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Transposed Letter Effects in Prefixed Words: Implications for Morphological Decomposition

Kathleen M. Masserang
University of Massachusetts Amherst, katie.masserang@gmail.com

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TRANSPOSED LETTER EFFECTS IN PREFIXED WORDS: IMPLICATIONS FOR MORPHOLOGICAL DECOMPOSITION

A Thesis Presented

by:

KATHLEEN M. MASSERANG

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by
KATHLEEN M. MASSERANG

Approved as to style and content by:

Alexander Pollatsek, Chair

Adrian Staub, Member

Neil E. Berthier, Member

Melinda A. Novak, Department Head
Psychology

ABSTRACT

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KATHLEEN M MASSERANG, B.A. UNIVERSITY OF DETROIT MERCY

M.A. UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Alexander Pollatsek

The nature of morphological decomposition in visual word recognition remains unclear regarding morphemically complex words such as prefixed words. To investigate the decomposition process, the current study examined the extent to which effects involving transposed letters are modulated when the transposed letters cross a morpheme boundary. Previous studies using masked priming have demonstrated that *transposed letter effects* (i.e. superior priming when the prime contains transposed letters than when it contains replacement letters) disappear or markedly decrease when the transposition occurs across a morpheme boundary. The current experiments further investigated transposed letter effects in prefixed words using both parafoveal previews in natural reading and masked priming. There were significant differences between both the correct and transposed letter conditions and the replacement letter condition, but no interaction between the preview effects and type of target word in both the natural reading and masked priming tasks. Thus, unattenuated transposed letter effects can be elicited when the transposition occurs across the morpheme boundary between prefix and root morpheme, indicating that morphemic decomposition is not involved in the early processes of word recognition reflected in parafoveal previews and masked primes.

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CHAPTER I

INTRODUCTION

Morphological decomposition has been identified as an important component of the visual word recognition process. Over the last 10-20 years, there has been a large amount of empirical work on the role of morphological decomposition process; it has been guided by various theory-specific assumptions about fundamental word recognition processes. However, there is still considerable disagreement about when and how the decomposition of a polymorphemic word occurs. Consider the word *misuse*. There are undoubtedly two meaningful units, *mis*-, and *use*, but what is not so obvious, is how these constituents are recognized. Does the reader first recognize the prefix, then the stem, and finally the whole word unit? Alternatively, does the reader first recognize the stem, then the prefix, and finally the whole word unit? A third possibility is that the reader has a separate lexical entry for the whole world unit, and decomposition is unnecessary. Perhaps it is not only one of these possibilities that accomplish recognition, but some combination.

A separate, but complementary, line of research in visual word recognition has investigated transposed letter effects. The *transposed letter effect* is the robust finding that prime or preview of a target word in which two adjacent letters are transposed (e.g., *jugde* as a prime for *judge*) is significantly less disruptive as a than a prime in which the same two letters are replaced by similar letters (e.g., *jukpe*) (Andrews, 1996; Bruner & O’Dowd, 1958; Chambers, 1979; Christianson, Johnson, & Rayner, 2005; Perea & Carreiras, 2006a, 2006b; Perea & Lupker, 2003a, 2003b, 2004; Schoonbaert & Grainger, 2004; Taft & van Graan, 1998). This line of work has resulted in a wealth of critiques of and improvements on visual word recognition models. For example, earlier models of word recognition (e.g. McClelland & Rumelhart, 1981; Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Paap, Newsome, McDonald, & Schvaneveldt, 1982) assumed letters were processed in parallel across the entire word in channel-specific slots, which the transposed letter research clearly contradicts. Additionally, transposed letter effects have recently been used to investigate the morphological decomposition process. This recent empirical research has suggested that models assuming slot based coding and parallel processing of letters across words may be incorrectly generalizing the processing of short monomorphemic words to morphemically complex words. That is, recent findings suggest that constituents of morphemically complex words may not be encoded in parallel across the entire word. Furthermore, the transposed letter effect provides evidence that coding of letter position is not a strictly channel-specific process and word encoding can be facilitated if the letters are in the wrong order, as long as the correct letters are present.

My research focused on how these phenomena interact, specifically, whether having the correct letters in the wrong order is still facilitative if the morpheme boundary is disrupted. First, I will discuss the earlier models of visual word recognition that were developed to explain how short monomorphemic words are encoded. Next, I will discuss the evidence that morphemes are involved in early stages of visual word recognition and the consequences of this evidence for the earlier models. Then, I will discuss the evidence that letter position encoding is not channel specific and the right letters in the wrong position can facilitate word recognition. Finally, I will present the experiments, which investigated how morphemic decomposition relates to letter position encoding.

Early Word Recognition Models

The *interactive activation* model (McClelland & Rumelhart, 1981) is a model based on the assumption that perceptual processing occurs within a system consisting of several levels, each concerned with forming a representation of the input at a different level of abstraction. In the model, word perception is the result of inhibitory and excitatory interactions of detectors at the feature, letter and word levels, as well as other higher level processing levels. The model assumes that visual perception is spatially parallel and that visual processing occurs at several levels at the same time. The interactive nature of the model is in the assumption that knowledge about the words of the language interacts with incoming featural information in codetermining the course of perception of the letters and words (McClelland & Rumelhart, 1981). This model can account for the word and pseudoword superiority effect (i.e., the finding that a letter is better recognized as part of a word or pseudoword than in isolation), and various associated findings (see Rayner & Pollatsek 1989 for a review). The *activation-verification model* (Paap et al. 1982) shares many of the same basic assumptions as the interactive activation model and can account for the same word and pseudoword superiority findings.

The *dual route cascaded* (DRC) model (Coltheart et al. 2001) is a computational model of visual word recognition and is a generalization of the interactive activation model. The DRC can handle words up to eight letters long, while the others can only account for words up to four letters long. The DRC has a lexical route, which utilizes word-specific knowledge, a lexical nonsemantic route, and a non-lexical Grapheme-to-Phoneme Conversion (GPC) route, which utilizes a sublexical spelling-sound correspondence rule system. The essentials of the feature and letter level processing modules from the interactive activation model are maintained. Processing occurs in parallel in all modules except the GPC where processing is serial.

The slot-based or channel-specific coding in these models assumes that there are units that code letter identity and position together, such that a given letter is tagged to a specified location in the string. This method of letter encoding is highly efficient in computational models. For example, in the interactive activation model, letter strings are processed in parallel by position-specific length-dependent letter detectors. This implies there is a detector for the letter K in the first position of a three-letter word, a separate detector for the letter K in the second position of a three-letter word, and a separate detector for the letter K in the first position of a four-letter word. While efficient, this coding scheme implies an enormous amount of detectors necessary to code all possible positions of letters in the alphabet. The DRC version of slot-based coding includes the addition of anchor points, introducing a relative position-coding scheme. In this version, left-to-right length-independent letter detectors process letter strings. This implies a position detector for a letter in the third position in a three-letter word is the same as the third letter of a seven-letter string.

In summary, early word recognition research and identification models were based on phenomena associated with short monomorphemic words. These models can accurately account for short, monomorphemic words, but fail to account for longer, polymorphemic words. The slot-based coding inherent in all of these models, regardless of the specifics, is problematic for the ability of the models to account for certain phenomena, namely the effects of transposed letters.

Transposed-Letter Effect

Research across a number of tasks and paradigms (Andrews, 1996; Bruner & O’Dowd, 1958; Chambers, 1979; Christianson et al, 2005; Perea & Carreiras, 2006a, 2006b; Perea & Lupker, 2003a, 2003b, 2004; Schoobaert & Grainger, 2004; Taft & van Graan, 1998) has shown that transposed letter (TL) nonwords are easier to recognize than substitute letter (SL) nonwords. For example, the TL nonword *jugde* facilitates *judge* better than the SL nonword *jukpe*. This implies that the identities of letters must be computed during visual word recognition at least somewhat independently of letter position.

Perea and Lupker (2003a) conducted a series of lexical decision experiments using masked priming investigating TL priming effects and, specifically, whether the position of the transposition (internal versus final) matters. They examined differences between TL-internal (*uhser*) and TL-final (*ushre*) nonwords in priming base words (*usher*) in comparison with control SL primes in which the two TLs were substituted with replacement letters (*ufner* and *ushno*) and identical primes (*usher* primes *usher*). Compared to SL primes, they found a strong 30 ms effect for TL-internal primes and a rather weak 13 ms effect for TL-final primes. In another set of experiments, they examined differences between TL-internal (*jugde*) nonwords, TL-final (*judeg*) and SL (*jukpe*) as primes for COURT. Compared to an unrelated condition, masked TL-internal primes produced a significant semantic/associative priming effect. The priming effect was was only slightly less than the effect for the identical (*judge*) condition, indicating that the transposed letter primes were nearly as facilitative as an identical prime. No effect was observed for the SL nonword primes or for the TL-final nonword primes.

Perea and Lupker concluded that the orthographic representations of TL-internal words must be far more similar to their base words than the orthographic representations of TL-final or SL nonwords are to their base words.

The TL effect has also been observed in experiments using an eye-contingent display change technique, called the *boundary paradigm* (Rayner, 1975). In these experiments, readers' eye movements are sampled every millisecond by a high-speed computer during normal silent reading. The display is then changed contingent upon the readers' location. As the eyes move over the invisible boundary, the display is changed. In the TL experiments, the changing display is a target word that is altered from the target word itself; typically, two adjacent letters are transposed. During a saccade, when visual input is suppressed, the change will occur and the target word will replace the altered version of itself, which readers will not notice.

