order (e.g., Kinoshita & Norris, 2009). Both stimulus construction and theoretical issues are avoided by using items that do not contain repeated letters.

Method

Participants

Eighty Iowa State University students (54 female) participated in exchange for course credit. All participants were monolingual English speakers, except two who were bilingual learning English before the age of five. Participant age ranged from 18 – 27 (*M* = 18.9) years.

Materials

The stimulus list consisted of 128 word target trials and 64 nonword target trials. Each trial contained a six-letter nonword prime and a six-letter target; all word targets were obtained from the English Lexicon Project database (ELP; Balota et al., 2007). Two sets of 64 target words were selected; half were low-frequency (*M* = 10.8; Kučera & Francis, 1967), half were high-frequency (*M* = 150.3). All word targets had few orthographic neighbors, i.e., they were from low-density neighborhoods (range = 0 – 5, *M* = 1.6). Sixty-four nonword targets were obtained from the ARC nonword database (Rastle, Harrington, & Coltheart, 2002) with the constraint that they had pronounceable bodies and had few orthographic neighbors (range = 0-5; *M* = 0.97).

All primes in the experiment were nonword primes. Four orthographically similar prime conditions were created for each target: neighbor, 8-bigram anagram, 4-bigram anagram, and 0-bigram anagram. Neighbor primes shared 5/6 letters with the target in the same positions (examples of the conditions used in the experiment appear in Table 1). All neighbor primes were interior neighbors in that the one letter that was different was not the first or last letter (e.g., *thione* – *THRONE*); this ensured that the prime and target shared seven or eight bigrams. Anagram primes shared all six letters with the target, but no letters appeared in the same position or in the same contiguous order (i.e., two adjacent letters in the target were never adjacent in the same order in the prime). For the remaining anagram conditions, the letter order of the primes is described according to the letters' original positions in the target. In the 8-bigram anagram condition, each successive pair of letters – letters 1 and 2, letters 3 and 4, letters 5 and 6 – were transposed (e.g., *htoren – THRONE*) to create a prime that shared eight bigrams with the target. Using the number coding scheme, the 8-bigram anagram prime would be represented as 214365. In the 4-bigram anagram condition, prime letter order was 461532 (e.g., *oetnrh – THRONE*); the prime and target shared 4 bigrams. In the 0-bigram anagram condition the letters in the prime were in the reverse order of the target, 654321 (e.g., *enorht – THRONE*), and the prime and target shared no bigrams. All of the word target trial stimuli appear in Appendix A.

Table 1

Examples of the Conditions used in Experiments 1 and 2

	Target: THRONE		Target: CLAMPS	
Prime Condition	Similar	Control	Similar	Control
0-bigram (0 B, 6 L)	enorht	spmalc	spmalc	enorht
4-bigram (4 B, 6 L)	oetnrh	mscpal	mscpal	oetnrh
8-bigram (8 B, 6 L)	htoren	lcmasp	lcmasp	htoren
Neighbor (7-8 B, 5 L*)	thione	clamds	clamds	thione

Note. B = number of shared bigrams between prime and target, L = number of letters shared between prime and target in any position. L* indicates that the letters appeared in the same positions in the prime and target.

Control conditions were created for each of the orthographically similar conditions. Because some primes are more word-like than others (e.g., *clamds* vs. *spmalc*) there is a question of which controls are the most appropriate. For example, it is possible that using a nonword prime with illegal letter combinations has different influences on target processing than a nonword prime containing legal letter combinations. To control for these potential differences, a yoking technique was used whereby an orthographically similar prime in one condition would be compared to an orthographically different prime from the same condition. The assumption is that the primes in any one condition tend to be more similar in terms of the legality of their letter combinations than primes in different conditions (e.g., most primes in the 0-bigram anagram condition contain illegal letter combinations but primes in the neighbor condition tend to contain only legal letter combinations). Differences in the mean number of orthographic neighbors for each of the prime conditions support the assertion that differences exist across primes in the various conditions (see Table 2).

Table 2

Mean Number of Orthographic Neighbors for Primes in Each Condition

Target Frequency	0-bigram	4-bigram	8-bigram	Neighbor
Low	.125	.016	.000	1.11
High	.016	.016	.000	1.06

Creation of the control conditions was done by yoking together two targets that did not share any letters (e.g., *THRONE* and *CLAMPS*) and then by trading primes for each of their respective orthographically similar conditions. For example *spmalc – THRONE* would be the control condition for *enorht – THRONE* and *enorht – CLAMPS* would be the control condition for *spmalc – CLAMPS* (see Table 1). The same procedures for yoking and creating control conditions were used for the word and nonword targets. Eight experimental lists were constructed so that each word and nonword target was presented in each of the eight conditions across experimental lists. Each list contained 24 trials (eight low-frequency, eight high-frequency, eight nonword) in each of the eight conditions. Participants saw only one list during an experiment and never saw any item more than once.

Ten additional trials were constructed for use in the practice block. All items contained six letters, all primes were nonwords, and five of the trials contained word targets.

Apparatus and Procedure

For all experiments reported in this dissertation, stimulus presentation was controlled by PsyScope experimental software (Cohen, MacWhinney, Flatt, & Provost, 1993) run on a Macintosh G4 and presented on a 40 cm Mitsubishi Diamond 73 monitor. Participants were seated approximately 60 cm from the monitor and all items were presented in black 48 point Arial font on a white background. Participant responses were collected using a Psyscope button box (New Micros, Dallas, TX).

Each experimental trial began with a fixation cross in the middle of the screen for 500 ms. After that, the trial proceeded as follows: 500 ms premask (######), 35 ms lowercase prime, and uppercase target (primes and targets were presented in different case to reduce the likelihood of visual fusion). The target remained on the screen until the participant pressed a button indicating that the target was a word or pressed a different button indicating that the target was a nonword.

The experimental trials were preceded by ten practice trials giving participants the opportunity to become accustomed to the procedure. Participants were told that they would see a plus sign followed by a row of pound signs, then they would see a briefly flashed item followed by a second item in uppercase. They were instructed to respond by pressing the left button for "No" if the uppercase item was a nonword or by pressing the right button for

"Yes" if the uppercase item was a word. Participants were encouraged to respond both quickly and accurately to the uppercase word (target). The next trial began 1500 ms after the participant response. Trial order was randomized. There were four breaks during the experiment.

Results

Responses faster than 200 ms or slower than 1500 ms were classified as outliers and excluded from all analyses. This procedure resulted in exclusion of less than 2% of the data. Three participants were replaced due to excessive error rates (30% or more of their data consisted of errors or outliers). Only correct responses were included in the response time analyses. Mean response times and error rate percentages appear in Table 3.

Word Target Trials

A 2 x 2 x 4 repeated-measures ANOVA with the variables orthographic similarity (similar, control), target frequency (high, low), and condition (0-bigram, 4-bigram, 8-bigram, neighbor) was conducted for subjects and items. Participant responses were faster to targets in orthographically similar conditions (M = 568) than in control conditions (M = 576), $F_1(1, 79) = 7.53$, MSE = 2,663; $F_2(1, 126) = 6.48$, MSE = 2,349, both ps < .05. Participant responses were also faster to high-frequency (M = 551) than to low-frequency targets (M = 592), $F_1(1, 79) = 142.38$, MSE = 3,719; $F_2(1, 126) = 40.22$, MSE = 11,373, both ps < .001. In addition, the main effect of condition was significant reflecting the fact that responses tended to be faster in the neighbor and 8-bigram anagram conditions (M = 567 and M = 568 respectively) than the 0- and 4-bigram anagram conditions (M = 578 and M = 574), $F_1(3, 77) = 3.51$, MSE = 2,676; $F_2(3, 124) = 3.30$, MSE = 2,808, both ps < .05. The interaction between target frequency and condition was significant in the subject analysis and approached significance in the item analysis, $F_1(3, 77) = 3.65$, $p = .016$, $MSE = 2{,}285$; $F_2(3, 124) = 2.45$, $p = .067$, $MSE = 2{,}808$. No other interactions were significant.

Table 3

Mean Response Times and Error Rates obtained in Experiment 1

	Target Type					
	Low-Frequency		High-Frequency		Nonword	
Condition	RT	Error Rate	RT	Error Rate	RT	Error Rate
0-Bigram						
Similar	603 (12)	4.1 (0.9)	554 (11)	0.6 (0.5)	700 (16)	9.2 (1.4)
Control	600 (11)	3.3 (0.9)	553 (10)	0.9 (0.3)	694 (14)	10.6 (1.7)
Difference	-3 (9)	-0.8 (1.1)	-1 (6)	0.3 (0.6)	-6 (11)	1.4 (1.9)
4-Bigram						
Similar	596 (12)	3.1 (0.8)	552 (11)	1.4 (0.6)	699 (16)	7.3 (1.1)
Control	597 (11)	3.4 (0.8)	553 (11)	0.8 (0.4)	709 (16)	7.7 (1.2)
Difference	1 (9)	0.3 (1.0)	1 (9)	-0.6 (0.7)	10 (12)	0.4 (1.5)
8-Bigram						
Similar	566 (10)	2.5 (0.7)	554 (12)	0.6 (0.3)	696 (14)	9.5 (1.7)
Control	596 (12)	3.1 (0.9)	555 (11)	0.5 (0.3)	713 (14)	7.0 (1.0)
Difference	30 (9)	0.6 (1.0)	1 (7)	-0.1 (0.4)	17 (10)	-2.5 (1.6)
Neighbor						
Similar	577 (12)	2.8 (0.7)	539 (11)	1.4 (0.5)	713 (16)	7.7 (1.3)
Control	601 (12)	2.3 (0.5)	551 (11)	0.3 (0.3)	718 (15)	8.3 (1.3)
Difference	23 (9)	-0.5 (0.8)	12 (8)	-1.1 (0.4)	5 (12)	0.6 (1.6)

Note. Standard error of the mean appears in parentheses.

As the purpose of the experiment was to examine differences produced by orthographic similarity across the four conditions, the results of most interest are those pertaining to the differences between orthographic similarity and condition. Difference scores (difference between control and orthographically similar conditions) of the mean response times appear in Figure 4. Planned comparisons between the orthographically similar and control conditions for each of the orthographic conditions (0-bigram, 4-bigram, 8-bigram, neighbor) test for the presence of interference or facilitation resulting from orthographic similarity between the prime and target. These comparisons were performed for both high- and low-frequency targets across participants and items. Responses were faster for low-frequency targets preceded by 8-bigram anagram primes compared to the control condition, $t_1(79) = -3.69$, $SEM = 8.86$; $t_2(63) = -3.56$, $SEM = 8.36$, both ps $< .01$; response times were also faster for low-frequency targets preceded by neighbor primes, $t_1(79) = -2.83$, $SEM = 9.06$; $t_2(63) = -2.46$, $SEM = 8.69$, both ps $< .05$, compared to control conditions. No other response time planned comparisons reached significance in the subject and item analyses.

Separate ANOVAs were performed for error rates. The only significant effect was a main effect of target frequency with participants making more errors on low-frequency targets ($M = 3.1$) than on high-frequency targets ($M = 0.8$), $F_1(1, 79) = 33.24$, $MSE = .005$; $F_2(1, 126) = 22.82$, $MSE = .006$, both ps $< .001$. No other main effects or interactions were significant in the error rate ANOVA.

Planned comparisons revealed that more errors were made when high-frequency targets were preceded by neighbor primes than in the control condition, $t_1(79) = 2.40$, $p = .019$, $SEM = .005$; $t_2(63) = 1.99$, $p = .051$, $SEM = .006$. The apparent interference for neighbors most likely reflects a speed-accuracy tradeoff as there was a trend toward facilitation in the response time data for these stimuli (shown in Table 3). No other planned comparisons for error rates reached significance.

