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Investigations of Lexical Competition and Repeated Letter Effects in Visual Word Recognition

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Thesis submitted for the degree of Doctor of Philosophy

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April 2018

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Acknowledgements

I would like to express my gratitude to my supervisor James S. Adelman for all the help and guidance and all the inspiration and interesting discussions during my studentship. I also want to thank my family and my friends for supporting and encouraging me. Special thanks to my mother and Hanna.

Declaration

The work in this thesis is my own. It has benefited from the supervision of James S. Adelman, who is also a co-author of Chapter 3. This chapter has been published in *Journal of Experimental Psychology: Learning, Memory and Cognition* and has been reviewed by Kenneth Forster, Serje Robidoux and Stephen Lupker.

Summary

The present work explores two different effects in orthographic processing in visual word recognition. The first part is motivated by the lexical competition hypothesis which suggests that the process of recognizing a word is mediated by competitive mechanisms between visually similar possible candidates. The lexical competition effects are explored in lexical decision studies accompanied by competitive network model simulations. The studies compare findings with the conventional masked-priming paradigm with those obtained with a modified version of this procedure, designed to decrease lexical competition effects. The results are discussed in terms of their theoretical and methodological contributions. The second part of the thesis relates to letter level processing in word recognition. It explored effects of repeated letters with the regression and the factorial approaches in combination with computational modelling methodology. The regression approach is applied to megastudy data in English, Dutch, and French. The factorial approach explores the effect across several different experimental paradigms: masked-primed lexical decision and same-different tasks as well as a two-forced-choice perceptual identification task. The findings are presented along with discussions of their important implications for developing theories of letter and word processing and models of visual word recognition.

Chapter 1

The Interactive Activation Model and its Influence on Visual Word Recognition

One of the early compelling findings with important implications for development of visual word recognition research and computational modelling is the *word superiority effect.* In a tachistoscopic identification procedure, in which masked stimuli were presented for a brief duration, followed by two alternative response options, Reicher (1969) and Wheeler (1970) demonstrated that letters were more accurately identified when they were embedded in words than when they were presented in isolation. These results suggested that four-letter words were recognized more easily than single letters. The finding was also extended to pronounceable pseudowords. These results were not predicted by contemporary researchers advocating either parallel or serial processing of visual information. As Wheeler pointed out, in a serial processing model there should be a delay if letters were to be processed one at a time, while a parallel model would predict no difference between letters and words. Neither of those would predict superior performance in the case of more information than in the case of less information. How could a whole word be recognized faster than one of its constituents? The word superiority effect encouraged the development of several computational models that focused on providing an explanation of the context effects facilitating letter identification. One of these models would have a profound impact on visual word recognition research.

The Interactive Activation model (IA; McClelland & Rumelhart, 1981), referred to by Davis (2003) as "the first model of visual word recognition", one of the most influential models in the field, was motivated by the finding of the word superiority effect. This localist connectionist model has a hierarchical structure with three distinct levels of meaningful representations: features, letters and words. The set of features was identical to the one earlier presented by Rumelhart and Siple (1974). However, unlike their model the features were not stochastically extracted and were implemented as localist network representations. The word lexicon of the model contained only four-letter words. The presence of these levels and their hierarchical order are some of the basic assumptions of the model. The rest of the assumptions relate to the manner in which the perceptual process is achieved. The model assumes parallel processing of information within levels suggesting that several letters are processed simultaneously. Furthermore, the parallel assumption is also applied between levels, as visual processing of letters and words occurs at the same time. Another basic assumption of the model accommodates for the word superiority effect directly. This is the assumption of interactivity. Information is transmitted not only between the adjacent units at each of the levels, but also from the bottom to the top level and vice versa. The letter level is affected by and affects the activity of the word level. In this way, the model successfully implements top-down as well-as bottom-up effects on word recognition. The communication within and between the levels is achieved through a mechanism of spreading activation. The levels communicate through excitatory and inhibitory links. Units (nodes) that are consistent with a visual input receive activation while inconsistent ones are inhibited. One important characteristic of the model is that the consistent and inconsistent information is communicated through separate channels (letter positions) due to the model's slot-based position-specific encoding scheme. In this scheme every letter is assigned to a specific slot (position, channel) and projects its activity only on this channel. The letter *a* in first position will activate words containing the letter *a* in first position and will inhibit others that start with a different letter. It will not activate words in which *a* is in another position. It follows from this position-specific scheme and spreading activation mechanism that words that are similar in form and share features and letters in the corresponding positions (e.g. work - word) are simultaneously activated once a stimulus related to them is presented. The representation of the word that is identical to the input will get activated along with representations of other orthographically similar words. These will all be considered as candidates in the process of lexical selection. Activated word nodes inhibit each other through lateral inhibitory links. Thus, another assumption of the interactive activation model states that the process of lexical selection is mediated by a lexical competition.