In boundary change experiments, TL effects are investigated when the relevant information is in the parafovea. Many eye movement studies have shown that information is acquired at the parafoveal level (see Rayner, 1998 for a review). If preview information presented in the parafovea affects processing when the target is fixated, the effect is attributed to the parafoveal preview. When the word to the right of fixation (the preview) is altered during reading, reading rates are markedly increased. Furthermore, when a full preview is available, processing time on that word, when it is fixated, is facilitated, compared to when there is no preview or the when the preview is altered. (see Rayner, 1998 for a review). Johnson, Perea, and Rayner (2007) used target words from a Perea and Lupker (2003b) masked priming study and embedded them in neutral sentence frames. They had five preview conditions, TL-internal (*celrk* as the preview for *clerk*); SL-internal (*cohrk*); TL-final (*clekr*); SL-final (*clefn*); identity (*clerk*). The results showed a TL effect in normal silent reading; parafoveal previews that contained transposed letters provided greater facilitation than the previews that had substituted letters. These results indicated that TL effects found in naming and lexical decision tasks also exist in normal silent reading.

The reliable existence of transposed letter effects across tasks and paradigms pose a challenge to word recognition models that assume slot-based coding. Thus, the dual-route cascaded model (Coltheart et al., 2001), the interactive activation model (McClelland & Rumelhart, 1981), and the activation-verification model (Paap et al., 1982) are inadequate models of visual word processing. A way to account for the TL effect and consequently the processing of morphemically complex words would be to implement a different letter-coding scheme. Some models have incorporated the idea of spatial letter-coding. These include the SERIOL model (Whitney, 2001), the open-bigram model (Grainger & van Heuven, 2003; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006) and the SOLAR model (Davis, 1999). These models correctly predict that TL nonwords are more similar to their base words than SL nonwords and that the identity condition provides the greatest facilitation.

Letter Position Encoding Models

The letter position encoding SERIOL model (Whitney, 2001) consists of five layers: the retinal level, the feature level, the letter level, the bigram level and the word level. The layers are all comprised of nodes, which are responsible for recognizing the occurrence of a symbol. At the retinal level, the nodes represent pixels and perceptual acuity decreases as distance from fixation increases creating an *acuity gradient*. The nodes in the feature level are tuned to the retinal node locations and recognize suborthographic letter features, i.e. curves and lines of the letters. These nodes are assumedly tuned to respond most strongly to an occurrence of a stimulus in a specific location in the retina and less strongly to a less precise location thus creating a *locational gradient*. This locational gradient of the feature level creates a temporal firing pattern across the letter nodes, in which position in represented by the timing of the firing relative to other letter nodes. This coding scheme does not imply slot-based letter detectors; all feature nodes are connected to all letter detectors, thus allowing any letter node to represent any position.

Underlying the firing pattern are subthreshold oscillations, interacting with the locational gradient, which causes the letter node representing the letter in the first position to receive the most excitatory input; the second receives the next highest amount and so on. Lateral inhibition prevents multiple letter nodes from firing at the same time. The level of input affects the activation of the receiving letter node, where more input creates higher levels of activation. The locational gradient consequently creates a *positional gradient* across the letter nodes. The positional gradient is a product of the locational gradient interacting with internal letter node states and lateral inhibition between letter nodes, which results in a pattern of activation at the letter level that is not monotonically decreasing. These letter node dynamics activate the bigram units, which recognize ordered pairs of letters, converting the temporal representation of the letter level into a contextual representation. Bigram nodes become active if they receive enough input during an oscillatory cycle, which means bigram nodes can be activated by non-sequential or transposed letters in the input string. Bigram nodes subsequently activate word detectors. Thus, SERIOL has implemented a letter position encoding system that can account for transposed letter effects.

The SOLAR model (Davis, 1999) has a similar letter-position encoding scheme. The starting point for processing in the SOLAR model is a set of letter identities that provide serial, left-to-right input to the orthographic processing system, one letter at a time. There is only one node for each letter in the letter identification system. A latch-field mediates between letter input and nodes in the orthographic processing module. This latch-field controls the transfer of information from the sequential letter input to the spatial orthographic code. Activity in orthographic input nodes is then fed onto a layer representing sequences of letters, which may correspond to whole words or to affixes and bound stems. Like SERIOL, SOLAR can handle the transposed letter effect because of the activation gradient implemented in the model.

The open-bigram model is largely based on findings from relative-position priming experiments (see Grainger et al. 2006 for a review). Relative-position priming is a form of orthographic priming where priming effects depend on shared letters being presented in the same relative position in prime and in target (*apct* primes *apricot*). There are three levels in the functional architecture of the open-bigram model: the alphabetic array, the relative position map, and whole-word orthographic representations. The alphabetic array is a bank of detectors that simultaneously process all characters in a string of limited length. Retinal activity is lined up with the detectors in the array and the specific input to any one slot will result in activation of the corresponding character representation for that slot. The alphabetic array supplies a retinotopic map of all characters in a given string and each character detector gives information about the identity of a given character at a specified retinal location. This information is projected on to the relative order map that combines the information from the different retinal positions in order to process character positional information. The relative position map contains stimulus-centered representations that code the relative position of letters using open-bigram units. In other words, the open-bigram units receive activation from the alphabetic array such that a given letter order activates the open-bigram for that sequence, which is realized at any of the possible combinations of location in the array. Activated units then send information to the compatible whole-word orthographic representation. The open-bigram model considers orthographic processing to be a visual process that strongly adheres to the fundamental principles of the human visual system, which is hierarchically structured with massively parallel processing (Grainger & van Hueven, 2003).

In summary, all the previously mentioned models assume spatial coding of letter position. In this scheme, the relative position of spatially distributed items is coded in terms of their relative activation level, which is best achieved when the items in the list form a monotonically increasing or decreasing set of activation values, known as an activation gradient (Grainger & van Hueven, 2003). The models vary slightly on the nature of the activation gradient, but otherwise are very similar in their assumptions. These models can all account for TL effects, thus providing a better explanation for visual word perception. These models can also handle longer words, up to nine characters. However, it is unclear what these models predict about polymorphemic words. How is position encoding affected by morphemes? In the processing of longer, polymorphemic words, morphemic decomposition must be considered. For example, the word *unlikely* is composed of the base word *like*, the adverbial suffix –*ly*, and the negative prefix *un*-. How is a word of this type represented in the lexicon and consequently accessed and processed?

Morphemic Decomposition

Morphemic decomposition research has been primarily concerned with how polymorphemic words are represented in the mental lexicon. Morphologically complex words must be accessed one of three ways: (a) as a whole word representation, *unlikely* is its own entry, (b) by constituents, *un*-, *like*, and -*ly*, are each separate entries, or (c) the whole word and the constituents are all separate entries.

Taft and Forster (1975) conducted a series of experiments investigating lexical decision times for the stems of prefixed words and pseudoprefixed words. They compared nonword stems of prefixed words (e.g. *juvenate*) to nonword stems of pseudoprefixed words (e.g. *pertoire*) and found that it took longer to classify nonword prefixed stems as nonwords than the pseudoprefixed nonword stems. Adding an illegal prefix to the items (*dejuvenate*/*depertoire*) did not change the pattern of results. They further compared words that can occur both as a free and bound morpheme where the bound form is more frequent than the free form (e.g. *tribute*/*contribute*) and vice versa (e.g. *pending*/*impending*) to items having only a free form (e.g. *card/discard*). Reaction times were longer for the words where the bound form is more frequent compared to the words with only a free form. There were no differences between words where the free form is more frequent than the bound form compared to the words with only free forms. Because participants spent more time on the roots of the prefixed words, these findings suggest that prefixed words are processed differently than non-prefixed words.

Dunabeitia, Perea, and Carreiras (2007) conducted a lexical decision task comparing Spanish and Basque polymorphemic and monomorphemic words. Using TL and SL nonwords as primes, they positioned transpositions or substitutions to occur within (e.g., polymorphemic word ESCOMBRO could be primed by TL *escobmro* or SL *escohcro*) or across (e.g., the prefixed word *BIZNIETO* could be primed by TL *binzieto* or SL *bicsieto*) a morpheme boundary. They observed a significant transposed-letter effect for non-affixed words, whereas there were no signs of a transposed-letter effect across morpheme boundaries for affixed words for either prefixed words or suffixed words. Transposed-letter effects did occur for polymorphemic words for within-morpheme transpositions. Christianson, Johnson, and Rayner (2005) also found interference between the transposed letter effect and decomposition. Using masked priming with naming, Christianson et al. (2005) compared targets containing the derivational suffix *–er* (e.g. *baker*) to targets containing the pseudo suffix *–er* (e.g. bluster). The derivational items contain an English word plus a suffix whereas the pseudo-suffixed items do not contain an English word if *–er* is removed, i.e. *baker* is someone who bakes, but *bluster* is not someone who blusts. The authors compared identical, transposed letter and substitute letter primes and found a significant transposed letter effect for pseudo-suffixed items (55 ms difference between substitute letter prime and transposed letter conditions), but a rather weak transposed letter effect for derivational items (12 ms difference between substitute letter prime and transposed letter conditions). However, the interaction was not significant. It should also be noted that Christianson et al. (2005) only had 12 items in their sample, in addition to testing only one suffix, -*er*. Collectively, the results from these experiments suggest that morphemic decomposition occurs early in processing, as disruption of the morpheme boundary resulted in the loss or weakening of the TL effect for affixed words.