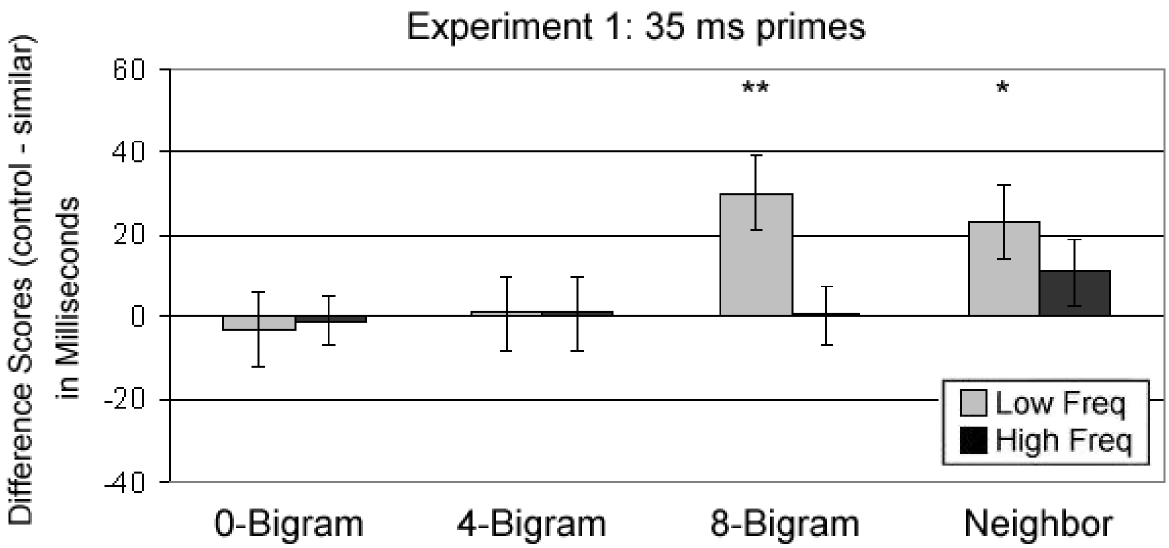

Figure 4. Mean differences between control and orthographically similar conditions in Experiment 1. Error bars represent the standard error of the mean difference. * $p < .05$; ** $p < .01$; *** $p < .001$.

Nonword Target Trials

A 2 x 4 repeated-measures ANOVA with the variables orthographic similarity (similar, control), and condition (0-bigram, 4-bigram, 8-bigram, neighbor) were conducted for subjects and items. No main effects or interactions reached significance in the subject and item analyses. ANOVAs were also conducted for error rates; no main effects or interactions were significant.

Discussion

The results of Experiment 1 are easily accounted for by current models of word recognition that use relative position letter coding schemes (e.g., SOLAR, Overlap model, SERIOL, Open-Bigram model). Facilitation was found in the two conditions where many letters appear in the same relative positions in the prime and target (e.g., 8-bigram anagram and neighbor conditions); no evidence of orthographic priming effects were observed in the two conditions in which few, if any, letters appear in the same relative positions in the prime and target (e.g., 0- and 4-bigram anagram). The data fit the Open-Bigram model predictions very well as it was the only model predicting similar amounts of facilitation for the 8-bigram anagram and neighbor conditions. Although this could be taken as confirmatory evidence for current models of word recognition, an explanation for the mirror anagram interference (Still & Morris, 2008) is still lacking.

Mixed evidence was obtained for the influence of target word frequency on the size of the orthographic priming effect. The interaction between frequency and orthographic similarity was not significant, nor was the three-way interaction between target frequency, orthographic similarity, and condition. Nevertheless, significant facilitation was found for low-frequency targets in the 8-bigram and neighbor conditions but not for high-frequency targets in any condition. This finding suggests that target frequency does influence the size of the orthographic priming effect; in this case low-frequency targets gained the largest benefit from the presentation of primes that shared bigrams with the target.

The purpose of Experiment 1 was to further investigate the origins of mirror anagram interference in two ways: 1) by investigating the contributions of letters and bigrams to the orthographic priming effect and 2) by examining the robustness of anagram interference. Based on the findings of Still and Morris (2008) it was suggested that letters in the wrong position between primes and targets may lead to interference while shared bigrams between primes and targets leads to facilitation. While finding facilitation in the 8-bigram anagram and neighbor conditions and null effects in the 4-bigram condition is consistent with Still and

Morris' LABL hypothesis, the absence of interference in the 0-bigram anagram condition raises questions about the validity of the hypothesis and the robustness of anagram interference. The primary difference between Experiment 1 and the previous investigation by Still and Morris was the length of the stimuli – Still and Morris used 4-letter items, while Experiment 1 used 6-letter items. It is possible that the absence of the anagram interference is related to processing differences in longer words and shorter words.

CHAPTER 3. EXPERIMENT 2

Experiment 2 was designed to further examine anagram interference and the LABL hypothesis by using longer prime exposure durations. Previous studies have shown that orthographic priming effects in masked priming paradigms are affected by prime exposure duration. Recall that Grainger et al. (2006, Experiment 6) found facilitation for seven-letter targets using 33-ms prime exposure durations, but no evidence of orthographic priming effects was observed when 83-ms prime exposure durations were used. Although Grainger et al. findings suggest that smaller priming effects should be found in Experiment 2, what should be kept in mind is that Grainger et al.'s 33-ms primes were not preceded by a forward mask. Masking effects likely slow prime processing so that the prime exposure duration in Experiment 1 is functionally shorter than the prime exposure duration Grainger et al. used. Therefore, it is possible that orthographic priming effects would be larger in Experiment 2 than in Experiment 1.

In addition, anagram interference has only been shown once before, so there are no data related to how it might be affected by prime exposure duration. It is reasonable to propose that interference might take longer than facilitation to emerge. In the IA model (McClelland & Rumelhart, 1981), interference occurs when a prime activates at least one representation that competes with the target. The representations compete by inhibiting one another. Because the strength of the inhibition depends on the activation of the representation, a representation with higher activation should produce more inhibition. By increasing the prime exposure duration, the activation levels of competing representations in the word recognition system may reach a level substantial enough to create more inhibition (in comparison to Experiment 1) and interfere with target processing. The competition model also predicts that prime exposure duration could influence whether facilitation or interference is obtained. In particular, a prime with a longer exposure duration is better encoded and the outcome of the competition is more likely to result in interference, as the prime will compete more with the target.

An alternative proposal is that interference simply takes more time to emerge. This could be the case if a minimum amount of activation is required before any inhibition is produced. Along these lines, longer stimuli (six-letter) may take more time to process than shorter (four-letter) stimuli thereby delaying the point at which a longer stimulus will inhibit the target. If it is the case that six-letter stimuli take more time to process, by increasing the prime exposure duration in Experiment 2, the likelihood of obtaining anagram interference should increase.

Another outcome of using increased prime exposure durations is that it provides an opportunity to investigate the contributions of letters and bigrams to orthographic priming effects over time. This premise is based on the assumption that when primes have longer exposure durations (e.g., 70 ms) more processing has been completed before the target is presented in comparison to when primes have shorter exposure durations (e.g., 35 ms). Inferences can then be made about how the process of word recognition unfolds over time by comparing the pattern of results obtained under different prime exposure durations. To this end, Experiment 2 employed the same stimuli as Experiment 1, but used 70-ms prime exposure durations. Word recognition model and LABL hypothesis predictions for Experiment 2 were the same as Experiment 1 because they do not specify how orthographic priming effects change with increased prime exposure durations.

Method

Participants

Eighty Iowa State University students (48 female) participated in exchange for course credit. All participants were monolingual English speakers. Participant age ranged from 18 – 45 (M = 19.7) years.

Materials and Procedure

Materials and procedures were the same as those used in Experiment 1 except that primes were displayed for 70 ms instead of 35 ms.

Results

Responses faster than 200 ms or slower than 1500 ms were classified as outliers and excluded from all analyses. This procedure resulted in exclusion of less than 3% of the data. Four participants were replaced due to excessive error rates (30% or more of their data consisted of errors or outliers). Only correct responses were included in the response time analyses. Mean response times and error rates appear in Table 4.

Word Target Trials

Two 2 x 2 x 4 repeated-measures ANOVAs with the variables orthographic similarity (similar, control), target frequency (high, low), and condition (0-bigram, 4-bigram, 8-bigram, neighbor) were conducted one for subjects and one for items. Participant responses were significantly faster for high-frequency targets (M = 594) than for low-frequency targets (M = 639), $F_1(1, 79) = 112.16$, MSE = 5,811; $F_2(1, 126) = 40.79$, MSE = 13,294, both ps < .001. In addition, there was a main effect of condition reflecting faster responses in the neighbor condition (M = 604) than in the other conditions (0-bigram M = 619, 4-bigram M = 621, 8-bigram M = 621), $F_1(3, 77) = 7.75$, MSE = 3,179; $F_2(3, 124) = 6.92$, MSE = 2,937, both ps <

.001. There was a significant interaction between orthographic similarity and condition, reflecting the tendency for interference in the anagram conditions and facilitation in the neighbor condition, $F_1(3, 77) = 12.74$, $MSE = 3{,}256$; $F_2(3, 124) = 17.07$, $MSE = 3{,}285$, both $ps < .001$. No other main effects or interactions were significant in the ANOVA.

Table 4

Mean Response Times and Error Rates obtained in Experiment 2

	Target Type					
	Low-Frequency		High-Frequency		Nonword	
Condition	RT	Error Rate	RT	Error Rate	RT	Error Rate
0-Bigram						
Similar	652 (13)	4.1 (0.8)	608 (11)	1.3 (0.4)	743 (16)	7.2 (1.1)
Control	632 (12)	2.7 (0.7)	586 (10)	0.6 (0.4)	758 (15)	5.0 (1.1)
Difference	-20 (11)	-1.4 (1.1)	-22 (7)	-0.6 (0.5)	15 (11)	-2.2 (1.6)
4-Bigram						
Similar	648 (13)	3.4 (0.8)	605 (13)	1.6 (0.5)	747 (16)	6.7 (1.2)
Control	649 (14)	2.7 (0.6)	584 (10)	0.5 (0.3)	745 (14)	5.6 (1.1)
Difference	1 (10)	-0.7 (1.1)	-21 (8)	1.1 (0.6)	-2 (12)	-1.1 (1.5)
8-Bigram						
Similar	643 (14)	3.6 (0.9)	610 (12)	2.0 (0.6)	743 (16)	7.7 (1.2)
Control	635 (13)	2.2 (0.7)	599 (13)	1.1 (0.4)	750 (16)	7.7 (1.2)
Difference	8 (10)	-1.4 (1.2)	-11 (10)	-0.9 (0.7)	7 (13)	0.0 (1.4)
Neighbor						
Similar	606 (12)	2.7 (0.8)	566 (10)	0.6 (0.3)	755 (17)	7.2 (1.1)
Control	648 (14)	2.7 (0.8)	597 (13)	0.3 (0.2)	745 (16)	6.7 (1.1)
Difference	42 (10)	0.0 (0.9)	31 (10)	-0.3 (0.4)	-10 (15)	-0.5 (1.5)

Note. Standard error of the mean appears in parentheses.

Difference scores (control – orthographically similar) of the mean response times appear in Figure 5. Planned comparisons between the similar and control conditions for each of the orthographic conditions (0-bigram, 4-bigram, 8-bigram, neighbor) tested for the presence of interference or facilitation resulting from orthographic similarity. These comparisons were performed for both high- and low-frequency targets across participants and items.

Interference was significant for high-frequency targets in the 0-bigram anagram condition, $t_1(79) = 2.97$, $SEM = 7.43$; $t_2(63) = 3.00$, $SEM = 8.10$, both *p*s < .01, and approached significance for low-frequency targets, $t_1(79) = 1.90$, $p = .061$, $SEM = 10.82$; $t_2(63) = 1.64$, $p = .106$, $SEM = 10.75$. Interference was also obtained for high-frequency targets preceded by 4-bigram anagram primes, $t_1(79) = 2.55$, $SEM = 7.43$; $t_2(63) = 2.12$, $SEM = 9.22$, both *p*s < .05. In contrast, facilitation was obtained in both neighbor conditions: low-frequency targets, $t_1(79) = -4.30$, $SEM = 9.63$; $t_2(63) = -4.03$, $SEM = 10.22$, both *p*s < .001 and high-frequency targets, $t_1(79) = -3.19$, $SEM = 9.67$; $t_2(63) = -3.56$, $SEM = 8.68$, both *p*s < .01. No other response time planned comparisons reached significance.

Two separate ANOVAs (one subject, one item) were performed for error rates. Participants made significantly more errors on low-frequency targets ($M = 3$) than on high-frequency targets ($M = 1$), $F_1(1, 79) = 52.15$, $MSE = .003$; $F_2(1, 126) = 22.95$, $MSE = .005$, both *p*s < .001. In addition, participants made significantly more errors in the orthographically similar conditions ($M = 2.4$) than in the control conditions ($M = 1.6$), $F_1(1, 79) = 5.06$, $MSE = .004$; $F_2(1, 126) = 8.78$, $MSE = .002$, both *p*s < .05. No other main effects or interactions were significant in the ANOVA.