The interactive activation framework suggests that the processing of a single letter in a letter string not only takes place in parallel to the processing of the other word or pseudoword letters but is in fact enhanced by them through interactive bottom-up and top-down mechanisms. Each of the input letters activate consistent word nodes, which in turn increase the activation of corresponding letter nodes and therefore facilitate the recognition of each individual constituent letter. The process of letter reinforcing iterates as the stronger activation of the consistent letters further increases the word nodes which in turn produce stronger top-down effects on letter processing. It should be noted that another important assumption of the model is the cascaded flow of activation that ensures fast activation of the word nodes.

In the second paper showcasing the IA model, Rumelhart and McClelland (1982) put the interactive activation explanation of the word superiority effect to the test and further explored contextual effects on letter perception. They extended the previous findings of Reicher (1969) and Wheeler (1970) with different context type conditions and various onset asynchronies between the presentation of the context and the target letter. The context and the target letter were also presented for different durations. The authors argued that an interactive activation interpretation of the perceptual processes underlying the context effects suggested that the degree of the observed context effects should be dependent on the time of the presentation of the context relative to the presentation of the target letter. One prediction of the model is therefore that there should be enhanced contextual effects in cases in which the context is displayed for a longer duration and precedes the presentation of the target. This and other predictions of the model were tested in a set of 10 different experiments which employed Reicher's forced-choice paradigm. The results of the experiments were compared with the specific predictions of the model and effectively demonstrated its ability to account for a large variety of experimental conditions. In Reicher's paradigm, a string of letters (often a word) is briefly presented and followed by a mask and presentations of two alternative letter options above the target letter position. The task for the participants is to indicate which of the two alternative letters were presented by pressing one of two corresponding buttons. When the letters form a word, care is usually taken to minimize guessing by ensuring that both options form a genuine word. For example, if the presented string is WORD and the tested position is the final one, the two given options might be D or K.

In accordance with the IA model's prediction, Rumelhart and McClelland (1982) demonstrated that longer presentation of the context letters relative to the presentation of the target letter improved the accuracy in performance of letter identification. When the onset of the context letters preceded the onset of the target letter and proceeded until its offset, the target letter was recognized more accurately in comparison to conditions in which the context onset was at the same time or after the target onset. The increase of the context duration relative to the one of the target did not have any effect on the letter recognition when the target letters were embedded in numbers, rather than in word letters. These results were in accordance with the predictions of the IA model, which explained the enhanced context effects with preactivation of consistent word nodes, which in turn facilitated the target letter recognition through top-down effects. Contextual facilitation could not be observed with the digit strings as they could not activate any word nodes. Another result that was consistent with the results of the IA model simulation was that the decreased contextual effects in cases when the context was presented after the target letter than when it was presented before or simultaneously with the target letter. The model successfully predicted several other results of experiments with different manipulations of the timings and durations of the context and the target letter. The good fit to the data suggested the ability of the model to account for a variety of conditions.