Another line of experiments has compared word identification times for affixed and non-affixed words. Manelis and Tharp (1977) conducted a lexical decision experiment and found no significant differences between affixed and nonaffixed words. From their manipulations, they concluded that words are accessed in a direct and continuous manner without any prior decomposition. Rubin, Becker and Freeman (1979) conducted a lexical decision experiment based on the Taft and Forster (1975) findings and did not replicate them (i.e., they did not find any differences between prefixed and non-prefixed words). They suggested that morphological decomposition might be a special strategy induced by the overrepresentation of polymorphemic stimuli. The findings from these experiments suggest that morphemically complex words are not processed differently, as participants did not spend any more time on the prefixed items compared to the pseudoprefixed items.

Caramazza et al. (1988) conducted a lexical decision experiment, using Italian stimuli, and found a gradation of processing difficulty with polymorphemic words: morphologically non-decomposable nonwords were easiest to process; nonwords with partial morphological structure were processed with greater difficulty; and nonwords that are exhaustively decomposable into morphemes were processed with the greatest difficulty. Marlsen-Wilson et al. (1994) conducted a set of experiments using *cross-modal immediate repetition* priming. This is a task in which the participant hears a spoken prime (e.g., *loveliness)* and immediately at the offset of this word sees a visual probe (e.g., *lovely*) that is related in some way to the prime. The participant then makes a lexical decision response to this probe. They found evidence for morphological decomposition of semantically transparent forms. Semantically opaque forms, in contrast, behaved like monomorphemic words. Rastle, Davis and New (2004) compared the stem priming of words composed of stem and suffix (e.g., *cleaner*) to words composed of pseudostem and pseudosuffix (e.g., *corner*) to words composed of pseudostem and nonsuffix (e.g., *brothel*). The first two conditions, in which prime and target had the appearance of a morphological relationship elicited significant and equal priming effects, and priming in both of these conditions were significantly different from the third condition. The findings of these experiments suggest that there are different processes for different types of morphemically complex words.

The interpretation of the findings from these studies led to distinct theories of morphemic decomposition. These theories can be divided into three positions, (a) whole-word access first, (b) access by components first and (c) both whole-word and decomposition routes working in parallel.

Models of Morphemic Decomposition

The findings from the outlined morphemic decomposition research resulted in three major theories as to how morphemically complex words are processed. The first type of model is based on the assumption that identification of component morphemes occurs before whole word access. The second type of model is based on the assumption that morphological decomposition occurs only after a word has initially been accessed by the whole word process that would occur for monomorphemic words. The third type of model is a sort of hybrid of the first two, where there are two routes, a decomposition route and a whole word route, that operate in parallel.

Based on their findings, Taft and Forster (1975) developed a word recognition model incorporating morphological analysis. The morphological analysis is attempted prior to lexical search. Processing a polymorphemic word begins with identifying the prefix and subsequently “stripping off” the prefix. After the prefix is removed, the search for the stem begins. When it is found, the contents of the entry are examined to determine if the prefix is appropriate. If the prefix is appropriate, then the word is processed. If the prefix is not appropriate, then a search must be performed for the whole word. Proponents of this prelexical position (Dunabeitia et al. 2007) generally posit that polymorphemic words are first parsed into their constituents, which are identified individually, and then put back together for identification of an overall meaning.

In contrast, the full-listing or supralexical (Giraudo & Grainger, 2001) model of morphological decomposition posits that words are represented and retrieved as their full forms, so that *unlikely*, *likely*, *likable*, and *like* would all have their own lexical representation and would be accessed separately in the lexicon (Butterworth, 1983; Manelis & Tharp, 1977; Rubin, Becker & Freeman, 1979). After accessing the whole word, units corresponding to the root and the affix or suffix will receive activation from the whole-word representation and send back activation to all whole-word representations that are compatible with either the root or the affix. Thus, root representations impose an organization on the lower level form representations in terms of “morphological families” (Giraudo & Grainger, 2001).

The third type of model incorporates both whole-word and compositional representations of polymorphemic words in the lexicon (Caramazza, Laudanna, & Romani, 1988; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Rastle, Davis, & New, 2004). The simplest form of these models posit a “horse race” model, where the two processes are independently operating in parallel, and whichever process is fastest determines how the morphologically complex word is processed.

Specific Aims and Hypotheses of the Study

As described, there are current letter position encoding models that can account for transposed letter effects. There are also models of morphemic decomposition that posit different processing approaches for affixed and non-affixed words. The current study aims to investigate the effect of morphemic decomposition on the transposed letter effect. To accomplish this, transpositions will occur across morpheme boundaries, disrupting the prime or preview of the affixes. Previous research using this technique, (e.g. Dunabeitia et al. 2007; Christianson et al. 2005) has thus far shown a weakened, or disappearing transposed letter effect in affixed words, suggesting that decomposition is interfering with letter position encoding. The current study examined the transposed letter effect in polymorphemic words in an attempt to order decomposition and letter position encoding in the visual word recognition timeline.

Experiments 1 and 2 used natural silent reading with the boundary technique and Experiment 3 used masked priming with lexical decision. The use of these paradigms allowed for investigation of the transposed letter effect in both the parafovea and the fovea. All three experiments investigated transposed letter effects in prefixed words. Experiments 1 & 2 were designed to examine the transposed letter effect in prefixed words in the parafovea. According to early decomposition models, the transposed letter effect should not be elicited as the prefix boundary was disrupted by the transposition, and decomposition occurs prior to, or during, letter position encoding. According to late decomposition models, the transposed letter effect should be elicited as decomposition occurs after letter position encoding is accomplished. Experiments 1 & 2 were conducted to test these hypotheses. Experiment 3 was designed to examine the transposed letter effect in prefixed words in the fovea. It also was an attempt to replicate the findings of Dunabeitia et al. (2007). Dunabeitia et al. (2007) tested the transposed letter effect in affixed Spanish and Basque words; Experiment 3 used English prefixed words. Dunabeitia et al. (2007) obtained results supporting the early decomposition model; when the transposition occurred across a morpheme boundary, the transposed letter effect disappeared. Experiment 3 used English words to test the reliability of these effects across languages. Taken collectively, it was expected that these experiments would reveal new information about the transposed letter effect in English prefixed words, both in the parafovea and the fovea.

CHAPTER II

EXPERIMENTS

Experiment 1

In Experiment 1, the effects of a parafoveal preview manipulation were examined for (a) novel prefixed words (e.g. *miscentered*), (b) lexical prefixed words (e.g. *misapplied*) or (c) monomorphemic words (e.g. *modified*) during the reading of single sentences. To test whether preserving morpheme boundaries modulates the effects of parafoveal preview, I compared identical (e.g., *miscentered/misapplied/modified*), transposed letter (e.g., *micsentered*/*miaspplied*,*moidfied*) and substitute letter (e.g., *mizventered*/*mizepplied*/*molufied*) as previews for *miscentered*, *misapplied* and *modified*, respectively.

Method

Participants

Forty-two undergraduate students from the University of Massachusetts of Amherst participated in the study for extra credit in their psychology courses. All had normal or corrected-to-normal vision. They were all naïve to the purpose of the experiment.

Apparatus

Participants were seated 60 cm from a color monitor displaying three characters subtending one degree of visual angle. Eye movements were recorded with a SR Research Ltd. EyeLink 1000 eye tracking system that has high spatial resolution and a sampling rate of 1000 Hz (1 ms sampling resolution). Viewing was binocular but only the right eye was tracked. Sentences were presented on a single line in black letters against a white background in Courier New font so that all the characters had the same width. The letters were presented as in normal text, with lowercase and uppercase letters appearing where appropriate. Custom-built software controlled the presentation of the sentences and accomplished the display changes. The monitor refresh rate was set at 150 Hz to ensure the display changes were not detectable.

Procedure

When participants arrived for the experiment, they were given a written description of the experimental situation and procedure followed by verbal instruction about the task. The participants were told they would be expected to read a series of sentences on a computer screen while their eye movements were being monitored. They were told to read the sentences normally, for comprehension. Each participant read 10 practice trials, 36 experimental trials, and 70 filler trials. Approximately 20% of the sentences were followed by a comprehension question requiring a yes/no response made by pressing a button on a response box. After instruction and informed consent, an initial calibration lasting about 5 minutes was performed. After getting a good calibration, the participant was instructed to fixate on the leftmost calibration box, and the experimenter initiated the trial. When a sentence was initially presented on the monitor, the participant was fixating on the first letter of the first word in the sentence and the target word was replaced with one of the preview conditions. Once the participant’s eyes crossed an invisible boundary between the last two characters of the word immediately preceding the target word, the preview changed to the target word (see Figure 1). The target word then remained present until the participant indicated that he or she was finished reading the sentence. Participants were told to read each sentence silently and to press a button on a response box when they finished reading the sentence. Upon finishing the sentence, either a yes/no comprehension question appeared or the calibration screen reappeared. Under certain conditions, the display change can occur during fixation and thus be visible to the participant. During debriefing, participants were asked to report what they noticed about the display changes. Data from participants who reported being aware of the display change on majority of the trials were discarded from the experiment.

Materials

Target words included prefixed and non-prefixed words of mean length 9.18 characters. There were 108 target words, with one word from each of the three target word conditions embedded in each of the 36 sentence frames. The three target word conditions were: (1) novel prefixed (e.g., *miscentered*), (2) lexical prefixed (e.g., *misapplied*), and (3) lexical non-prefixed (e.g., *modified*) words. Target words were never either the first or last word in the sentence. The Francis and Kucera (1982) frequency count was used to estimate root frequencies of the target words. Root frequencies ranged from 1 per million written words to 715 per million (M = 77).