One difference in planned comparisons of the error rates approached significance; participants tended to make more errors for high-frequency targets when preceded by 4-bigram anagrams, $t_1(79) = 1.83$, $p = .070$, $SEM = .006$; $t_2(63) = 1.99$, $p = .051$, $SEM = .006$.

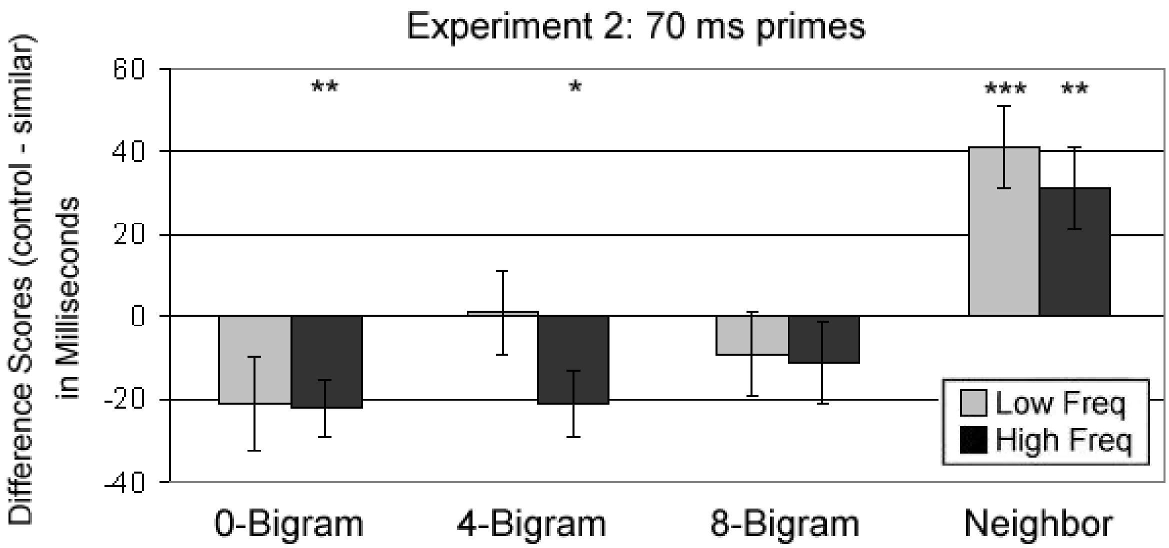

Figure 5. Mean differences between control and orthographically similar conditions in Experiment 2. Error bars represent the mean standard error of the difference. Interference in the low-frequency 0-Bigram condition approached significance, $p = .069$. * $p < .05$; ** $p < .01$; *** $p < .001$.

Nonword Target Trials

Two 2 x 4 repeated-measures ANOVAs (response time and error rate) with the variables orthographic similarity (similar, control), and condition (0-bigram, 4-bigram, 8-bigram, neighbor) were conducted for subjects and items. No main effects or interactions were significant in the RTs or error rates.

Discussion

In contrast to Experiment 1, the results of Experiment 2 are difficult to explain using current models of word recognition. Interference was found for 0- and 4-bigram anagrams. The first problem for existing models of word recognition is that, in both cases, the primes were nonwords. In models that use lexical inhibition to explain interference, the only way interference can be obtained is if the prime activates word representations that compete with the target for recognition. Nonwords, by definition, do not have word representations, so they do not activate their own word representation to compete with the target (Davis, 2003). In addition, based on the letter position coding schemes used in current models of word recognition, anagram primes should not activate many competing word representations. Thus, lexical inhibition is an unlikely candidate to explain the interference obtained in the 0- and 4-bigram anagram conditions. The second potential problem for current models of word recognition is that the results for the 8-bigram and neighbor conditions are not consistent from Experiment 1 to Experiment 2. Current models have difficulty accounting for priming differences related to different prime exposure durations. If an effect was significant in Experiment 1, it should also be significant in Experiment 2. When the Open-Bigram model coding scheme is used to code relative letter position, the similarity between the primes and targets in the 8-bigram anagram and neighbor conditions (containing seven or eight bigrams) is nearly the same. What this means is that if the neighbor condition produces facilitation, so should the 8-bigram condition. This was not the case in Experiment 2. These findings also challenge the SOLAR and SERIOL models of word recognition because they predict more facilitation for targets preceded by neighbor primes than those preceded by 8-bigram anagrams; this was the case in Experiment 2, but not in Experiment 1.

In contrast to the explanatory power of current models of word recognition, the data from Experiment 2 are readily explained by the LABL hypothesis. Interference was obtained in conditions in which anagram primes shared few bigrams with the target and no letters appeared in the same absolute positions. Facilitation was obtained when several bigrams were shared between the prime and target and no letters appeared in the same absolute positions. These findings support the assertion that facilitation emerges when bigrams are shared between the prime and target while interference emerges when letters are shared between the prime and target but those letters appear in different positions. Even though the LABL hypothesis provides a good fit for the results of Experiment 2, the fit for Experiment 1 is not as good. Therefore, current models of word recognition and the LABL hypothesis share one shortcoming: they do not explain why facilitation and interference change with prime exposure duration.

In order to explain the results of both Experiments 1 and 2, some additional assumptions must be made about the time course of interference and facilitation. Examination of the combined data from Experiments 1 and 2 reveals that the influence of bigrams in orthographic priming effects emerges earlier than the influence of letters in the wrong position. This can be inferred from several aspects of the data. First, in Experiment 1 the only evidence of orthographic priming effects appeared in the 8-bigram and neighbor conditions for which facilitation was obtained. These were the conditions in which primes and targets shared the most bigrams. Second, in Experiment 1, no evidence of interference was obtained, but interference was readily obtained in the 0- and 4-bigram anagram conditions of Experiment 2. Third, the null effect for 4-bigram anagrams in Experiment 1 becomes interference in Experiment 2 and facilitation for 8-bigram anagrams in Experiment 1 becomes a null effect in Experiment 2. What this difference may suggest is that the interference generated by letters in the wrong position becomes more prominent over time. Of particular note is that interference was restricted to the anagram conditions. Neighbor conditions produced facilitation in both Experiments 1 and 2. This finding suggests that it is the presence of shared letters *in the wrong positions* that produce interference and not just the presence of shared letters.

As in Experiment 1, frequency did not interact with condition and orthographic similarity. This could be taken as evidence that target frequency does not influence the size of the orthographic priming effect. Contrary to this assertion, interference was found in the 0- and 4-bigram anagram conditions for high-frequency targets, but interference only approached significance in the 0-bigram anagram condition for low-frequency targets. Experiments 1 and 2 demonstrate that the emergence of facilitation and interference change over time, and also suggest that target word frequency contributes to when these effects emerge.

Current models of word recognition and the LABL hypothesis do not predict any effect of target word frequency on interference or facilitation, but the competition model does. According to the competition model, word frequency is another variable that influences encoding and the competitive interactions between items presented in close temporal proximity. In particular, a high-frequency target is better encoded than a low-frequency target therefore interference should be easier to obtain using high-frequency targets and facilitation easier to obtain with low-frequency targets. To illustrate this point, consider the encoding function in Figure 6 where Point A represents a low-frequency target in an anagram condition while Point B represents a high-frequency target in an anagram condition. As illustrated in the figure, increased encoding associated with high-frequency targets is more likely to result in interference compared to more poorly encoded low-frequency targets.

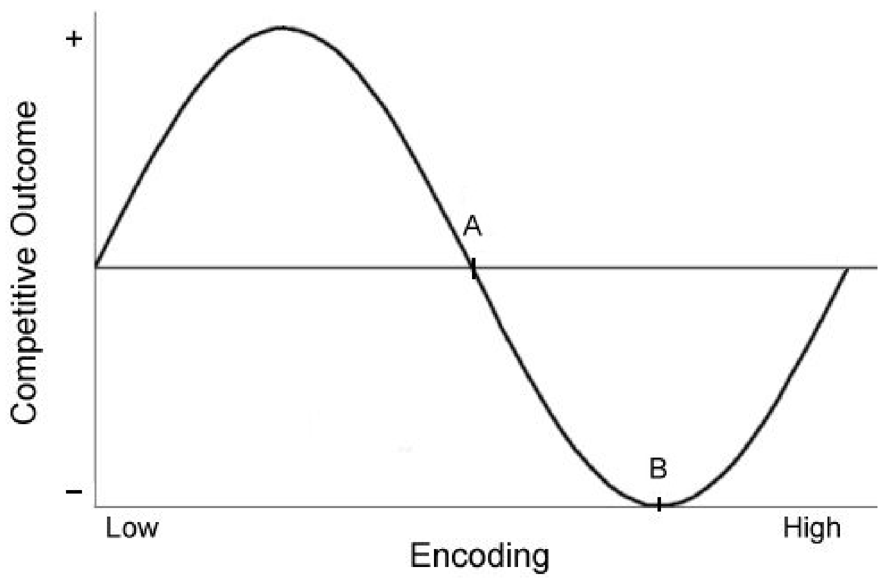

Figure 6. Point A represents an estimate of the encoding of low-frequency targets in anagram conditions in Experiment 2. Point B represents an estimate of the encoding of high-frequency targets in anagram conditions in Experiment 2.

Overall, the results of Experiment 2 replicate and extend Still and Morris' (2008) findings. Based on the general pattern of results, it appears that letters in the wrong position lead to interference while shared bigrams lead to facilitation. Accounting for these results will require substantial modifications to existing models of word recognition. It is, therefore, imperative that anagram interference be fully investigated. One issue motivating this series of experiments was the fact that Still and Morris (2008) found anagram interference using nonword primes while previous research using anagrams had not revealed such an effect. A noticeable difference between the current experiments and earlier investigations is that the primes in the current experiments contained all of the letters of the target but previous studies have often used partial-word primes (e.g., Grainger et al., 2006; Peressotti & Grainger, 1999). It is possible that when partial-word primes are used, interference is weakened to the point that it would not be observed. The purpose of Experiment 3 was to further test the robustness of anagram interference by using partial-word primes.

CHAPTER 4. EXPERIMENT 3

Four new anagram conditions were introduced in Experiment 3. Each of the primes in the experimental conditions were partial-word primes because they had fewer letters than the target (five-letter primes for six-letter targets) and the number of bigrams shared between the prime and target was varied. The experiment had two aims. The first aim was to examine the robustness of anagram interference. Experiment 2 revealed interference in both the 0- and 4-bigram anagram conditions, but, it may be that anagram interference is only obtained when *all* the letters in the prime appear in the target. The second aim was to provide an additional test of the LABL hypothesis. New bigram conditions were constructed such that Experiment 3 included 0-, 2-, and 4-bigram partial-word anagram conditions and a "neighbor" (like the neighbor condition but with one letter removed) condition that shared seven bigrams with the target. The LABL hypothesis predicted a pattern of results in which interference should be obtained in the 0-, 2-, and 4-bigram partial-word anagram conditions while facilitation should be obtained in the "neighbor" condition. If interference is reduced in partial-word primes then a null effect or a small amount of facilitation should be found in the 4-bigram condition. In contrast, if interference depends on all letters being present in the prime and target, no interference should be found in any condition. As in Experiments 1 and 2, current models of word recognition predict facilitation or null effects in the partial-word anagram conditions.

Method

Participants

Eighty Iowa State University students (43 female) participated in exchange for course credit. All participants were monolingual English speakers. Participant age ranged from 18 – 24 (M = 19.5) years.

Materials and Procedure

Materials were similar to those used in Experiments 1 and 2. For the most part, the same targets were used, but the primes contained all of the letters in the target except for the third letter. Four new prime conditions were created: 0-bigram anagram (65421), 2-bigram anagram (26514), 4-bigram anagram (51624), and “neighbor” (12456). The conditions were selected so that a wide range of bigram anagram conditions could be investigated while maintaining some conditions for comparison with those of Experiment 2. Overall, the conditions were similar to those used in Experiments 1 and 2 in that the 0-bigram anagram primes shared no letters in the same relative order with the targets while the “neighbor” primes shared all letters in the same relative positions as their targets (similar to the neighbor conditions in Experiments 1 and 2) with two of those letters appearing in the same absolute position. The 2-bigram and 4-bigram primes did not share any letters in the same position with the target, but did share some letters in the same relative position (similar to the 4-bigram anagram conditions in Experiments 1 and 2). Mean number of neighbors varied by condition as seen in Table 5.