Rumelhart and McClelland (1982) extended their contextual enhancement findings to the cases of nonword letter strings. As predicted by the model, the contextual enhancement effect was observed with pronounceable pseudowords, but not with an unusual letter strings formed by double adjacent transpositions such as OWDR and AWDR from WORD and WARD, respectively. In another experiment, the authors further showed that the nonword contextual effect was dependent on the orthotactic predictability of the letter strings, rather than on orthotactic regularity and pronounceability. In the final experiment of their study, they even demonstrated that orthotactic regularity and pronounceability are not necessary for a nonword contextual effects to be observed. They showed a strong contextual effect with illegal and unpronounceable consonant strings of letters. The crucial characteristic of these strings was that they had three letters out of four (all but one) that were consistent in position and identity ("orthographic neighbors") with several word units (e.g. SPCT – SPAT, SPIT, SPOT). Therefore, if one of the consistent letters is tested (e.g. P), its recognition would be facilitated by top-down effects of the activated word "friends". Consistent with the interactive activation account, these consonant strings produced a strong context facilitation relative to nonwordlike consonant strings (XPQJ). The facilitation effect did not differ significantly from the one observed with a pronounceable context (e.g. SPET). These results suggested that effects such as word and pseudoword superiority effects could be explained with orthographic processes and a relatively simple model (with complex network dynamics) without implementations of orthography-to-phonology mappings could account for the obtained data.

The IA model was not the only model to be motivated by the word superiority effect. Another model that was designed to address this effect was the Activation-Verification model (Paap, Newsome, McDonald, & Schvaneveldt, 1982). As in the IA model, the Activation-Verification model contains levels of representation that correspond to letters (alphabetum) and words (lexicon) and explains the word superiority effect with activation of lexical units. Unlike IA model, however, the Activation-Verification model makes use of confusion matrices for generating activities to these two levels. Another major difference between the two models is that unlike the IA model, in the Activation-Verification model there is no feedback from the lexical level to the letter level (and reinforcement of the context letters by the activated word nodes). Rather, top-down effects are implemented through a dual read-out mechanism, i.e. the letter recognition decision could be made on the bases of activities of alphabetum units as well as on highly active word units that have acceded some word-unit criterion and are available for the decision process. In cases of high global lexical activity, associated with exceeding of a lexical preset criterion, the decision is based on lexical rather than letter evidence. Like the IA model, the facilitation for a letter recognition is dependent on the ratio of "friends" and "enemies", i.e. words that contain the target letter at the same position and words that contain the alternative letter at the corresponding position. However, unlike the IA model, the amount of facilitation will not only be based on the number of words that share three letters with the stimulus (friends and enemies) but also on the overall confusability of the fourth mismatched letter. If the mismatched letter is not very confusable with the target letter, the corresponding neighbor word might not exceed the word-unit criterion and therefore will not be available for the decision process. The ratios between friends and enemies generated by the two models will often be different, with the Activation-Verification model containing only a subset of the neighbors considered by the IA model, therefore leading to different predictions between the two models.

Despite its inspiring ideas, such as the dual-read out implementation of top-down effects, the Activation-Verification model did not reach the same level of popularity as the IA model. The IA model remained extremely influential and shaped visual word recognition research. Grainger (2008) suggests that IA model is a "powerful theoretical framework" for the understanding of word and object recognition. Many computational models in visual word recognition have been based on the interactive activation architecture with extensions for lexical decision and word naming tasks, two largely used paradigms in visual word recognition (e.g. Dual route cascaded model, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Multiple read-out Model, Grainger & Jacobs, 1996; the open-bigram model, Grainger & van Heuven, 2003; the Spatial Coding Model, Davis, 2010). The open-bigram model by Grainger and van Heuven and the Spatial Coding Model by Davis, are at present among the most prominent models in the field and are largely used for developing theories of word and letter processing. These models will be further discussed and tested in the context of the studies of this thesis.

Much orthographic research has been motivated by previously untested assumptions of the IA model and predictions following some of those assumptions. The present thesis is yet another example. One such assumption is the lateral inhibition mechanism that implies that the process of lexical selection is mediated by competition among the selected word candidates. The lexical competition hypothesis was not the focus of the orthographic processing research for almost two decades after the IA model's publication. Since the hypothesis gained popularity, however, it has been stated as the underlying mechanism of many effects reported in the lexical selection research literature. The lexical competition hypothesis will be further discussed in chapters 2-4 of this thesis. Chapter 2 will discuss background literature related to this hypothesis. It will be followed by two chapters with studies based on this hypothesis. Chapters 3 will test a hypothesis that the *sandwich priming paradigm* designed by Lupker and Davis (2009) is an effective tool of measuring form similarity between two letter strings as it reduces inhibitory lexical effects. Lexical decision experiments will be presented along with simulations in the interactive-activation based Spatial Coding Model (Davis, 2010).