Each target word was placed in a neutral sentence context, preceded by at least two words. For each target word type, there were three preview conditions: (1) identical (e.g., *miscentered/modified*), in which the parafoveal preview was the same as the target word; (2) transposed letter (e.g., *micsentered/moidfied*), in which the parafoveal preview transposed the last letter of the prefix and the first letter of the stem; and (3) replacement letter (e.g., *mivzentered/molufied*), in which the parafoveal preview replaced the last letter of the prefix and the first letter of the stem. The replacement letters were chosen so that the overall letter shape was consistent with the original target word letters (i.e., ascending letters were replaced with ascending letters, descending letters with descending letters and neither ascending or descending letters with visually similar letters).

Results & Discussion

Participants were excluded from the analyses if they were not native speakers of English or if they reported seeing the display change on majority of the trials. These criteria excluded 10 participants. Data from the remaining participants were excluded for any of the following reasons: (1) A track loss occurred; (2) the eyes triggered the boundary change but actually landed on the word prior to the target word; (3) the first fixation of the target word was less than 120 ms, or a first-pass fixation was greater than 600 ms; and (4) the participant blinked on the pretarget word, target word or posttarget word. Trials in which there were two fixations on adjacent letters and one of the fixations was short (less than 120 ms) were pooled. After data were excluded from the analysis according to the criteria above, 70% of the data were left. The average correct response rate to the yes/no comprehension questions was 82%. Because novel stimuli were used, this correct response rate is not surprising as the meaning of novel stimuli is left open to the interpretation of the participant. The correct response rate is taken to mean that the participants understood the sentences.

Standard eye movement measures were computed to examine the manipulation of preview and word types in reading. These duration measures were *first fixation duration*, *gaze duration*, *go-past time* and *total time*. *First fixation duration* is the mean duration of the initial fixation on a word, conditional on the word being fixated on the *first pass* through the text (i.e., not being skipped over initially). *Gaze duration* is the average of the sum of all fixation durations on a word on the first pass, conditional on the word being fixated on the first pass. *Go-past time* is the time between when a word is first fixated on the first pass and when it is exited to the right (i.e., it includes regressions back from the word). *Total time* is the mean of the sum of all fixations on a word (including regressions back to the word).

For the purpose of my research questions, the primary comparisons of the data analysis were the difference between the transposed letter (TL) and substitute letter (SL) conditions which will be called the *transposed letter effect*, and the difference between the identical preview and SL conditions which will be called the *preview effect*. The former difference assesses whether there is any benefit from the preview having the right letters even when the order is not correct and the latter difference assesses the total benefit of the preview having the correct two letters in the correct position.

Analyses on first fixation duration (see Table 1) revealed a 17 ms overall preview effect (averages over the three target word conditions), $t_1(31) = 2.54$, $p < .05$, $t2(28) = 2.38$, $p < .05$, and a 22 ms overall transposed letter effect, $t_1(30) = 2.54$, $p < .01$, $t_2(20) = 1.94$, $p = .07$ (t_1 and F_1 indicate participant data; t_2 and F_2 indicate item data). Obviously, the 4 ms difference between the identical and TL conditions was not close to significant, t_1, $t_2 < 1$. The differences between the TL and SL conditions were 14, 30, and 21 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions, respectively. The interaction of this effect with target word condition was far from significant, F_1, $F_2 < 1$.

For gaze duration, the pattern of data was the same. There was a 34 ms overall preview effect, $t_1(31) = 2.70$, $p < .05$, $t_2(27) = 2.99$, $p < .01$ and a 37 ms overall transposed letter effect, $t_1(31) = 2.67$, $p< .05$, $t_2(20) = 2.88$, $p < .01$. Obviously, the 3 ms difference between the identical and TL conditions was not close to significant, t_1, $t_2 < 1$. The differences between the TL and SL conditions were 51, 16, and 43 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions, respectively. However, the interaction of this effect with target word condition was far from significant, F_1, $F_2 = < 1$.

The sizes of the effects were more or less the same for the later measures, but were less reliable because there was more variability in these measures. Go-past measures revealed a significant 46 ms overall preview effect, $t_1(31) = 2.39$, $p < .05$, $t_2(20) = 2.45$, $p < .05$ but a nonsignificant 26 ms overall transposed letter effect, $t_1(31) = 1.33$, $p = .19$, $t_2(28) = 2.99$, $p < .01$. Total time measures revealed a nonsignificant 10 ms overall preview effect t_1, $t_2 < 1$, and a nonsignificant 31 ms overall transposed letter effect for participants, $t_1(30) = 1.4$, $p = .17$ and marginally significant effect across items, $t_2(21) = 1.91$, $p = .07$.

Another interesting comparison was the *lexicality effect*, the difference between novel prefixed words and lexical prefixed words. For first fixation duration, there was a 17 ms effect of lexicality, $t_1(30) = 2.13$, $p < .05$, which was not significant across items, $t_2 < 1$. For gaze duration, there was a 72 ms effect of lexicality, $t_1(30) = 4.39$, $p < .001$, $t_2(26) = 2.28$, $p < .05$. The effect increased throughout the later measures. For example, for total time there was a 151 ms effect, $t_1(30) = 4.64$, $p<.001$, $t_2(26) = 3.58$, $p< .01$. These results replicate the findings of Pollatsek, Slattery, and Juhasz (2008) who found a 21 ms effect on first fixation, a 104 ms effect on gaze duration and a 156 ms effect on total time measures when comparing novel and lexical prefixed words in reading.

As expected, there was a preview effect in Experiment 1 – having an identical preview was more facilitative than a preview with substituted letters. Unexpectedly, and contrary to the findings of Dunabeitia et al. (2007), these data indicated that there was a significant transposed letter effect that was not smaller when the transposition disrupted the morpheme boundary. That is, the transposed letters were more facilitative than the substituted letters when presented parafoveally whether or not the transposed letters were in the prefixed conditions or the non-prefixed condition. The effect was significant in early measures of word processing, and although insignificant, it is consistent throughout the later measures as is evident in Table 1. These findings contradict the predictions of models that assume early morphemic decomposition, as the TL effect is elicited regardless of word type and morpheme boundary disruption.

Experiment 1 had considerable data loss, due both to excluded trials and participants. Using standard analysis of variance, empty cells result in the dropping of all of that particular participant's data, thus causing a loss of power. To ensure that the effects were robust, the data were examined using linear mixed models (LMM). Simulations were run in R (version 2.9.0) (R development core team, 2007) using the lme4 package of Bates and Sarkar (2007). With LMM, missing cells do not result in the loss of an entire participant. The LMM takes into account the unbalanced design and using participant, item and effect means estimates the missing cell values. The model uses individual data points as opposed to averages; thus missing cells are less damaging. In the analysis above, the data were first grouped into participants or items, whereas in the LMM analysis, all the individual data points are considered and contribute to a participant x item mean. Thus, this analysis will produce slightly different means and effect sizes. LMM was used to examine the specific contrasts of greatest interest, the transposed letter effect and the preview effect. For the transposed letter effect, I compared the substitute letter condition to the transposed letter condition using model contrasts, collapsing across word types, i.e. removing word type from the model. The same method was used for the preview effect, comparing the identical condition to the substitute letter condition. The interactions were examined via the full model. LMM computes the interactions differently than standard analysis of variance, by specifying cross-level interaction effects between variables located at different levels. Using the full model, with both word type (novel prefixed, lexical prefixed, lexical non-prefixed) and preview type (identical, transposed letter, substitute letter), LMM provides t-values for the cross-level interaction effects.

All effects were computed for the first fixation duration, gaze duration, go-past and total time measures. Using the LMM analysis in R, t-values are reported. Significance is calculated using a separate analysis (command “p-vals”). P-values are based on Markov chain Monte Carlo sampling. This calculation performs 10,000 simulations of the model to generate samples from the posterior distribution and returns a p-like value, pMCMC, which is very close to the p-value for the t statistic (Baayen, Davidson & Bates, 2008).

The means, as computed by the LMM analysis, are in Table 2. For first fixation duration, there was a 20 ms overall preview effect (averaged over the three target word conditions), $t = 2.93$, $pMCMC < .001$, and a 24 ms overall transposed letter effect, $t = 2.54$, $pMCMC < .001$. The 7 ms difference between the identical and TL conditions was not close to significant, $t < 1$. The differences between the TL and SL conditions were 22, 34, and 16 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was far from significant, t < 1.

For gaze duration, there was a 35 ms overall preview effect, t = 2.82, pMCMC <.01, and a 41 ms overall transposed letter effect, t = 3.30, pMCMC< .001. The 6 ms difference between the identical and TL conditions was not significant, t < 1. The differences between the TL and SL conditions were 52, 21, and 49 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was again far from significant, t < 1.

Analyses on go past revealed a 42 ms overall preview effect t = 2.58, pMCMC <.001, and a marginally significant 33 ms overall transposed letter effect, t = 1.78, pMCMC = .08. The 8 ms difference between the identical and TL conditions was not significant, t < 1. The differences between the TL and SL conditions were 57, 20, and 23 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was far from significant, t < 1. Analyses on total time revealed a 32 ms overall transposed letter effect, t = 2.02, pMCMC < .05, although there was no significant preview effect. As previously mentioned, there was increased variability in the later measures so they are expectedly less reliable.

Experiment 1 effectively showed transposed letter effects for both prefixed and non-prefixed words. For first fixation duration, there was a 34 ms transposed letter effect for the lexical prefixed items and a 16 ms transposed letter effect for the non-prefixed items. In contrast, the size of the TL effect was larger for non-prefixed items for gaze duration; there was a 21 ms TL effect for lexical prefixed words and a 49 ms TL effect for non-prefixed items. For go past, the effects were about equal: there was 20 ms TL effect for lexical prefixed items and a 23 ms TL effect for non-prefixed items. (These effects were calculated from the LMM analysis.)