Table 5

Mean Number of Orthographic Neighbors for Primes in Each Condition

Target Frequency	0-bigram	2-bigram	4-bigram	“Neighbor”
Low	.313	.016	.047	1.34
High	.188	.047	.031	1.31

Yoking was completed in the same way to create control conditions as in the previous experiments (see Table 6 for an example of the prime conditions and how they were yoked).

Also, as in Experiments 1 and 2, eight experimental lists were created so that each target was presented in all the conditions across lists, but no item was repeated in any list. Each list contained 24 trials (eight low-frequency, eight high-frequency, eight nonword) for each of the eight conditions.

Upon creating these new prime conditions, primes for fifteen of the targets were words instead of nonwords (e.g., *moths – MOUTHS*); when this occurred, that target was replaced with another word of similar lexical characteristics (e.g., frequency and neighborhood size). All of the word target trial stimuli appear in Appendix B. The procedure was the same as that used in Experiment 2.

Table 6

Example of the Conditions used in Experiment 3

	Target: THRONE		Target: CLAMPS	
Prime Condition	Similar	Control	Similar	Control
0-bigram (0 B, 5 L)	enoht	spmlc	spmlc	enoht
2-bigram (2 B, 5 L)	hento	lspcm	lspcm	hento
4-bigram (4 B, 5 L)	nteho	pcslm	pcslm	nteho
"Neighbor" (7 B, 5 L, 2 L*)	thone	clmps	clmps	thone

Note. B = number of shared bigrams between prime and target, L = number of letters shared between prime and target in any position. L* indicates that the letters appeared in the same positions in the prime and target.

A subset of participants (*N* = 26) was asked to rate their awareness of the prime after completing the experimental trials. Participants were asked to indicate which statement best described their awareness of the briefly flashed item (prime) during the experiment: 1) I could not see it at all, 2) I could see a flash, but that was all, 3) I could see that it had letters in it, 4) I could read the briefly flashed item.

Results

Participants reported limited awareness of the prime. The majority (18 out of 26) of the participants indicated that they could see that the prime had letters in it, and only one participant reported being able to read the prime. Seven participants reported very limited awareness of the prime with four reporting that they had only seen a flash, and three reporting that they could not see the prime at all.

For the experimental trials, responses faster than 200 ms or slower than 1500 ms were classified as outliers and excluded from all analyses. This procedure resulted in exclusion of less than 3% of the data. Seven participants were replaced due to excessive error rates (30% or more of their data consisted of errors or outliers). Only correct responses were included in the response time analyses. Mean response times and error rates appear in Table 7.

Word Target Trials

Two 2 x 2 x 4 repeated-measures ANOVA with the variables orthographic similarity (similar, control), target frequency (high, low), and condition (0-bigram, 2-bigram, 4-bigram, “neighbor”) were conducted for subjects and items. Participant responses were significantly faster to high-frequency targets (M = 594) than to low-frequency targets (M = 645), $F_1(1, 79) = 182.24$, MSE = 4,574; $F_2(1, 126) = 38.85$, MSE = 17,940, both ps < .001. A main effect of condition was also obtained, reflecting the fact that responses to targets in the “neighbor” condition tended to be faster (M = 604) than responses to targets in the other conditions (0-bigram M = 626, 2-bigram M = 622, 4-bigram M = 627), $F_1(3, 77) = 8.11$, MSE = 3,559; $F_2(3, 124) = 8.16$, MSE = 4,004, both ps < .001. There was a significant interaction between orthographic similarity and condition reflecting the tendency for interference in the 2- and 4-bigram anagram conditions and facilitation in the "neighbor" conditions, $F_1(3, 77) = 7.95$, $MSE = 3223$; $F_2(3, 124) = 8.07$, $MSE = 2925$, both $ps < .001$. No other main effects or interactions were significant in the response time ANOVA.

Table 7

Mean Response Times and Error Rates obtained in Experiment 3

	Target Type					
	Low-Frequency		High-Frequency		Nonword	
Condition	RT	Error Rate	RT	Error Rate	RT	Error Rate
0-Bigram						
Similar	650 (13)	3.1 (0.7)	606 (12)	0.9 (0.4)	747 (16)	8.1 (1.3)
Control	655 (15)	2.7 (0.7)	592 (12)	1.3 (0.4)	759 (14)	6.3 (1.3)
Difference	5 (11)	-0.4 (0.8)	-14 (9)	0.4 (0.5)	12 (13)	-1.8 (1.7)
2-Bigram						
Similar	656 (13)	2.2 (0.6)	606 (12)	1.9 (0.5)	757 (14)	7.7 (1.2)
Control	634 (14)	3.2 (0.7)	594 (11)	1.4 (0.5)	767 (15)	8.9 (1.5)
Difference	-22 (10)	1.0 (0.9)	-12 (9)	-0.5 (0.7)	10 (13)	1.2 (1.6)
4-Bigram						
Similar	667 (13)	5.2 (0.9)	603 (12)	0.9 (0.4)	751 (14)	7.3 (1.3)
Control	647 (12)	2.8 (0.6)	591 (13)	1.3 (0.5)	744 (14)	9.7 (1.4)
Difference	-20 (9)	-2.4 (1.0)	-12 (10)	0.4 (0.6)	-7 (13)	2.4 (1.6)
"Neighbor"						
Similar	611 (13)	2.0 (0.5)	568 (12)	1.3 (0.4)	743 (14)	6.1 (1.3)
Control	642 (13)	2.5 (0.6)	593 (13)	1.6 (0.5)	765 (16)	7.7 (1.4)
Difference	31 (11)	0.5 (0.8)	25 (9)	0.3 (0.6)	22 (13)	1.6 (1.8)

Note. Standard error of the mean appears in parentheses.

Difference scores of the mean response times appear in Figure 7. Planned comparisons between the similar and control conditions for each of the orthographic conditions (0-bigram, 2-bigram, 4-bigram, “neighbor”) test for the presence of interference or facilitation resulting from orthographic similarity. These comparisons were performed for both high- and low-frequency targets across participants and items.

Interference for high-frequency targets when preceded by 0-bigram anagrams approached significance, $t_1(79) = 1.61$, $p = .111$, $SEM = 8.67$; $t_2(63) = 1.81$ $p = .076$, $SEM = 8.33$. Responses were slower to low-frequency targets when preceded by 2-bigram anagrams, $t_1(79) = 2.07$, $p < .042$, $SEM = 10.49$; $t_2(63) = 1.80$, $p = .077$, $SEM = 10.11$, and low-frequency targets when preceded by 4-bigram anagrams, $t_1(79) = 2.18$, $SEM = 9.36$; $t_2(63) = 2.52$, $SEM = 11.42$, both ps $< .05$. In contrast, responses were faster for high- and low-frequency word targets preceded by “neighbor” primes: low-frequency targets, $t_1(79) = -2.90$, $SEM = 10.69$; $t_2(63) = -3.11$, $SEM = 10.70$, both ps $< .01$; high-frequency targets, $t_1(79) = -2.86$, $SEM = 8.73$; $t_2(63) = -2.53$, $SEM = 9.79$, both ps $< .05$. No other planned comparisons for response times reached significance.

Two separate ANOVAs (one subject, one item) were performed for error rates. Participants made significantly fewer errors to high-frequency targets ($M = 1$) compared to low-frequency targets ($M = 3$), $F_1(1, 79) = 32.04$, $MSE = .003$; $F_2(1, 126) = 6.64$, $MSE = .011$, both ps $< .05$. The interaction between target frequency and condition was significant in the subject analysis but not in the item analysis, $F_1(3, 77) = 3.97$, $p = .011$, $MSE = .002$; $F_2(3, 124) = 1.75$, $p = .159$, $MSE = .002$. The interaction between target frequency, orthographic similarity, and condition also approached significance, $F_1(3, 77) = 2.26$, $p = .088$, $MSE =$

.002; $F_2(3, 124) = 2.66$, $p = .051$, $MSE = .002$. No other main effects or interactions in the ANOVA were significant.

Planned comparisons for error rates revealed significant interference for low-frequency targets in the 4-bigram anagram condition, $t_1(79) = 2.30$, $SEM = .010$; $t_2(63) = 2.00$, $SEM = .012$, both ps < .05. No other planned comparisons were significant for error rates.

Nonword Target Trials

Two 2 x 4 repeated-measures ANOVAs (subject and item response time ANOVAs and subject and item error rate ANOVAs) with the variables orthographic similarity (similar, control), and condition (0-bigram, 2-bigram, 4-bigram, "neighbor") were conducted across subjects and items. No main effects or interactions were significant in the response times or error rates.

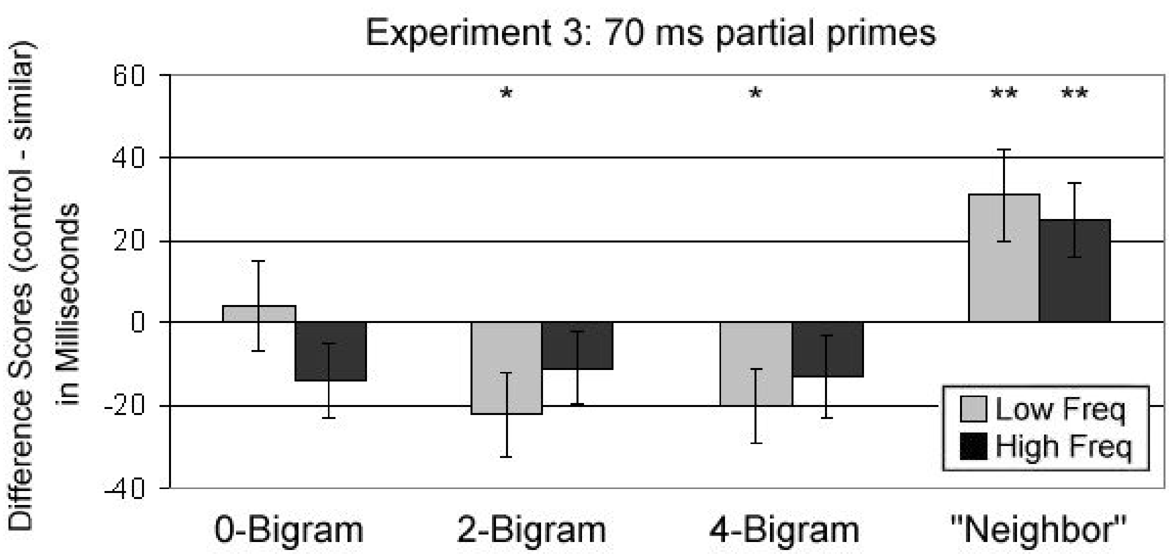

Figure 7. Mean differences between control and orthographically similar conditions in Experiment 3. Error bars represent the mean standard error of the difference. * $p < .05$; ** $p < .01$; *** $p < .001$.

Discussion

The results for high-frequency targets are easily accommodated by the hypothesis that 1) interference occurs when letters are shared between a prime and target, but those letters appear in the wrong position and 2) facilitation occurs when bigrams are shared between the prime and target (the LABL hypothesis). Because one letter was removed from the primes, it was expected that the amount of potential interference in the anagram conditions would be reduced. This appears to have been the case for high-frequency targets. In Experiment 2 interference was found for high-frequency targets when preceded by 0-bigram and 4-bigram anagram primes. By comparison, interference only approached significance for high-frequency targets in the 0-bigram anagram condition when partial-word primes were used.

Results for low-frequency targets were more varied and less easily explained by the LABL hypothesis. In Experiment 2, the only interference found for low-frequency targets approached significance in the 0-bigram condition. In contrast, the results of Experiment 3 revealed interference for low-frequency targets in the 2- and 4-bigram anagram conditions. No hint of interference was found in the 0-bigram condition. If there is any validity to the LABL hypothesis, interference should not be found in the 2- and 4-bigram anagram conditions unless interference is also found in the 0-bigram anagram condition. Thus the lack of interference in the 0-bigram anagram condition is puzzling.