Despite its complex architecture (see Figure 1.1), the Spatial Coding model (Davis, 2010) has retained many of the basic assumptions of its predecessor, the IA model (McClelland & Rumelhart, 1981). Like the IA, the feature, letter and word levels of localist representations are still present, as is the assumption of lateral inhibition. The lateral inhibition mechanism is incorporated by summation nodes that encode the total lateral inhibition signal. The inhibition signal is a function of weighted sums of words' activation for each word length, where long words induce stronger inhibition signal than short words. The amount of inhibition to a single word node is then determined by the total word sum inhibitory signal, the length of the word node and a counteractive word-word excitation signal. As the excitation signal is a function of the word node's activity, words with higher activation levels receive less inhibition. Furthermore, they produce more inhibition to other words, thus dominating the word level. This outcome has motivated the creation of the sandwich priming paradigm, which aims to boost the activation of target words, thus making them stronger competitors. This paradigm will be discussed in greater detail in Chapter 3. Chapter 4 will continue exploring the lexical competition mechanism with sandwich priming and a lexical decision task.

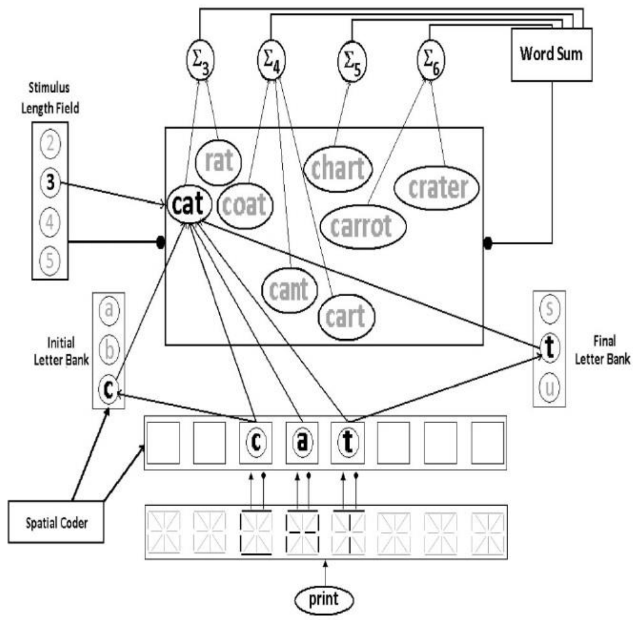

Figure 1. 1 Architecture of the Spatial Coding Model. Taken from Davis (2010) without permission.

The second part of the thesis will address the channel-specific limitation of the IA model's encoding scheme. Although Rumelhart and McClelland (1982) admit that this assumption is an oversimplification, the limitations of the channel independent assumption were also not addressed for decades after the IA papers' publication. According to this scheme the presence of a letter identity in a particular position does not affect the perception of letters in other positions and words containing this identity in different position. The letter *a* in initial position will not activate words containing *a* in other positions. Furthermore, *a* in initial position is different from *a* in third position. Therefore, this scheme will not predict any effects of repeated or transposed letters on word identification. This channel specific scheme has been falsified by a great deal of evidence in the literature suggesting interference between the channels and considerable degree of positional intolerance of the perceptual system (e.g. Guerrera & Forster, 2008; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003, 2004; Peressotti & Grainger, 1999). To account for this evidence, the interactive-activation based open-bigram (Grainger & van Heuven, 2003) and spatial coding model (Davis, 2010), incorporated two entirely conceptually different encoding schemes. This difference between the two models is reflected in their predictions of specific orthographic effects. This will be further illustrated in the second part of the thesis. Chapter 5 will discuss evidence on letter processing. Chapter 6 will present a study of repeated letter effects on word recognition using the regression approach on megastudy data. The results will be accompanied by simulations in Spatial Coding Model and the open-bigram model and an evaluation of their encoding schemes.