Because the transposed letter effect seemed to fluctuate in both size and direction, an analysis of the transposed letter effect with only the lexical prefixed words and non-prefixed words was conducted. For first fixation duration, after removing the novel prefixed words from the model, the overall 26 ms transposed letter effect was significant, $t = 3.01$, $pMCMC < .001$, and the interactions were not, $t < 1$. For gaze duration, the overall 35 ms TL effect was significant, $t = 2.81$, $pMCMC < .05$, and the interactions were not, $pMCMC > .05$. The transposed letter effect was not significant in the later measures, $pMCMC > .05$, but was in the right direction. Thus, both the size and the direction of the difference in TL effect varied across the measures, but not significantly so as demonstrated by the nonsignificant interactions.

The results of Experiment 1 do not support early decomposition theories. Early decomposition theories posit an equally costly effect for transposed letters and substituted letters compared to an unaltered preview. According to this view, morphological decomposition is occurring prior to letter position encoding, thus the disruption of the morpheme boundary is costly regardless of the type of disruption. These data are clearly contradictory to this view. There was a clear transposed letter effect for all word types. The transposed letter effect was demonstrated regardless of word type, with two analyses, participant and item t-tests and linear mixed modeling.

Participants consistently experienced a greater cost when parafoveally previewing substituted letters compared to transposed letters. Importantly, for first fixation and gaze duration, the identical and transposed letter condition means were nearly the same for all three word types. According to the analysis of variance means, for the novel prefixed words, there was no difference between the identical and transposed letter condition means for first fixation and a nonsignificant 8 ms difference for gaze, $t < 1$. In the lexical prefixed word condition, there was a nonsignificant 9 ms difference between the identical and transposed letter means for first fixation, $t < 1$, and no difference between the two for gaze duration. This same pattern is observed in the non-prefixed words, with a nonsignificant 2 ms difference for first fixation and no difference for gaze. This effect was consistent for the LMM means, although there were greater, but insignificant, differences between the identical and transposed letter condition means for the lexical prefixed words. This demonstrates that the transposition of two adjacent letters, even across morphemes, does not cost the reader much, especially compared to substituted letters. This further suggests that readers are not doing any sort of decomposition in the parafovea, at least not before letter position encoding.

Experiment 1 had considerable data loss, due both to excluded trials and participants. Although the effects were robust, as demonstrated by the LMM analysis, a replication was conducted to examine the reliability of the effects.

Experiment 2

Experiment 2 was conducted to replicate Experiment 1 – but with less data loss. In Experiment 1, the boundary was placed in between the last and second-to-last character of the word right before the target word. This boundary location was unorthodox as most studies employing the boundary technique place the boundary just before the space before the target word (Johnson, Perea & Rayner, 2007; Kambe, 2004). The placement in Experiment 1 resulted in a large number of excluded trials and participants, as participants often fixated the boundary location, thus making the display change visible. For Experiment 2, the boundary was moved to just before the space before the target word (see Figure 2).

Method

Participants

Fifty-eight undergraduate students from the University of Massachusetts of Amherst participated in the study for extra credit in their psychology courses. All were native speakers of English and had normal or corrected-to-normal vision. They were all naïve to the purpose of the experiment.

Apparatus

The same as in Experiment 1.

Procedure

In Experiment 1, the boundary was placed between the last and second-to-last character of the word just before the target. Because nearly 80% of the target words were preceded by a 2-3 character function word, the boundary was often fixated resulting in visible display changes. For Experiment 2, the procedure was the same as in Experiment 1, except that the boundary location was moved to directly after the last character in the word just before the target word (see Figure 2.) This boundary location ensures that the display change will occur during a saccade, when visual input is suppressed. None of the participants reported seeing more than one display change, which was described as a "flicker."

Materials

The same as in Experiment 1.

Results and Discussion

Data and participants were excluded according to the same criteria as in Experiment 1, after this, 100% of the participants and 71% of the data were left. The average correct response rate to the yes/no comprehension questions was 85%.

As in Experiment 1, standard eye movement measures were computed to examine the manipulation of preview and word types in reading. These duration measures were *first fixation duration, gaze duration, go-past time* and *total time*.

As in Experiment 1, the primary comparisons of the data analysis were the *transposed letter effect*, which was considered the difference between the transposed letter (TL) and substitute letter (SL) conditions; and the *preview effect*, which was considered the difference between the identical conditions and the SL conditions.

Using the standard analyses examining reliability over participants and items, there was a 13 ms overall preview effect on first fixation duration (averaged over the three target word conditions), $t_1(57) = 2.45$, $p < .05$, $t_2(35) = 2.27$, $p < .05$ and a marginally significant 10 ms overall transposed letter effect for participants, $t_1(57) = 1.69$, $p = .09$ and a significant effect for items, $t_2(35) = 2.71$, $p < .01$ (see Table 2). Obviously, the 1 ms difference between the identical and TL conditions was not close to significant, t_1, $t_2 < 1$. The difference between the TL and SL conditions was 3, 11, and 14 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was far from significant, F_1, $F_2 < 1$.

For gaze duration, there was a 41 ms overall preview effect, $t_1(57) = 3.00$, $p < .01$, $t_2(35) = 4.58$, $p < .001$ and a 45 ms overall transposed letter effect, $t_1(57) = 3.81$, $p < .01$, $t_2(35) = 3.29$, $p < .01$. Obviously, the 3 ms difference between the identical and TL conditions was not close to significant, t_1, $t_2 < 1$. The differences between the TL and SL conditions were 59, 40, and 32 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was far from significant, F_1, $F_2 < 1$. This time the transposed letter effect was actually bigger for the lexicalized prefixed words than for the non-prefixed words.

As in Experiment 1, the sizes of the effects were more or less the same for the later measures, but were less reliable because there was more variability in these measures. Go-past measures revealed a nonsignificant 21 ms overall preview effect for participants, $t_1(51) = 1.31$, $p = .19$, a marginally significant effect for items, $t_2(34) = 1.86$, $p = .07$, but a significant 30 ms overall transposed letter effect, $t(51) = 2.24$, $p < .05$, $t_2(34) = 2.43$, $p < .05$. Total time measures reveal a nonsignificant 15 ms overall preview effect $t_1 < 1$, $t_2(34) = 1.09$, $p = .29$, and a nonsignificant 24 ms overall transposed letter effect, $t_1(51) = 1.56$, $p = .12$ for participants, and a significant effect for items, $t_2(34) = 2.25$, $p < .05$.

The lexicality analyses also yielded results similar to those in Experiment 1. For first fixation duration, there was a nonsignificant 10 ms effect of lexicality, $t_1(50) = 1.5$, $p = .13$, $t_2(34) = 1.10$, $p = .27$. For gaze duration, there was a 70 ms effect of lexicality,

$t_1(50) = 5.09$, $p < .001$, $t_2(34) = 5.15$, $p < .001$. The effect increased throughout the later measures e.g., for total time there was a 138 ms effect, $t_1(50) = 8.05$, $p<.001$, $t_2(34) = 7.47$, $p< .001$.

Consistent with Experiment 1, there was a preview effect: having an identical preview was more facilitative than a preview with substituted letters. These data also replicated the significant transposed letter effect across word types, again suggesting that despite the disruption of the morpheme boundary, the transposed letters were more facilitative than the substituted letters when presented parafoveally. These results further suggest that, in parafoveal preview, prefixed and non-prefixed words are not processed differently, which is contradictory to the early decomposition models.

Experiment 2 was conducted with a different boundary location than in Experiment 1, in an attempt to reduce loss. While no participants were excluded from this analysis based on awareness of the display change, the data loss for the remaining participants was not improved, with 30% and 29% data loss in Experiments 1 & 2 respectively. In a set of similar display change experiments, Johnson et al. (2007) reported data loss for three experiments as 31%, 16% and 18%. Thus, data loss may be unavoidable in experiments using display changes. Because data loss remained high, the data from Experiment 2 were also examined using LMM.

The means, as computed by the LMM analysis are in Table 4. For first fixation duration, there was a 15 ms overall preview effect (averages over the three target word conditions), $t = 2.61$, $pMCMC < .01$, and a 15 ms overall transposed letter effect, $t = 3.12$, $pMCMC < .001$. The 1 ms difference between the identical and TL conditions was not close to significant, $t < 1$. The differences between the TL and SL conditions were 17, 13, and 16 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was not significant, t < 1.

For gaze duration, there was a 47 ms overall preview effect t = 4.20, pMCMC <.001, and a 49 ms overall transposed letter effect, t = 4.41, pMCMC< .001. The 2 ms difference between the identical and TL conditions was not significant, t < 1. The difference between the TL and SL conditions was 75, 42, and 30 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was not significant, t < 1.

The sizes of the effects were more or less the same for the later measures, but again were less reliable because there was more variability in these measures. Go-past measures revealed a marginally significant 26 ms overall preview effect t = 1.73, pMCMC = .08, and a significant 37 ms overall transposed letter effect, t = 2.47, pMCMC< .05. Total time measures revealed a nonsignificant 20 ms overall preview effect, pMCMC >. 05, and a marginally significant 29 ms overall transposed letter effect, t = 1.87, pMCMC = .06.