One possibility is that some characteristic of the primes in the low-frequency, 0-bigram condition makes it difficult to find interference. This may, in fact, have been the case. It just happens that in this experiment the primes used in the low-frequency, 0-bigram condition were more wordlike (they had more neighbors) than the primes used in the 2- and 4-bigram conditions as shown in Table 5. According to the competition model (Morris et al., 2009), nonword primes that are more wordlike are better encoded and would compete more with the target. This difference in encoding is evident by slower response times in the control conditions for the 0-bigram condition than in the 2- and 4-bigram conditions. When responses in the control condition are slower, there is less opportunity to observe interference. This may be why anagram interference was absent in the low-frequency, 0-bigram condition.

In addition to the absence of interference in the 0-bigram anagram condition, the fact that interference was present for low-frequency targets but not high-frequency targets is puzzling. According to the LABL hypothesis, removing a letter from the prime should reduce the potential for anagram interference no matter the word frequency of the target. The competition model (Morris et al., 2009) has the potential to explain why interference is found for low-frequency words in Experiment 3 while interference was found for high-frequency words in Experiment 2. According to the competition model, primes with fewer letters are better encoded than primes with more letters, thus they are more likely to interfere with target processing. What this means for low-frequency targets is that interference can be found in the anagram conditions (Figure 8, Point A) and that interference may be “missing” from the high-frequency target conditions because the primes have passed the point at which they interfere with the target (Figure 8, Point B).

Although the anagram interference that was found for low-frequency targets was unexpected, there was one expected finding. Significant facilitation was observed for both high- and low-frequency targets when they were preceded by “neighbor” partial-word primes. The results of Experiment 3, for the most part, are consistent with the proposal that interference emerges when letters shared between the prime and target appear in different positions, while bigrams shared between the prime and target lead to facilitation. Although the LABL hypothesis in its current form does not explain the entirety of the data, its explanatory power is greater than that of current models of word recognition.

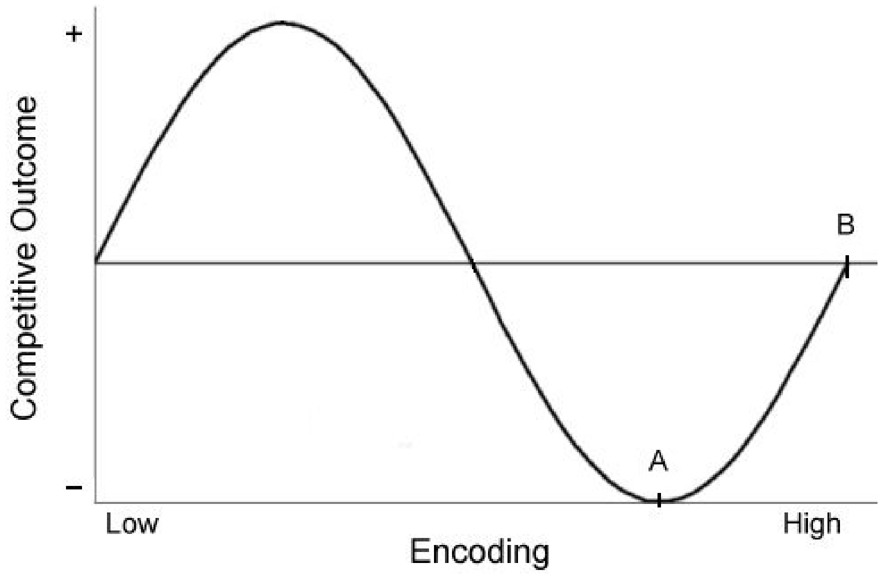

Figure 8. Point A represents an estimate of the encoding of low-frequency targets in anagram conditions in Experiment 3. Point B represents an estimate of the encoding of high-frequency targets in anagram conditions in Experiment 3.

CHAPTER 5. GENERAL DISCUSSION

The primary goal of this investigation was to replicate and extend Still and Morris' (2008) finding of interference for word targets preceded by masked nonword anagram primes. This was accomplished in both Experiments 2 and 3. In combination with the findings of Still and Morris, the present investigation has revealed several characteristics of anagram interference: anagram interference can occur in shorter (four-letter) and longer (six-letter) words; anagram interference is not limited to the 0-bigram anagram (mirror) condition; anagram interference can be found using partial-word primes (e.g., *lspcm – CLAMPS*); and anagram interference is modulated by prime exposure duration and target word frequency. Thus, the anagram interference is robust and should be considered by researchers who model word recognition or orthographic priming effects.

Another goal of this investigation was to gain some insight as to why interference from nonword anagrams has not been observed before as several studies have used nonword anagram primes. There are several differences between the current study and previous studies. Differences include whether or not partial-word primes were used, prime length, target length, target word frequency, and the number of bigrams shared between the prime and target (see Table 8). The characteristics of the experiments listed in Table 8 provide some indication as to why anagram interference has not been reported previously. First, the experiments generally used longer-length target stimuli with shorter prime exposure durations. The results of the present experiments and the data obtained by Still and Morris suggest that if short prime exposure durations are used, anagram interference is more likely to occur for short words than for long words. However, anagram interference can be found with longer-length word targets if a longer prime exposure duration is used (e.g., 70 ms).

Second, two of the experiments listed in Table 8 used partial-word primes that contained only four letters of the six or seven letters in the target. When fewer letters are present in the prime, the possibility to find anagram interference is likely reduced. Third, each anagram condition in the previous studies preserved some relative letter positions; this is apparent by the fact that at least one bigram was always shared between the prime and target.[10] Facilitation from shared bigrams could have offset any interference from shared letters appearing in the wrong positions.

Finally, as can be seen in Table 8 previous experiments did not investigate the effects of target word frequency, although there was a tendency to use low-frequency targets. In the present experiments the mean frequency for low-frequency targets was ten per million, while the mean frequency for high-frequency targets was 150 per million. Clear differences were found between low- and high-frequency targets with anagram interference occurring for high-frequency targets but not low-frequency targets in Experiment 2 and with more interference appearing in low-frequency targets than high-frequency targets in Experiment 3. The absence of significant interference in previous experiments may stem from the failure to manipulate word frequency. Based on the results of the present experiments, the optimal situation for obtaining anagram interference with longer length targets would include using high-frequency targets and longer prime exposure durations. Also, the present results indicate that when interference is found for high-frequency targets, for example, a null effect was found for low-frequency words. If frequency is not well controlled, the effects could be

[10] One exception appears to be Guerrara and Forster's (2008) 43218765 anagram condition. It does not preserve any bigrams as defined by Schoonbaert and Grainger (2004), but several letters do appear in the correct relative position (e.g., letters four and eight in the 43218765 prime condition)

obscured as interference may only occur for a subset of the stimuli. In short, there are several possible explanations for why anagram interference has not been found previously.

Table 8

"Scrambled" Primes used in Previous Experiments

		Target		Prime		
Article	Experiment	Length	Frequency	Duration in ms	Letter Order	Shared Bigrams
Peressotti & Grainger (1999)	3a	6	NA	33	1346	5
					6341	1
					1436	4
Grainger et al. (2006)	1b	7	7-175	50	1-543-7	2
					7-345-1	3
	6	7	*M* = 29	33	1537	2
					7351	1
				83	1537	2
					7351	1
Guerrera & Forster (2008)	1a,1b	8	*M* = 34	40	13254768	12
					21345687	14
	2	8	*M* = 28	40	13254768	12
					12436587	13
					21436578	13
	3	8	*M* = 34	40	13254768	12
					21436587	13
					43218765	0

Note. Recent experiments that failed to find interference from nonword anagram primes. In Grainger et al. (2006, Experiment 6) the prime was not preceded by a pattern mask. Frequency measures are per million.

The LABL Hypothesis

Still and Morris' (2008) LABL hypothesis was intended to provide an explanation for how interference emerges in mirror (0-bigram) anagrams but not in another anagram condition in which some bigrams were shared between the prime and target. It was proposed that interference from letters appearing in different positions in the prime and target could be offset by facilitation that occurs when primes and targets share bigrams. In this regard, testing the LABL hypothesis was straightforward; the hypothesis would be supported if additional evidence of a tradeoff between interference and facilitation was found in the present experiments, and the hypothesis would be disconfirmed if no evidence of a tradeoff was found.

In general, the results from the present experiments support the LABL hypothesis, but the results also show that the LABL hypothesis was underspecified. The hypothesis predicts that targets preceded by anagram primes that share few bigrams (e.g., 0-bigram, 2-bigram, 4-bigram) with the target should result in interference, while anagram primes sharing more bigrams (8-bigram and neighbors) with the target should result in facilitation. The combination of the results of both Experiments 1 and 2 support these predictions, but there is substantially less support for the LABL hypothesis if the results of either experiment are examined in isolation. In Experiment 1, facilitation was found in the 8-bigram and neighbor conditions for low-frequency targets. Interference was found in Experiment 2 for high-frequency targets in the 0- and 4-bigram anagram conditions. No interference was found in Experiment 1, and no facilitation was found for the 8-bigram anagram condition in Experiment 2. What these results suggest is that prime exposure duration affects the likelihood of observing facilitation or interference with facilitation emerging with brief prime exposure durations and interference emerging only with longer prime exposure durations. The implication is that facilitation and interference follow different time courses. Thus, the only way the LABL hypothesis could account for these data is by assuming that either facilitation emerges faster than interference or that the relative strengths of facilitation and interference change with prime exposure duration (e.g., facilitation is stronger than interference early on, but decreases with increased prime exposure duration).

A second finding that challenges the LABL hypothesis is how target word frequency influences interference and how that influence changes over time. Across Experiments 1 and 2 low-frequency targets generally yielded facilitation while high-frequency targets generally yielded interference. It is possible that the LABL hypothesis could be modified to account for the frequency results of Experiments 1 and 2. Using an explanation put forth in the introduction, perhaps the slower response to low-frequency words (in comparison to high-frequency words) allows them to benefit more from facilitation. In addition, because low-frequency words are responded to more slowly, it would be more difficult to demonstrate interference with them. In contrast, high-frequency words are responded to more quickly, so facilitation is more difficult to detect, while interference is easier to detect. While these additional assumptions would allow the LABL hypothesis to describe the majority of the data, they do not explain all of the results in Experiment 3.

The LABL hypothesis predicts that interference should be weaker when one letter is removed from the prime. This prediction holds for the high-frequency targets, as interference only approached significance in the 0-bigram condition and was not significant in the 2- or 4-bigram anagram conditions (recall that interference for both 0- and 4-bigram conditions was significant in Experiment 2). The problematic results are those for low-frequency targets, as interference was found in both the 2- and 4-bigram anagram conditions (in Experiment 2, interference for the 0-bigram anagram condition only approached significance). From these results it appears that removing one letter from the prime either increased the interference or decreased the facilitation for low-frequency words. In either case, the results cannot be accounted for by the LABL hypothesis alone. This is not surprising as the purpose of the LABL hypothesis was simply to suggest the presence of two influences on orthographic priming effects. At this point what should be considered is how the present data and the LABL hypothesis could be used to inform explanations of word recognition and masked orthographic priming.

A Word Recognition Framework Explanation

The finding of nonword anagram interference cannot be explained by any current models of word recognition. Interference is expected with word primes, not nonword primes. One question is whether or not current models could be adapted to account for anagram interference. Apart from the letter position coding scheme, most models of word recognition make predictions that are quite similar to those of the IA model. The predictions are similar because most models make similar assumptions about lexical inhibition and word frequency. Therefore, discussion of how models of word recognition might be modified to account for these data is presented in terms of a generic word recognition model.

Explaining interference for nonwords is difficult. There are at least two ways this might be accomplished. One method involves modifying the criteria for lexical inhibition; the other method involves assuming qualitatively different contributions of individual letters and of bigrams to word recognition. In either case, the modification must be able to account for anagram interference *and* relative position priming effects.