The Spatial Coding Model (Davis, 2010), as already discussed, retains the IA model's (McClelland & Rumelhart, 1981) letter representations in its architecture. Unlike the IA model, however, the letter position and identity encoding scheme is not channel specific. In the Spatial Coding Model, the letter positions in word representations are represented by spatial patterns. To incorporate letter position uncertainty, each letter position code of the input stimulus has the shape of a normal distribution, rather than a single value, with its spread representing positional uncertainty. The spatial pattern of the input is compared to the spatial pattern of a stored word representation with a procedure called superposition matching. The matching algorithm includes computing the signal-weight difference functions for each letter of the word representation, sums up all the difference functions and finally divides the obtained peak of the superposition function by the length of the word representation. When a stimulus word is compared to the identical word representation, a perfect match score of 1 is obtained, as all the difference functions are perfectly aligned with a mean of 0.

The Spatial Coding Model (Davis, 2010) has an explicit mechanism that deals with repeated letter cases. It uses bins of clones of letter receptors that compete, interact, and cooperate with the final goal of achieving the maximum match score between the input and a word representation. As can be seen in Figure 1.2., when the input stimulus contains repeated letters (e.g. stoop) and is matched with the identical word representation (template word), more than one clone gets activated in the banks of the repeated letters. The optimal signal-weight difference of 0 that contributes to the highest match score, however, is achieved only in the case when the letters of the stimulus are matched with their expected positions in the word template. As a letter from the stimulus could be associated with only one receiver clone (the winner), a letter unit (repeated or not) contributes only once for the match score calculation. With this mechanism, the Spatial Coding effectively treats repeated letters as different items and is unlikely to predict any effect of letter repetition.

The relative position parallel open bigram model (Grainger & van Heuven, 2003) like the Spatial Coding Model (Davis, 2010), is also based on the interactive-activation architecture but has an entirely different schemes with which it accounts for the evidence for the letter position tolerance of the perceptual system. In the parallel open-bigram model, the letter level representations from the IA model (McClelland & Rumelhart, 1981) are replaced by representations of open bigrams (see Figure 1.3). They are in the relative position map level, at which the letter positions are encoded after letters have been initially identified. Position encoding is achieved through activating bigram units containing information of the position of one letter relative to the others, or more specifically, whether a letter is located to the left or to the right of the other letters in the word (up to two intervening letters). The word SILENCE is therefore represented by the open bigrams SI, SL, SE, IL, IE, IN, LE, LN, LC, EN, EC, EE, NC, NE, CE. In cases of letter repetitions that occur in up to two intervening letters in the stimulus, one or more bigrams will be repeated, but counted only once (e.g. STOOP – ST, SO,TO,TP, OO, OP) and therefore fewer bigrams will be activated than with stimuli with the same length and unique letters (e.g. STRIP – ST, SR, SI, TR,TI, TP, RI, RP, IP). For this reason, the expectation is that the open bigram model would be likely to predict inhibitory effects of repeated letters (as noted by Schoonbaert & Grainger, 2004). The exact predictions of the Spatial Coding Model and the open-bigram model regarding effects of repeated letters will be firther discussed in Chapter 6. Chapter 7 will continue the exploration of repeated letter effects with the factorial approach and various experimental paradigms. Finally, Chapter 8 will summarize the contributions of the present work and will discuss possible future research directions.

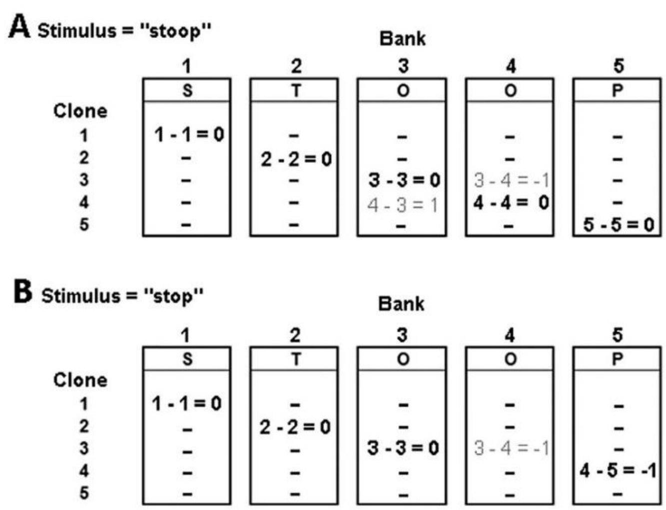

Figure 1. 2 Banks of cloned receiver nodes in the Spatial Coding Model. Illustration of computations performed by receiver nodes associated with the STOOP word node. Taken from Davis (2010) without permission.