Experiment 2 effectively showed transposed letter effects for both prefixed and non-prefixed words. For first fixation duration, there was a 13 ms transposed letter effect for the lexical prefixed items and a 16 ms transposed letter effect for the non-prefixed items. Unlike in Experiment 1, there was a larger TL effect for prefixed words for gaze duration; there was a 42 ms TL effect for lexical prefixed words and a 36 ms TL effect for non-prefixed items. Clearly, the nonsignificant interaction from Experiment 1 was not reliable as the TL effect is in the opposite direction in Experiment 2. The effect is relatively consistent for first fixation, larger for prefixed items for gaze duration and for go past; there was 39 ms TL effect for lexical prefixed items and a 17 ms TL effect for non-prefixed items. The direction and size of these effects are strong evidence for a real transposed letter effect in prefixed words. These effects were calculated from the LMM analysis.

As in Experiment 1, an analysis of the transposed letter effect with only the lexical prefixed words and non-prefixed words was conducted. For first fixation duration, after removing the novel prefixed words from the model, the overall 18 ms transposed letter effect was significant, $t = 2.34$, $pMCMC < .05$, and the interactions were not, $t < 1$. For gaze duration, the overall 35 ms TL effect was significant, $t = 3.35$, $pMCMC < .01$, and the interactions were not, $pMCMC > .05$. The effect was not significant in the later measures, $pMCMC > .05$, but was in the right direction. In go-past and total time, the size of the transposed letter effect was actually larger for prefixed words (38 ms for go-past, 47 ms for total time) than for non-prefixed words (17 ms for go-past, 11 ms for total time). This analysis replicates the comparison of lexical items in Experiment 1; the TL effect is significant regardless of lexical word type, with no significant interactions.

The LMM analyses confirmed the robustness of the transposed letter effect across all three word types. As in Experiment 1, there were no significant differences between the transposed letter and identical condition means, suggesting that the transposed letter preview was not costly, especially compared to the substitute letter preview. Experiment 2 effectively replicated Experiment 1, lending strong evidence for later decomposition.

There was virtually no difference between Experiment 1 and Experiment 2, except for a minor methodological change, the boundary location, which saved some data points in Experiment 2, but did not appear to affect the results significantly. Consequently, an analysis of the pooled data of the experiments was conducted, using LMM. The means, as computed by the LMM analysis are in Table 5. For first fixation duration, there was a 16 ms overall preview effect, t = 4.03, pMCMC < .001, and an 18 ms overall transposed letter effect, t = 4.15, pMCMC < .001. The 2 ms difference between the identical and TL conditions was not close to significant, t < 1. The differences between the TL and SL conditions were 18, 21, and 15 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was not significant, t < 1. For gaze duration, there was a 43 ms overall preview effect t = 4.95, pMCMC <.001, and a 45 ms overall transposed letter effect, t = 5.27, pMCMC< .001. The 3 ms difference between the identical and TL conditions was not significant, t < 1. The difference between the TL and SL conditions was 66, 33, and 37 ms for the novel prefixed word, lexicalized prefixed word, and non-prefixed word conditions. The interaction of this effect with target word condition was not significant, t < 1.

With the increased power, most of the effects were significant in the later measures as well. Go-past measures revealed a significant 13 ms overall preview effect, t = 2.71, pMCMC < .01, and a significant 31 ms overall transposed letter effect, t = 3.02, pMCMC< .01. Total time measures revealed a nonsignificant 12 ms overall preview effect, pMCMC >. 05, and a significant 30 ms overall transposed letter effect, t = 2.47, pMCMC < .01.

With the pooled data, the preview and transposed letter effects were more reliable, with much larger t-values. For first fixation, the preview effect (16 ms) and the TL effect

(18 ms) were nearly the same, suggesting that the transposed letter preview is as facilitative as an unaltered preview, regardless of word type. This was true for gaze as well (43 ms preview effect, 45 ms TL effect). There was no evidence of a weakened or diminishing transposed letter effect as all of the interactions were nonsignificant.

The size and direction of the transposed letter effect were more or less consistent for both word types in the early measures. For first fixation, there was a 21 ms TL effect for lexical prefixed items and a 15 ms TL effect for non-prefixed items. For gaze duration, there was a 33 ms TL effect for lexical prefixed items and a 37 ms TL for non-prefixed items. For the later measures, the prefixed items showed a larger transposed letter effect. For go-past, there was 32 ms TL effect for lexical prefixed items and a 20 ms TL effect for non-prefixed items. The effect was much larger for prefixed items in total time; there was a 47 ms TL effect for lexical prefixed items and a 10 ms TL effect for non-prefixed items.

Taken collectively, the two experiments demonstrate that in the timeline of visual word processing, letter position encoding likely occurs prior to any morphemic decomposition, in the parafovea. This is contradictory to the results reported in the Dunabeitia et al. (2007) and Christianson et al. (2004) studies, where the transposed letter effect either diminished or disappeared when the letters crossed a morpheme boundary. Both of these studies used foveal measures to examine the transposed letter effect in polymorphemic words, whereas Experiments 1 & 2 used parafoveal measures. Experiment 3 seeks to examine the timeline of visual word identification processes in the fovea.

Experiment 3

The conflict between the results of Dunabeitia et al. (2007) and those of Experiments 1 & 2 motivated Experiment 3. Dunabeitia et al. (2007), using lexical decision with masked priming, found that the transposed letter effect virtually disappeared when the transposition occurred across a morpheme boundary. The analyses in Experiments 1 & 2 suggest that the right letters in the wrong position are facilitative regardless of whether a morpheme boundary is removed. Indeed, in both experiments they were as facilitative as the right letters in the right position. Experiment 3 was designed to determine the factors responsible for the conflicting results.

Dunabeitia et al. (2007) used masked priming with lexical decision, a foveal paradigm. Experiments 1 & 2 used the boundary change technique, a parafoveal technique. Letter position encoding is not performed equally well in the parafovea and the fovea, and is probably done weakly outside of the first few letters in the parafovea. This fuzzy encoding in the parafovea could possibly be responsible for the facilitative nature of transposed letters across prefix boundaries. Perhaps in the fovea, the transposition across prefix boundaries is more disruptive as letter position encoding is straightforward.

In addition to the paradigm differences between Experiments 1 and 2 and Dunabeitia et al. (2007), there were also different languages: Dunabeitia et al. (2007) used Spanish and Basque. Basque is a unique, pre-Indo-European, ergative-absolute language. Romance language Spanish has a very different phonological system than West Germanic English, although the languages share a Latin influence and have many cognates. It is plausible that these, and possibly other linguistic properties of a language, modulate the transposed letter effect.

To investigate both hypotheses, Experiment 3 used the same procedure as Dunabeitia et al. (2007) but with the English words from Experiments 1 & 2.

Method

Participants

Fifty-four undergraduate students from the University of Massachusetts of Amherst participated in the study for extra credit in their psychology courses. They were all native speakers of English and had normal or corrected-to-normal vision. They were all naïve to the purpose of the experiment.

Apparatus

Stimulus presentation and data recording was controlled by E-Prime (Version 2.0; Psychology Software Tools, 2008) software on a PC compatible computer with a CRT monitor. Participants indicated their responses using the keyboard.

Procedure

When participants arrived for the experiment, they were given a written description of the experimental situation and procedure, followed by verbal instruction about the task. They were told that they would be seeing a series of letter strings presented one at a time and that they would be required to decide as quickly and accurately as possible whether or not each string was a word. The participants were not told of the existence of the prime stimulus. Participants viewed a centered forward mask of pound signs (#s) for 500 milliseconds, followed by the prime presentation for 66 milliseconds, and the immediate appearance of the uppercased centered target word (see Figure 3). Participants then indicated their lexicality judgment via the keyboard. Participants performed 20 practice trials before beginning the experiment.

Materials

The prime conditions were (1) identical (e.g., *miscounted/modified*), in which the prime was the same as the target word; (2) transposed letter (e.g., *micsounted/moidfied*), in which the prime transposed the last letter of the prefix and the first letter of the stem; and (3) replacement letter (e.g., *mizrounted/molufied*) in which the prime replaced the last letter of the prefix and the first letter of the stem. Dunabeitia et al. (2007) did not use identical primes, which were used in Experiment 3 to compare TL vs. SL priming and identical vs. SL priming similar to the TL and preview effects computed in Experiments 1 & 2.

There were a total of 72 words and 72 nonwords. Target words were taken from the 36 lexical prefixed and 36 lexical non-prefixed conditions in Experiments 1 & 2. For the nonwords, 36 prefixed nonword stimuli and 36 non-prefixed nonword stimuli were created. For both nonword lists, root frequency was matched to the lexical items, and then a consonant was substituted for an internal vowel to create a nonword (e.g., support becomes pmpular, as support and popular are matched). The consonant change was done to ensure that the lexical decision task was not too difficult, and the root frequency matching was done to ensure that the task was not too easy. Because the goal was for participants to take this task seriously, but not spend too long deciding if the word was lexical and just infrequent, I excluded the novel prefixed items from Experiments 1 & 2. These items would have been very difficult for participants to judge, as they are interpretable and consist of lexical constituents. For pseudo-prefixed nonwords, the prefix was matched to the lexical targets to ensure that participants do not use prefixes as a cue for lexical legality (e.g, misapplied becomes misspklled, as spell and apply are matched in frequency and length). The words and nonwords were presented in uppercase and were preceded by primes of the previously outlined conditions in lowercase. This helps to minimize priming due to mere physical overlap between prime and target.

Three lists of materials were used so that each target appears once in each list, but each time in a different priming condition (identical, transposed-letter or substitute-letter). Different groups of participants were used for each list.

Results and Discussion

Data from incorrect responses (4.6% of word trials) as well as the percentage of trials beyond the 250-1500 ms cutoff (10% of the data) were excluded from the response time analysis. Items that were represented by fewer than nine (out of a possible eighteen) observations were also excluded from the analysis (4% of the data). The mean response latencies and percentages of error are presented in Table 5. Word type (prefixed vs. non-prefixed) was a within-subject variable for the participant analysis, and a between-item variable in the item analysis, as the prefixed and non-prefixed items were not matched.