Several modifications would be necessary to explain how lexical inhibition could be responsible for anagram interference. The inhibitory connections between lexical units act as a “clean up” mechanism allowing for faster settling times. In the original IA model an activated word representation inhibits all other word representations (McClelland & Rumelhart, 1981), but in subsequent versions of the model selective inhibition has been used as it produces better model fits. In particular, Davis and Lupker (2006) suggested that inhibition should be restricted to word representations sharing at least one letter in the same position with the input string. A possible modification would be to increase the scope of lexical inhibition so that an activated word representation would inhibit more word representations. This could be done by implementing a system in which words sharing letters in any position with the input string are inhibited. If it were also assumed that word representations of any length inhibit one another, activation of a single word representation would have the potential to inhibit many word representations. With this assumption even 0-bigram anagram primes would likely activate word representations that would compete with the target for recognition. For example, any anagram of the target *THRONE* would activate, at minimum, the following competitors: *ton*, *horn*, *tone*, *one*, *north*, *ore*, *thorn*, *ten*, *hen*, *rent*, *note*, *enthrone*. The inhibition of these “subset” and “superset” words could be seen as an extension of Bowers, Davis, and Hanley’s (2005) finding that interference can occur for words that are subsets (e.g., participants are slower to reject *drama* as a type of animal) or supersets (e.g., participants are slower to reject *seep* as a type of animal) of one another.

Simply modifying the selective inhibition criterion may be insufficient to explain both anagram interference and facilitation typically found with orthographically similar nonword primes. In the IA model, the inhibitory mechanism acts based on the overall activation of the word representation so that when one representation is active it sends inhibition proportionate to its own activation level. The activated word representations send inhibition to all other word representations whose activation levels are greater than zero (McClelland & Rumelhart, 1981). In order for *both* lexical inhibition and facilitation from shared bigrams to be implemented, separate word representations would be required. This could be done by creating two parallel systems, with one responsible for facilitation and the other responsible for inhibition. The "inhibition system" would require at least three levels – feature, letter, and lexical – with the letter level containing position-independent letter representations. Both systems would work in parallel with the output of the word recognition system consisting of the sum of the activation levels of the word representations in the inhibition and facilitation systems (see Figure 9 for the general architecture of this proposed modification).

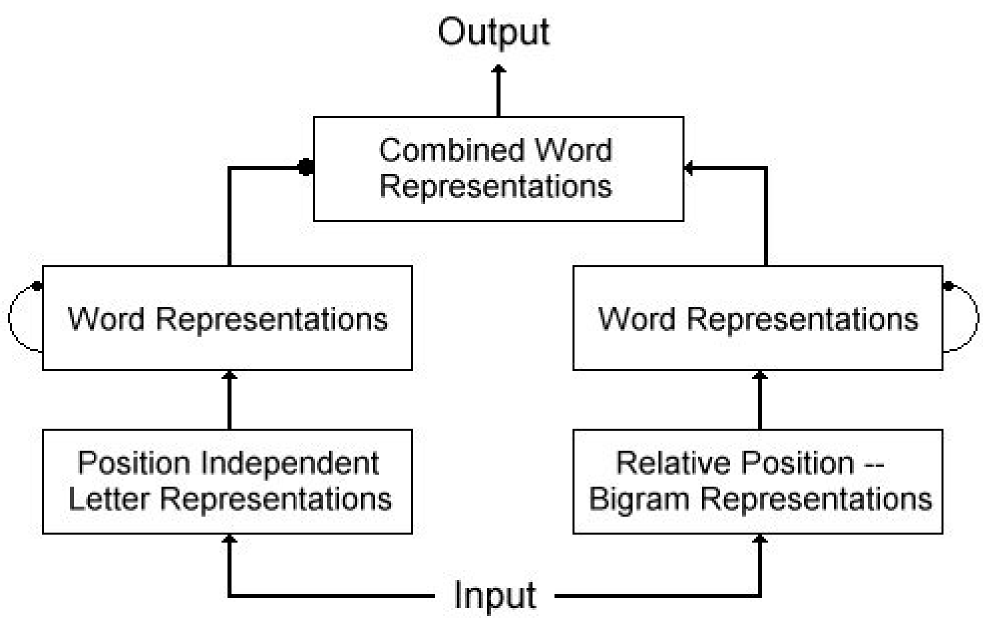

Figure 9. Generic model of word recognition with modifications to the lexical inhibition criterion. Arrows indicate activation passing from one level to the next. Lines with circle terminators indicate the presence of inhibitory connections.

A second option for accounting for anagram interference would be to assume that both individual letters and bigrams have direct influence on the activation levels of the same word representations. In the previous option it was suggested that letter representations would be position independent. In contrast, the present option would use position-specific letter representations which inhibit word representations that contain the same letters as the input string when those letters appear in the wrong position. For example, the *e* in *enorht* would inhibit *throne* and any other word containing an *e* in a position other than the first position. This type of inhibition could be implemented by assuming that when a letter appears in a specific position, the activation level of that position-specific letter representation will be higher than that of the same letter representation in another position (e.g., for the prime *enorht* the *e* in position one has higher activation than the *e* in position two or three) and that inhibitory connections exist between letter positions (e.g., inhibitory connections exist between the *e* in position one and the *e* in position two, between the *e* in position one and the *e* in position three, etc.). The inhibition of lexical representations from position-specific letter representations and the facilitation from the already implemented bigram/relative position coding system would both contribute to the activation level of word representations (see Figure 10 for the general architecture of this proposed modification).

Whichever way anagram interference is accounted for, word recognition models would have to include some explanation for how facilitation and interference change over time or with various prime exposure durations. One way to implement this might be to assume that it takes more time (or takes more accumulated activation) for letter or word units to inhibit one another than for sublexical units to activate word representations. With these assumptions facilitation would tend to emerge earlier, or with shorter prime exposure durations, than interference.

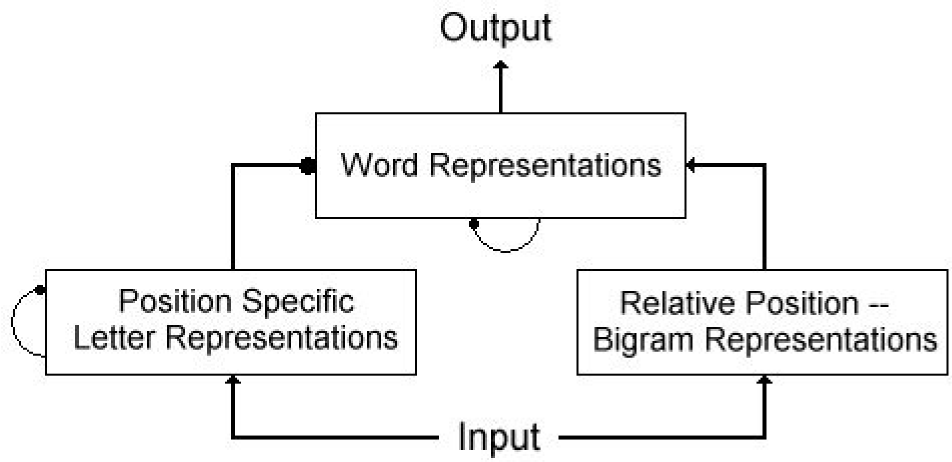

Figure 10. Generic model of word recognition with the primary modification being the addition of position-specific letter representations. Arrows indicate activation passing from one level to the next. Lines with circle terminators indicate the presence of inhibitory connections.

Even with these substantial modifications, word recognition models would have difficulty explaining the way in which interference was modulated by target word frequency in Experiments 2 and 3. A general approach to modeling word frequency is to implement a higher resting level of activation for high-frequency words and a lower resting level of activation for low-frequency words. Because inhibitory effects are tied to the activation level of a word representation, higher-frequency words tend to inhibit lower-frequency words, but lower-frequency words only weakly inhibit higher-frequency words. What this means is that interference should be found less often for high-frequency words than for low-frequency words. This was true in Experiment 3, but not in Experiment 2. It is not clear what modifications could account for these word frequency effects. The only way to know if the proposed modifications could account for these data is by running a full simulation.

Competitive Interactions between Primes and Targets

It is possible that, with some modifications, the competition model could provide an adequate explanation of the entire pattern of results reported in this dissertation. Before getting to the specific modifications, additional discussion of encoding effects in the competition model is warranted. Recall that encoding refers to the accuracy and/or speed with which an individual item is processed and encoding is modeled by signal-to-noise ratio in the representation (e.g., poorly encoded items have a lower signal-to-noise ratio than items that are better encoded). Characteristics of items that are poorly encoded include those with nonword lexical status, that have short exposure durations, that are low-frequency (in comparison to high-frequency words), and have low-density neighborhoods (Morris et al., 2009; Morris & Still, 2008; Still & Morris, 2007). A poorly-encoded item generally competes less effectively for access to awareness than a well-encoded item.

When a prime and target are orthographically similar, the outcome (i.e., facilitation or interference) depends, in part, on how well the prime is encoded. A poorly-encoded prime competes minimally with the target for access to awareness, but the target still benefits from an increased signal-to-noise ratio. The result is that recognition of the target is facilitated (see Figure 11, Point A). When a prime is better encoded it competes more effectively with the target, but now the reduction in total activation that accompanies the increased signal-to-noise ratio hinders recognition of the target. The result is that recognition of the orthographically similar target is slowed (see Figure 11, Point C). Figure 11 depicts a function that represents the difference between the outcome of the competition for an orthographically similar prime and target and a control prime and target. From this function, one can see how facilitation for a target can become interference if the encoding of the prime or target is increased. This function will be used as an aid for describing how the variables investigated in the present experiments could be conceptualized as encoding effects within the competition model.

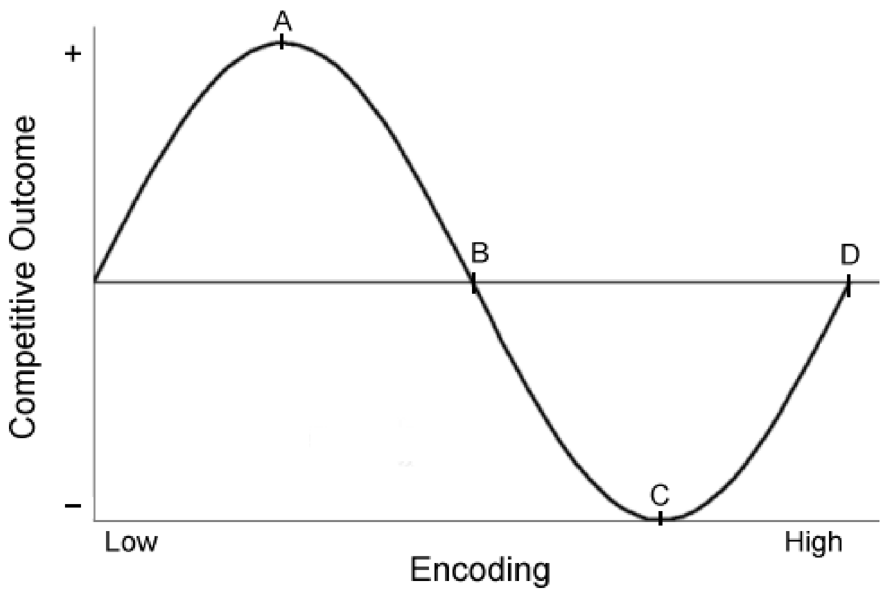

Figure 11. Generic function depicting the outcome of a competitive interaction between a prime and a target as proposed by the competition model.

The competition model was designed specifically to predict the outcome of competitive interactions between items presented in close temporal proximity, but one challenge to applying the competition model to word recognition research is that it makes very basic assumptions about letter position coding. As mentioned previously, the original implementation of the model used position-independent letter representations. Based on the present results and those of Still and Morris (2008) it could be argued that two sublexical units – one that is position independent and one that is based on bigrams or relative letter positions – should be used conjointly to compute orthographic similarity in the competition model. Thus one modification to the competition model would be to add a bigram level of representation. Unlike the modifications suggested for word recognition models or the LABL hypothesis, the two "systems" of letter position coding used in the competition model would operate under similar assumptions – i.e., it would not be assumed that the position-independent system is responsible for interference while the bigram system is responsible for facilitation. An encoding assumption would be made in which individual letters are encoded better than bigrams. The representations for individual letters are so well encoded that even with short prime exposure durations (e.g., 35 ms in Experiment 1) interference is obtained. In order to obtain facilitation with this letter coding system, prime exposure durations would have to be shorter than they are in Experiment 1. In contrast, bigrams are more poorly encoded. What this means is that with the prime exposure durations used in the present experiments, orthographic similarity in the bigram system tends to lead to facilitation. Based on this encoding assumption, it should be possible to find interference from shared bigrams between the prime and target if encoding of the bigrams was improved. This could be conceptualized as moving from Point A to Point C on Figure 11.