Word Data

For the word data, the *transposed letter effect* was calculated as described in Experiments 1 & 2: the difference between the substitute letter and transposed letter conditions. For Experiment 3, there is a *priming effect* as opposed to the preview effect measured in Experiments 1 & 2. This is the difference between the substitute letter and identical conditions.

The latency analysis revealed a 27 ms overall (averaged across word types) transposed letter effect, $t_1(53) = 2.91$, $p < .01$, $t_2(57) = 2.06$, $p < .05$, and a 41 ms overall priming effect, $t_1(53) = 3.64$, $p < .001$, $t_2(57) = 3.18$, $p < .01$. The 12 ms difference between the identical and transposed letter conditions was not significant, $t_1 = 1.15$, $p > .20$, $t_2 = 1.12$, $p > .20$. The differences between the SL and TL conditions were 38 ms and 17 ms for prefixed and non-prefixed words, respectively. The interaction of these effects was not significant, $t_1(53) = 1.09$, $p > .20$, $t_2(57) = 1.45$, $p > .10$.

The error data for the non-prefixed words showed better performance for targets preceded by identical (4.1%) and transposed letter (4.0%) primes than for substitute letter primes (4.6%), though not significantly so, $t < 1$. The error data was mildly suggestive of a speed-accuracy tradeoff for the transposed letter effect in prefixed words as participants made more errors in the transposed letter condition (5.2%) than in the identical (3.7%) and substitute letter (4.3%) conditions, but the differences were not significant, $t < 1$. This difference in pattern in the errors might explain, in part, why the transposed letter effect was bigger for the prefixed words.

Nonword Data

Usually, the pattern of data for nonwords in masked priming data is not particularly informative. That is because a prime that facilitates perception may also make the stimulus feel more “wordlike” and, as a result, slow the correct *nonword* response. The latency analyses showed only an advantage of targets preceded by an identical prime relative to a substitute letter prime, significant by participants, $t_1(53) =$

2.37, $p < .05$, but not by items, $t_2 < 1$. For the nonprefixed nonwords, a 33 ms transposed letter effect was not significant, $t < 1$. The other effects were not significant and were typically in the wrong direction. For the pseudoprefixed nonwords, the response times were longest for targets with an identical prime and quickest for targets preceded by a substitute letter prime. These effects are difficult to interpret as processing of the nonwords involves additional processing (e.g. rejection of lexicality) in addition to the processing time prior to rejection. The error data for nonwords showed that participants were significantly more accurate when targets were preceded by substitute letter primes relative to transposed letter primes, $t_1(53) = 2.78$, $p < .01$, $t_2(74) = 2.25$, $p < .05$.

Experiment 3 was conducted as an English replication of Dunabeitia et al. (2007). The findings, however, replicated Experiments 1 & 2, and contradicted the results found in Dunabeitia et al. (2007). Participants were quicker to respond “yes” to prefixed words preceded by a transposed letter prime compared to a substitute letter prime. Dunabeitia et al. (2007) actually found an 8 ms cost for the transposed letter condition compared to the substitute letter condition with their prefixed Spanish targets. In marked contrast, there was a 38 ms transposed letter benefit in Experiment 3 for English prefixed words. While there was a slightly higher error rate for the prefixed words preceded by transposed letter primes compared to substitute letter primes, it was not close to significant, so a speed-accuracy tradeoff is not a viable explanation.

There was a nonsignificant 19 ms difference between the identical primes and the transposed letter primes for the prefixed targets and a significant 38 ms difference between the transposed letter and substitute letter primes. These results suggest that while there may be some minor cost to altering the prime, as indicated by the 19 ms difference, transposed letters are still more facilitative than substitute letters, as indicated by the significant 38 ms difference. These data lend further support for late decomposition theories.

CHAPTER III

GENERAL DISCUSSION

Experiments 1 & 2 demonstrated that decomposition does not occur in the parafovea prior to letter position encoding and Experiment 3 demonstrated that these processes also do not interfere with each other in the fovea. Taken collectively, these experiments are strong evidence for a late decomposition model. In the timeline of visual word processing, these experiments demonstrate that morphemic decomposition does not occur prior to letter position encoding, as the transposed letter effect was elicited in prefixed words, when the transposition occurred across the prefix boundary. These experiments do not necessarily support specific models, but they clearly argue against models proposing “prelexical” morphological decomposition.

Proponents of the early decomposition model include Dunabeitia et al. (2007) whose findings motivated Experiment 3. Dunabeitia et al. (2007) found evidence supporting early decomposition (i.e. a disappearing transposed letter effect when the transposition occurs across a morpheme boundary). This disappearing TL effect occurred using masked priming with Basque and Spanish words. In an attempt to replicate, I used our English materials with the same paradigm, hypothesizing that (a) the different paradigms in Experiments 1 & 2 and the Dunabeitia et al (2007) were measuring different phases of word processing or (b) polymorphemic words may be treated differently in Spanish and Basque than they are in English.

In Experiment 3, there were strong transposed letter effects elicited in both prefixed and non-prefixed words. This is contradictory to the difference in paradigm hypothesis, which proposed that the differences in letter position encoding in the fovea and parafovea were responsible for the inconsistent results. Had I found congruent results, the focus of this discussion would be on foveal vs. parafoveal processing and letter position encoding. Because I found no evidence of decomposition with foveal measures, the discussion will focus on the second hypothesis, the differences between Spanish and Basque, and English.

Dunabeitia et al. (2007) used both Basque and Spanish stimuli. Basque is a unique language; it is the last pre-Indo-European language in Western Europe and has no demonstrable relationship to any other currently spoken language (Perea, Urkia, Davis, Agirre, Laseka & Carreiras, 2006). It is an agglutinative language, meaning words are formed by joining morphemes together. Because Basque has such distinct morphology and syntax, it is not surprising that different effects were elicited with Basque words and English words. The different effects produced by English and Spanish prefixed stimuli, however, merit a more thorough discussion.

A relevant difference between Spanish and English is their respective orthographies. Spanish has a shallow orthography, meaning there is one-to-one mapping between sounds and letters. English has a deep orthography; there is not a close relationship between sounds and letters. Both Experiment 3 and the experiments of Dunabeitia et al. (2007) examined the decomposition of polymorphemic words in the fovea. To accomplish this, the studies examined the effect of transpositions and substitutions across morpheme boundaries. However, there is, in some sense, a confound, because the morpheme boundary is usually also a syllable boundary in prefixed words. The two languages differ, however, in their syllable structure. In English, syllable boundaries are not always clearly defined, whereas in Spanish, syllables have clearly defined boundaries and there is a close relationship between letters and sounds (Carreiras, Alvarez & De Vega, 1993). If syllable boundaries are often less clearly defined in English, it follows that readers may not use the syllable as a lexical access unit in word processing. In Spanish, where syllable boundaries are clear, the syllable may hold a more privileged role in word processing. Evidence in favor of syllabic processing during visual word recognition has been mostly obtained in Romance languages with clear syllable boundaries, like Spanish, rather than in English (Alvarez, Carreiras, & Perea, 2004).

The studies on the role of syllable in English word processing have yielded inconsistent results. Because syllable boundaries are not well defined and ambisyllabicity cases (phonemes that can belong to the preceding or to the following syllables) occur often (Selkirk, 1982, see also Alvarez, Carreiras, & Taft, 2001), the definition and investigation of the syllable has been expanded. Taft (1979), based on a series of lexical decision experiments, proposed a syllable based on orthographic and morphemic properties, with no consideration of the phonological properties. This “syllable” was called the Basic Orthographic Syllabic Structure (BOSS) and was considered the first part of the root morpheme of a word, plus all the consonants following the first vowel, but without creating an illegal consonant cluster (the BOSS of *faster* is *fast*) (Alvarez et al., 2007). In contrast, Hansen and Rodgers (1968) proposed the Vocalic Center Group (VCG), which was a phonological account of the written syllable (the VCG of *faster* is *fas*). The BOSS, in contrast to the VCG, preserves morphological relationships by assigning a common BOSS to all affixed forms of a root (Lima & Pollatsek, 1983). In his experiments with monomorphemic words, Taft (1979) found that a division of a word immediately after its initial VCG was more costly than a division after the BOSS. Taft (1979) cited this as evidence for the BOSSs representation in the lexicon.

Lima and Pollatsek (1983) conducted a series of experiments examining the role of the VCG and the BOSS in word identification. Their experiments were designed to test the claim by Taft (1979) that the BOSS was the lexical access unit implicated in word recognition. Lima and Pollatsek (1983) did not replicate Taft’s findings; they found no BOSS advantage with monomorphemic words when BOSS-divided words were compared to VCG-divided words. They also used polymorphemic words and found no significant priming effects of either the VCG or the BOSS. Lima & Pollatsek (1983) concluded that while syllabic units may be helpful in lexical access, they are not the only lexical representations of words.

In contrast to English, there is considerable and consistent evidence regarding the role of the syllable in word processing in Spanish. Carreiras, Alvarez and De Vega (2004) conducted a series of masked priming with lexical decision experiments to investigate the possible influence of the syllable on visual word recognition for Spanish-skilled readers. To accomplish this, they designed experiments that tested the effects of the frequency of the syllables embedded in words.

Their first experiment used high- versus low-frequency words that contained high- versus low-frequency syllables. They hypothesized that if participants used syllables to visually recognize words, then reaction times should be shorter for high-frequency syllables. They found the typical word frequency effect, reaction times were faster for high frequency words than for low-frequency words, but the opposite effect was found for syllable frequency. Reaction times were slower for words with high frequency syllables than low frequency syllables. There was no interaction. The authors concluded that these results were strong evidence for the importance of syllables as a processing unit in Spanish, as they have a strong effect on visual word recognition. They further explain their results as explainable by a parallel distributed processing-type model, in which the higher frequency syllables fire a larger set of lexical candidates than the low-frequency syllables. Importantly, the results demonstrate a clear role of syllables in Spanish word processing.

The authors replicated the effect using a different paradigm, masked priming with naming, again finding the effect of syllable frequency opposite to the effect of word frequency with no interaction. They then conducted a third experiment, designed to control for bigram frequency and again found the same pattern, where the inhibitory effect of syllable frequency was significant, independent of bigram frequency. Alvarez, Carreiras and Taft (2001) also demonstrated the inhibitory syllable-frequency effect with three lexical decision experiments. Alvarez et al. (2004) found priming effects for disyllabic pairs sharing the first three letters and the first consonant-vowel syllable (ju.nas-JU.NIO), but not for pairs that shared the first three letters but not the first consonant-vowel syllable (jun.tu-JU.NIO).

Taken collectively, these studies are strong evidence for the syllable’s privileged role in visual word recognition in Spanish. The picture in English is less clear. If syllable boundaries are not well defined, readers may not be using the syllable as a lexical access unit and may be less sensitive to their boundary disruption. On the other hand, in Spanish, readers are clearly using syllables as processing units and will be very sensitive to their boundary disruption. This seems to be the most plausible explanation for the incongruent results of Dunabeitia et al. (2007) and Experiments 1-3. English readers are benefiting from the transposed letter effect because the boundary disruption does not interfere with processing units, whereas Spanish readers are not benefiting from a transposed letter effect because the transposition disrupts a syllabic boundary, thus destroying the unit necessary for lexical access.

These results are suggestive of the hypothesis that English and Spanish readers process and identify words differently, which further suggests that a single letter-position or morphemic decomposition model will not satisfy both languages. Experiments 1-3 provide evidence for a late decomposition model, as the transposed letter effect is elicited despite the disruption of morpheme boundaries. The Spanish literature demonstrates a different effect, where decomposition interferes with letter position encoding, suggesting these are co-occurring processes. Thus, any model of letter-position encoding or morphemic decomposition must consider the qualities of the language it is trying to capture.

APPENDIX A

TABLES

Table 1
Means as a Function of Word Type and Preview Type for Experiment 1

	First Fixation	Gaze Duration	Go Past	Total Time
Novel Prefixed Identical	264	374	433	563
Novel Prefixed TL	264	366	465	565
Novel Prefixed SL	284	419	517	601
Lexical Prefixed Identical	249	309	344	450
Lexical Prefixed TL	240	309	353	390
Lexical Prefixed SL	269	326	358	430
Lexical Non-Prefixed Identical	245	293	336	401
Lexical Non-Prefixed TL	243	293	362	393
Lexical Non-Prefixed SL	256	335	375	413

Note. All durations are in milliseconds.

Table 2
LMM Means as a Function of Word Type and Preview Type for Experiment 1

	First Fixation	Gaze Duration	Go Past	Total Time
Novel Prefixed Identical	257	372	440	573
Novel Prefixed TL	258	364	447	557
Novel Prefixed SL	280	416	504	586
Lexical Prefixed Identical	253	322	359	465
Lexical Prefixed TL	236	313	346	385
Lexical Prefixed SL	270	334	366	435
Lexical Non-Prefixed Identical	240	300	335	405
Lexical Non-Prefixed TL	243	301	366	403
Lexical Non-Prefixed SL	259	350	389	420

Note. All durations are in milliseconds.

Table 3

Means as a Function of Word Type and Preview Type for Experiment 2

	First Fixation	Gaze Duration	Go Past	Total Time
Novel Prefixed Identical	264	412	530	628
Novel Prefixed TL	257	396	504	574
Novel Prefixed SL	265	461	539	609
Lexical Prefixed Identical	242	336	411	475
Lexical Prefixed TL	251	332	381	435
Lexical Prefixed SL	261	371	420	473
Lexical Non-Prefixed Identical	242	308	343	369
Lexical Non-Prefixed TL	240	303	361	409
Lexical Non-Prefixed SL	256	335	379	420

Note. All durations are in milliseconds.

Table 4

LMM Means as a Function of Word Type and Preview Type for Experiment 2

	First Fixation	Gaze Duration	Go Past	Total Time
Novel Prefixed Identical	259	394	518	608
Novel Prefixed TL	252	392	496	580
Novel Prefixed SL	269	467	551	613
Lexical Prefixed Identical	239	331	411	464
Lexical Prefixed TL	250	329	381	425
Lexical Prefixed SL	263	371	420	472
Lexical Non-Prefixed Identical	244	298	338	366
Lexical Non-Prefixed TL	238	297	356	405
Lexical Non-Prefixed SL	254	327	373	412

Note. All durations are in milliseconds.

Table 5

LMM Means as a Function of Word Type and Preview Type for Experiments 1 & 2 Combined

	First Fixation	Gaze Duration	Go Past	Total Time
Novel Prefixed Identical	258	387	492	596
Novel Prefixed TL	254	383	480	571
Novel Prefixed SL	272	449	534	607
Lexical Prefixed Identical	244	327	393	465
Lexical Prefixed TL	245	324	369	412
Lexical Prefixed SL	266	357	401	459
Lexical Non-Prefixed Identical	242	299	337	380
Lexical Non-Prefixed TL	240	298	360	405
Lexical Non-Prefixed SL	255	335	401	415

Note. All durations are in milliseconds.

Table 6

Mean lexical decision times and % of errors (in parentheses) for targets in Experiment 3

	Type of Prime			Priming
	Identical	Transposed	Substitute	(SL-TL)
Word Trials				
Prefixed Pairs	789(3.7)	808(5.2)	846(4.3)	38
Non-prefixed Pairs	770(4.1)	777(4.0)	794(4.6)	17
Nonword Trials				
Psuedoprefixed Pairs	936(4.9)	925(4.3)	915(2.8)	-10
Non-prefixed Pairs	899(8.8)	894(10.2)	927(3.4)	33

Note. All durations are in milliseconds.

APPENDIX B

FIGURES

Figure 1

Example Sentence for Experiment 1 for the Lexical Prefixed Condition

*   **I**

Because the student *miaspplied* the mathematical equation, the exam was confusing.

I   *

Because the student *misapplied* the mathematical equation, the exam was confusing.

Preview Conditions
Identical = misapplied
Transposed Letter = miaspplied
Replacement Letter = miorpplied

The asterisk denotes the position of the eye, and the “**I**” denotes the invisible boundary.

Figure 2

Example Sentence for Experiment 2 for the Lexical Prefixed Condition

*   **I**

Because the student *miaspplied* the mathematical equation, the exam was confusing.

I   *

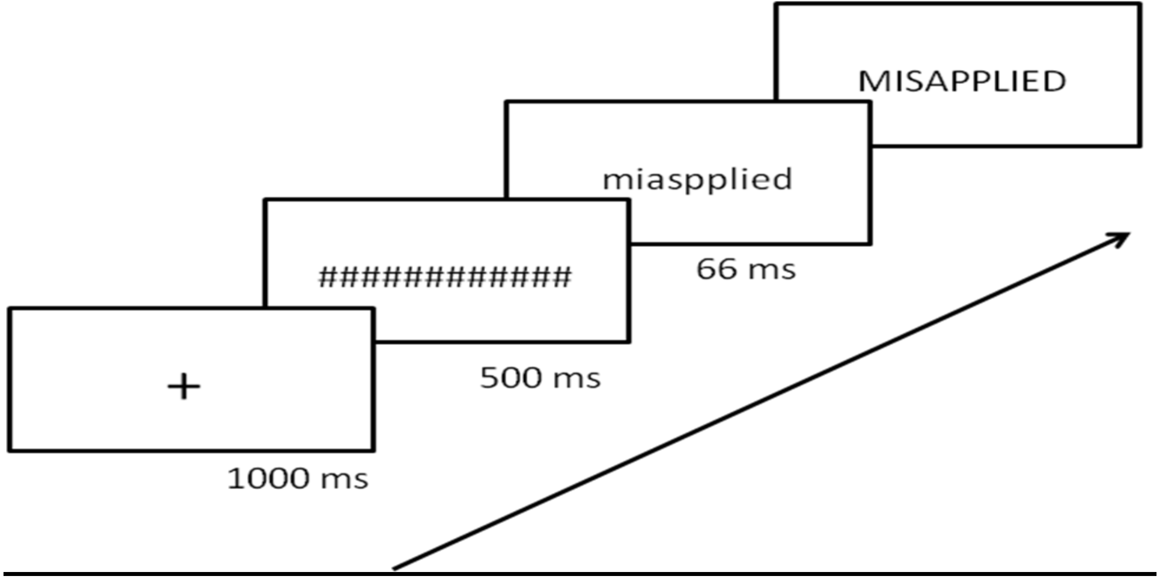
Because the student *misapplied* the mathematical equation, the exam was confusing.

Preview Conditions
Identical = misapplied
Transposed Letter = miaspplied
Replacement Letter = miorpplied

The asterisk denotes the position of the eye, and the “**I**” denotes the invisible boundary.

Figure 3

Figure Representing Masked Priming with Lexical Decision Paradigm with Prefixed Transposed Letter Prime for Experiment 3



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