Encoding differences can also be used to describe how orthographic priming effects are modulated by prime exposure duration and target word frequency. Primes with shorter exposure durations (e.g., Experiment 1) compete less effectively against the target; thus, responses to orthographically similar targets will tend to be facilitated. When exposure durations are longer (e.g., Experiments 2 and 3) the prime competes more with the target allowing the opportunity for interference to emerge. Encoding differences in the target also affect the outcome of the competition. High-frequency words are better encoded than low-frequency words. In terms of the general function in Figure 11, high-frequency words would be further right on the continuum than low-frequency words. For example, in Experiment 1 low-frequency words might be near Point A in Figure 11 while high-frequency words might be near Point B. In Experiment 2, the outcome for low-frequency targets would be near Point B and for high-frequency targets would be near Point C. This illustrates how, at times, responses to lower-frequency words tend to be facilitated (e.g., Experiment 1) while responses to higher-frequency words tend to be interfered with (e.g., Experiment 2).

The explanation for the results of Experiment 3 is more complex. The prime exposure duration and the targets were the same in Experiments 2 and 3, but interference was limited to high-frequency targets in Experiment 2 and to low-frequency targets in Experiment 3. First, one must consider what happens when one letter is removed from the prime. According to the LABL hypothesis, interference should be reduced when one letter is removed. But, according to the competition model, encoding is affected by the length of the letter string, with shorter-length letter strings being better encoded than longer-length letter strings (Morris & Still, 2009). By removing one letter from the prime in Experiment 3, the prime is better encoded and interferes with the target as illustrated in Figure 11 by moving further to the right on the encoding continuum. Notice that when encoding increases to a certain point the magnitude of interference subsides. Thus with the increased encoding of the prime it is possible that the high-frequency targets have passed the point at which they demonstrate significant interference (Figure 11, Point D), but low-frequency targets have just reached a point at which they can demonstrate interference (Figure 11, Point C). As is apparent from this description of the competition model, competitive interactions between items are based on a number of characteristics; therefore, only a full simulation of the model would indicate whether or not these suggested modifications could account for the present data. Despite the inherent complexity of the interactions present in the competition model, it should be noted that only one primary assumption of the competition model – letter position coding – would need to be changed to potentially account for these data.

Feasibility of Anagram Interference

The goal of this research was to further investigate a surprising finding of anagram interference. Not only had the effect never been reported before, it was not predicted by any model of word recognition. It is likely that the effect was not reported before because there was no *a priori* reason to suspect that a nonword anagram would interfere with processing of a word target. Therefore one might ask why a system solely designed to recognize words would seemingly prioritize a nonword over a word. But there are alternative ways to conceptualize the issue. Perhaps interference is a byproduct of a type of "clean up" in the word recognition system that is meant to reduce noise. In current models of word recognition, interference emerges from the inhibitory connections between word representations. Those inhibitory connections increase the efficiency of the word recognition system by leading to faster selection in the model. If the proposed lexical inhibition modifications were implemented for models of word recognition so that anagrams inhibited many word representations, anagram interference would follow naturally from the mechanisms responsible for efficient word recognition.

A similar explanation is that anagram interference is indicative of a mechanism meant to eliminate improbable candidate word representations that may have been activated during an earlier stage of word recognition. One possibility is that the bigram/facilitatory system works to rapidly activate multiple target candidates, while the letter/inhibitory system works to eliminate candidates whose letters appear in the wrong positions. This type of explanation could be consistent with the observation that early word recognition processes appear to be less sensitive to absolute letter position than later stages in the recognition process (e.g., Grainger et al., 2006; Kinoshita & Norris, 2009). The implication of this type of system would be that word recognition involves a tradeoff between speed and accuracy. The benefits of a faster system that activates multiple word candidates, many of which will have to be inhibited, may outweigh the cost of a slower, more accurate system.

The competition model explanation for the existence of anagram interference is quite different. In the model, interference is a byproduct of competitive interactions between items. Any item, or in this case sublexical unit, that is well encoded will be more likely to result in interference than if it were poorly encoded. Therefore the apparent difference between processing of letters and bigrams could simply be a difference in encoding. Encoding differences would likely be related to the fact that letters are smaller units than bigrams and individual letters are, by necessity, encountered more often than bigrams. In short, no matter which of the three explanations is adopted, some explanation could be found for why anagram interference can be obtained.

Related to the question of the utility of anagram interference, is the issue of what sublexical code(s) is responsible for word recognition. Most models of word recognition propose the existence of multiple sublexical units, with only one of the sublexical units (e.g., bigram or individual letter) having direct influence on the activation of word representations. In contrast, the results of the present experiments have been interpreted as if two sublexical representations have direct influence on the activation of word representations. Whether one sublexical representation or two are used in word recognition is an empirical question. At present, it is unclear how anagram interference and previous orthographic priming findings could be accounted for *without* the influence of two sublexical units on word representations.

Reading and the Time Course of Facilitation and Interference

A final consideration is how masked orthographic priming results relate to reading. On the one hand reading is much different from masked orthographic priming, with the most obvious difference being that many words have to be recognized during reading, but only one word has to be recognized during orthographic priming. On the other hand, both reading and masked orthographic priming require words to be recognized. A large body of relevant reading research has come from eye movement studies. In these paradigms, participants' eye movements are tracked with the assumption that participants will fixate longer on or make more regressions (look back) to a word when processing is difficult (Rayner, 1998). The studies most comparable to masked orthographic priming use the boundary technique (Rayner, 1975) whereby one item in the sentence (preview) is replaced with another word (the target) before the reader fixates on it. The replacement occurs during a saccade so that the reader does not perceive the change. This design allows researchers to investigate what kind of processing occurs for a word before it is fixated – referred to as parafoveal preview – by observing participant responses to the target.

One eye movement experiment is of particular relevance to the present finding that facilitation emerges earlier than interference. Williams, Perea, Pollatsek, and Rayner (2006) investigated the influence of neighbor frequency on eye movements. The target was a low-frequency word (e.g., *sleet*) and it was replaced by a higher-frequency neighbor (e.g., *sweet*), by a nonword neighbor (e.g., *speet*) or by itself (this was essentially a condition where no replacement was made). Results indicated that fixation durations when the target was previewed by a higher-frequency word were statistically indistinguishable from when the target was previewed by itself. This result was unexpected. Models of word recognition predict that lower-frequency words are inhibited by higher-frequency word neighbors. What the eye movement results indicate is that the inhibitory processes that occur during word recognition may be inoperative during parafoveal preview. Williams et al. summarized the implications of these results by suggesting that processing of words involves two processes, an early stage (parafoveal preview) that encodes letter identities and activates word representations, and a later stage (fixation) in which lexical inhibition occurs.

The Williams et al. (2006) suggestion that facilitation emerges earlier than interference parallels the findings in the present experiment in which facilitation was obtained with short prime exposure durations and interference was obtained with longer prime exposure durations. One suggested explanation for the feasibility of anagram interference was that the word recognition system first activates several candidate words and then eliminates candidates if the letters appear in the wrong positions. A word recognition system operating under those assumptions would be similar to Williams et al.'s two-stage explanation. Thus, the eye movement literature provides converging evidence suggesting the operation of two systems in word recognition. Additional research is needed to examine whether or not facilitation is observed when the parafoveal preview is a nonword anagram; this would test the assumption that no inhibition occurs during parafoveal preview.

Conclusions

Still and Morris' (2008) finding that nonword anagram primes can interfere with target word processing was unexpected. The present experiments replicated and extended that finding. It was demonstrated that interference from anagrams can be found in shorter- and longer-length words; the effects vary by target word frequency, prime exposure duration, and prime length; interference is not limited to one type of anagram, but can be found in 0-, 2-, and 4-bigram anagrams. In most models of word recognition, the only source of interference is inhibition between word representations. Thus, models of word recognition have difficulty explaining how a nonword prime – that is not very wordlike – comes to inhibit a word representation. In addition to replicating and extending the anagram interference finding, this investigation revealed that in masked orthographic priming, facilitation was more likely to be observed with short (e.g., 35 ms) prime exposure durations while interference emerges with longer prime exposure durations (e.g., 70 ms). Finally, the pattern of facilitation and interference across the three experiments suggests that at least two sublexical representations are involved in word recognition. Further research is needed to determine the nature of these sublexical units and to determine whether or not current word recognition models can account for anagram interference.

APPENDIX A. WORD TARGET STIMULI USED IN EXPERIMENTS 1 AND 2

Targets	Prime Type				Targets	Prime Type			
Low Freq	0-Bigram	4-Bigram	8-Bigram	Neighbor	High Freq	0-Bigram	4-Bigram	8-Bigram	Neighbor
1 crowds	sdworc	wscdor	rcwosd	crolds	1 claims	smialc	iscmal	lciasm	cleims
1 knight	thgink	gtkhin	nkgith	knught	1 fourth	htruof	rhftuo	ofruht	foudth
2 blonde	ednolb	nebdol	lbnoed	blonfe	2 fields	sdleif	lsfdei	iflesd	fiulds
2 script	tpircs	itsprc	csirtp	scrupt	2 growth	htworg	whgtor	rgwoht	grodth
3 plunge	egnulp	nepgul	lpnueg	plufge	3 bridge	egdirb	debgir	rbdieg	brikge
3 charts	strahc	rsctah	hcrast	chirts	3 months	shtnom	tsmhno	omtnsh	munths
4 towers	srewot	estrwo	otewsr	tojers	4 points	stniop	nsptio	opnist	poikts
4 launch	hcnual	nhlcua	alnuhc	laumch	4 charge	egrahc	recgah	hcraeg	charde
5 guards	sdraug	rsgdau	ugrasd	guamds	5 friend	dneirf	edfnir	rfeidn	frield
5 client	tneilc	etcnil	lceitn	cloent	5 bought	thguob	gtbhuo	obguth	boaght
6 clamps	spmalc	mscpal	lcmasp	clamds	6 should	dluohs	udsloh	hsuodl	scould
6 throne	enorht	oetnrh	htoren	thione	6 breath	htaerb	ahbter	rbaeht	breaph
7 knives	sevink	vskein	nkvise	kniles	7 struck	kcurts	ukscrt	tsurkc	stwuck
7 coward	drawoc	adcrwo	ocawdr	cozard	7 joined	denioj	ndjeio	ojnide	joibed
8 lounge	egnuol	nelguo	olnueg	lounte	8 spring	gnirps	igsnrp	psirgn	sprihg
8 bricks	skcirb	csbkir	rbcisk	bwicks	8 talked	deklat	kdtela	atklde	tolked
9 flavor	rovalf	vrfoal	lfvaro	flivor	9 myself	flesym	efmlsy	ymesfl	mywelf
9 bucket	tekcub	ktbecu	ubkcte	bunket	9 action	noitca	inaotc	caitno	astion
10 jungle	elgnuj	gejlnu	ujgnel	junzle	10 county	ytnuoc	nyctuo	ocnuyt	coanty
10 format	tamrof	mtfaro	ofmrta	forbat	10 simple	elpmis	peslmi	ispmel	simdle
11 bishop	pohsib	hpbosi	ibhspo	bithop	11 factor	rotcaf	trfoca	aftcro	fuctor
11 cradle	eldarc	declar	rcdael	cravle	11 single	elgnis	geslni	isgnel	sidgle
12 typing	gnipyt	igtnpy	ytipgn	tyding	12 moving	gnivom	igmnvo	omivgn	mocing
12 locker	rekcol	krleco	olkcre	lohker	12 beauty	ytuaeb	uybtae	ebuayt	beaupy
13 hotels	sletoh	eshlto	ohetsl	hutels	13 father	rehtaf	hrfeta	afhtre	fabher
13 fabric	cirbaf	rcfiba	afrbci	fapric	13 column	nmuloc	uncmlo	oculnm	codumn
14 guitar	ratiug	trgaiu	ugtira	guiwar	14 sunday	yadnus	dysanu	usdnya	sunkay
14 dozens	snezod	esdnzo	odezsn	dolens	14 permit	timrep	mtpire	epmrti	perfit
15 turkey	yekrut	kyteru	utkrye	turpey	15 island	dnalsi	adinls	sialdn	islamd
15 finals	slanif	asflni	ifansl	fonals	15 poetry	yrteop	typreo	opteyr	poegry
16 walnut	tunlaw	ntwula	awnltu	wolnut	16 making	gnikam	igmnka	amikgn	muking
16 prizes	sezirp	zspeir	rpzise	phizes	16 theory	yroeht	oytreh	htoeyr	theoly
17 clergy	ygrelc	rycgel	lcreyg	clerpy	17 trying	gniyrt	igtnyr	rtiygn	tryang
17 domain	niamod	andimo	odamni	dotain	17 volume	emulov	uevmlo	ovulem	vobume
18 fluids	sdiulf	isfdul	lfiusd	fluigs	18 taking	gnikat	igtnka	atikgn	tyking
18 export	tropxe	oterpx	xeoptr	ebport	18 couple	elpuoc	pecluo	ocpuel	coudle

Note. The numbers indicate which items were yoked to create control conditions (e.g., *sdworc* was the 0-Bigram control for *KNIGHT*). Targets appeared in uppercase in the experiments.

Targets	Prime Type				Targets	Prime Type			
Low Freq	0-Bigram	4-Bigram	8-Bigram	Neighbor	High Freq	0-Bigram	4-Bigram	8-Bigram	Neighbor
19 voyage	egayov	aevgyo	ovayeg	vobage	19 coming	gnimoc	igcnmo	ocimgn	cyming
19 insult	tlusni	utilsn	niustl	indult	19 values	seulav	usvela	avulse	vadues
20 spiral	larips	rlsaip	psrila	spigal	20 acting	gnitca	igantc	caitgn	akting
20 monkey	yeknom	kymeno	omknye	motkey	20 double	elbuod	bedluo	odbuel	dousle
21 tubing	gnibut	igtnbu	utibgn	tufing	21 symbol	lobmys	blsomy	ysbmlo	sumbol
21 makers	srekam	esmrka	ameksr	mahers	21 advice	ecivda	ieacvd	daivec	adwice
22 sodium	muidos	imsudo	osidmu	sonium	22 almost	tsomla	otasml	laomts	alvost
22 gravel	levarg	vlgear	rgvale	grafel	22 figure	erugif	uefrgi	ifuger	fipure
23 boxcar	racxob	crbaxo	obcxra	boxtar	23 around	dnuora	udanor	rauodn	aroynd
23 sewing	gniwes	igsnwe	esiwgn	sewung	23 itself	flesti	efilst	tiesfl	itgelf
24 denial	lained	ildane	edinla	desial	24 method	dohtem	hdmote	emhtdo	mechod
24 trophy	yhport	pythor	rtpoyh	truphy	24 asking	gniksa	iganks	saikgn	alking
25 debris	sirbed	rsdibe	edrbsi	detris	25 impact	tcapmi	aticpm	miaptc	imsact
25 layout	tuoyal	otluya	aloytu	lavout	25 broken	nekorb	knbeor	rbkone	bruken
26 jockey	yekcoj	kyjeco	ojkcye	jocley	26 budget	tegdub	gtbedu	ubgdte	budgit
26 unfair	riafnu	aruifn	nuafri	umfair	26 normal	lamron	mlnaro	onmrla	nosmal
27 topics	scipot	istcpo	otipsc	tapics	27 travel	levart	vltear	rtvale	trapel
27 bundle	eldnub	deblnu	ubdnel	buhdle	27 cousin	nisuoc	snciuo	ocsuni	couwin
28 python	nohtyp	hnpoty	yphtno	pyghon	28 during	gnirud	igdnru	udirgn	durong
28 serial	laires	ilsare	esirla	sepial	28 places	secalp	cspeal	lpcase	ptaces
29 judges	segduj	gsjedu	ujgdse	judbes	29 forest	tserof	etfsro	oferts	forast
29 anchor	rohcna	hraocn	nahcro	alchor	29 public	cilbup	lcpibu	uplbci	punlic
30 coping	gnipoc	igcnpo	ocipgn	copung	30 social	laicos	ilsaco	osicla	sogial
30 metals	slatem	asmlte	ematsl	metyls	30 number	rebmun	brnemu	unbmre	nohber
31 kidney	yendik	nykedi	ikndye	kidpey	31 signal	langis	nlsagi	isngla	sigmal
31 mortal	latrom	tlmaro	omtrla	murtal	31 object	tcejbo	etocjb	boejtc	obfect
32 mating	gnitam	igmnta	amitgn	matung	32 junior	roinuj	irjonu	ujinro	juzior
32 shovel	levohs	vlseoh	hsvole	swovel	32 sample	elpmas	peslma	aspmel	samgle

Note. The numbers indicate which items were yoked to create control conditions (e.g., *sdworc* was the 0-Bigram control for *KNIGHT*). Targets appeared in uppercase in the experiments.

APPENDIX B. WORD TARGET STIMULI USED IN EXPERIMENT 3

Targets	Prime Type				Targets	Prime Type			
Low Freq	0-bigram	2-bigram	4-bigram	"Neighbor"	High Freq	0-bigram	2-bigram	4-bigram	"Neighbor"
1 crowds	sdwrc	rsdcw	dcsrw	crwds	1 claims	smilc	lsmci	mcsli	clims
1 knight	thgnk	nthkg	hktng	knght	1 ground	dnurg	rdngu	ngdru	grund
2 blonde	ednlb	ledbn	dbeln	blnde	2 fields	sdlif	isdfl	dfsil	filds
2 script	tpics	ctpsi	pstci	scipt	2 growth	htwrg	rhtgw	tghrw	grwth
3 plunge	egnlp	legpn	gpeln	plnge	3 plants	stnlp	lstpn	tpsln	plnts
3 charts	strhc	hstcr	tcshr	chrts	3 bridge	egdrb	regbd	gberd	brdge
4 towers	sreot	osrte	rtsoe	toers	4 points	stnop	ostpn	tpson	ponts
4 launch	hcnal	ahcln	clhan	lanch	4 charge	egrhc	hegcr	gcehr	chrge
5 guards	sdrug	usdgr	dgsur	gurds	5 friend	dnerf	rdnfe	nfdre	frend
5 client	tnelc	ltnce	nctle	clent	5 bought	thgob	othbg	hbtog	boght
6 clamps	spmlc	lspcm	pcslm	clmps	6 should	dluhs	hdlsu	lsdhu	shuld
6 throne	enoht	hento	nteho	thone	6 breath	htarb	rhtba	tbhra	brath
7 knives	sevnk	nsekv	eksnv	knves	7 player	reylp	lrepy	eprly	plyer
7 coward	draoc	odrca	rcdoa	coard	7 things	sgnht	hsgtn	gtshn	thngs
8 lounge	egnol	oegln	gleon	longe	8 course	esroc	oescr	sceor	corse
8 bricks	skcrb	rskbc	kbsrc	brcks	8 flight	thglf	lthfg	hftlg	flght
9 flavor	rovlf	lrofv	ofrlv	flvor	9 myself	fleym	yflme	lmfye	myelf
9 bucket	tekub	utebk	ebtuk	buket	9 action	noica	cnoai	oanci	acion
10 jungle	elguj	ueljg	ljeug	jugle	10 county	ytnoc	oytcn	tcyon	conty
10 format	tamof	otafm	aftom	fomat	10 simple	elpis	ielsp	lseip	siple
11 bishop	pohib	ipobh	obpih	bihop	11 factor	rotaf	aroft	ofrat	fator
11 cradle	eldrc	relcd	lcerd	crdle	11 single	elgis	ielsg	lseig	sigle
12 nudist	tsiun	utsni	sntui	nuist	12 moving	gniom	ognmi	nmgoi	moing
12 locker	rekol	orelk	elrok	loker	12 beauty	ytueb	eytbu	tbyeu	beuty
13 hotels	sleoh	oslhe	lhsoe	hoels	13 father	rehaf	arefh	efrah	faher
13 fabric	ciraf	acifr	ifcar	faric	13 column	nmuoc	onmcu	mcnou	coumn
14 guitar	ratug	uragt	agrut	gutar	14 sunday	yadus	uyasd	asyud	suday
14 dozens	sneod	osnde	ndsoe	doens	14 permit	timep	etipm	iptem	pemit
15 turkey	yekut	uyetk	etyuk	tukey	15 island	dnasi	sdnia	nidsa	isand
15 finals	slaif	islfa	lfsia	fials	15 poetry	yrtop	oyrpt	rpyot	potry
16 walnut	tunaw	atuwn	uwtan	wanut	16 toward	draot	odrta	rtdoa	toard
16 prizes	sezrp	rsepz	epsrz	przes	16 inches	sehni	nseih	eisnh	inhes
17 clergy	ygrlc	lygcr	gcylr	clrgy	17 trying	gnirt	rgnti	ntgri	tring
17 domain	niaod	onida	idnoa	doain	17 volume	emuov	oemvu	mveou	voume
18 fluids	sdilf	lsdfi	dfsli	flids	18 taking	gniat	agnti	ntgai	taing
18 export	troxe	xtreo	retxo	exort	18 couple	elpoc	oelcp	lceop	cople

Note. The numbers indicate which items were yoked to create control conditions (e.g., *sdwrc* was the 0-Bigram control for *KNIGHT*). Targets appeared in uppercase in the experiments.

Targets	Prime Type				Targets	Prime Type			
Low Freq	0-bigram	2-bigram	4-bigram	“Neighbor”	High Freq	0-bigram	2-bigram	4-bigram	“Neighbor”
19 voyage	egaov	oegva	gveoa	voage	19 coming	gnioc	ognci	ncgoi	coing
19 insult	tluni	ntliu	litnu	inult	19 values	seuav	asevu	evsau	vaues
20 spiral	larps	plasr	aslpr	spral	20 theory	yroht	hyrto	rtyho	thory
20 monkey	yekom	oyemk	emyok	mokey	20 fiscal	lacif	ilafc	aflic	fical
21 tubing	gniut	ugnti	ntgui	tuing	21 symbol	lobys	ylosb	oslyb	sybol
21 makers	sream	asrme	rmsae	maers	21 advice	ecida	decai	caedi	adice
22 sodium	muios	omusi	usmoi	soium	22 almost	tsola	ltsao	satlo	alost
22 gravel	levrg	rlegv	eglrv	grvel	22 figure	eruif	ierfu	rfeiu	fiure
23 boxcar	racob	orabc	abroc	bocar	23 around	dnura	rdnau	nadru	arund
23 sewing	gnies	egnsi	nsgei	seing	23 itself	fleti	tflie	lifte	itelf
24 denial	laied	eladi	adlei	deial	24 method	dohem	edomh	omdeh	mehod
24 trophy	yhprt	ryhtp	htyrp	trphy	24 asking	gnisa	sgnai	nagsi	asing
25 riches	sehir	iserh	ersih	rihes	25 impact	tcami	mtcia	citma	imact
25 layout	tuoal	atulo	ultao	laout	25 broken	nekrb	rnebk	ebnrk	brken
26 jockey	yekoj	oyejk	ejyok	jokey	26 budget	tegub	utebg	ebtug	buget
26 unfair	rianu	nriua	iurna	unair	26 normal	lamon	olanm	anlom	nomal
27 topics	sciot	oscti	ctsoi	toics	27 travel	levrt	rletv	etlrv	trvel
27 bundle	eldub	uelbd	lbeud	budle	27 cousin	nisoc	onics	icnos	cosin
28 python	nohyp	ynoph	opnyh	pyhon	28 during	gniud	ugndi	ndgui	duing
28 serial	laies	elasi	aslei	seial	28 places	seclp	lsepc	epslc	plces
29 judges	seguj	usejg	ejsug	juges	29 forest	tseof	otsfe	sftoe	foest
29 anchor	rohna	nroah	oarnh	anhor	29 public	cilup	ucipl	ipcul	pulic
30 shovel	levhs	hlesv	eslhv	shvel	30 social	laios	olasi	asloi	soial
30 wizard	draiw	idrwa	rwdia	wiard	30 number	rebun	urenb	enrub	nuber
31 kidney	yenik	iyekn	ekyin	kiney	31 signal	lanis	ilasn	aslin	sinal
31 mortal	latom	olamt	amlot	motal	31 object	tcebo	btcoe	cotbe	obect
32 lockup	pukol	opulk	ulpok	lokup	32 junior	roiuj	uroji	ojrui	juior
32 adverb	breda	dbrae	rabde	aderb	32 sample	elpas	aelsp	lseap	saple

Note. The numbers indicate which items were yoked to create control conditions (e.g., *sdwrc* was the 0-Bigram control for *KNIGHT*). Targets appeared in uppercase in the experiments.

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