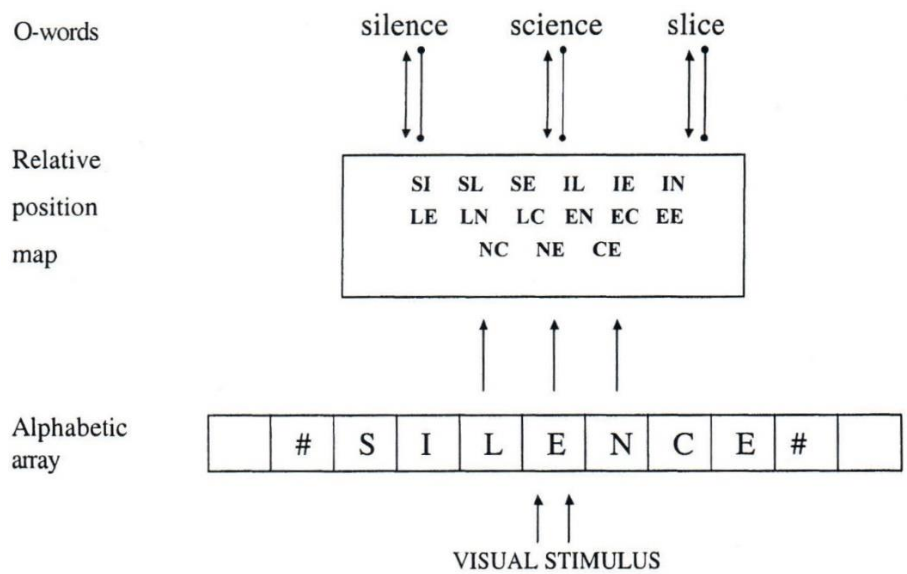

Figure 1. 3 Architecture of the relative position open-bigram model. Taken from Grainger and van Heuven (2003) without permission.

Chapter 2

Lexical Competition

As already discussed in the previous chapter, in the Interactive Activation model (McClelland & Rumelhart, 1981) the representation of the word that is identical to the input will get activated along with those of other orthographically similar words. All lexical units that are sufficiently consistent with the input and share features and letters with the target will be considered as candidates in the process of lexical selection. This process is mediated by competitive mechanisms that arise between the activated candidates. As the nodes on the top level are connected (only) with inhibitory links, activated word units send inhibition to other words, a mechanism known as lateral inhibition. Thus, the authors of the interactive activation model and those of other models based on the same architecture (e.g. Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. 2001; Davis, 2010; Grainger & van Heuven, 2003) assume that the process of lexical selection (recognizing a letter string as a word) is mediated by a lexical competition. This competition arises as the activation of the target is accompanied by the activation of other similar words which compete until a winner is selected. The competition ends once the activity of one of the lexical candidates exceeds a certain activation threshold.

There have been several reported effects in the literature that are consistent with this lexical competition hypothesis. One prediction of the Interactive Activation model related to lexical competition (McClelland & Rumelhart, 1981) follows from its implementation of the word frequency effect. In the competitive interactive activation framework, high-frequency words get activated more strongly sooner, as their resting level is higher than that of low frequency words. Words with high activity are strong competitors and induce strong inhibition to other lexical units. Therefore, high-frequency words that are closely related in form to target words, such as orthographic neighbors (words of equal length that differ by only one letter in the same position, such as take–cake or take–tape; Coltheart, Davelaar, Jonasson, & Besner, 1977) should be one of the target's strong competitors. One test of the lexical competition hypothesis, therefore, relates to whether words that have high-frequency neighbors are more difficult to recognize (due to the inhibitory influence of the neighbor competitor) than words with no high-frequency neighbors, or not.

Such an effect was indeed demonstrated by Grainger, O'Regan, Jacobs, and Segui (1989) who coined the term *neighborhood-frequency effect*. The authors used an unprimed lexical decision task in which participants indicated whether a letter string presented on a computer screen formed a genuine word or not by pressing one of two corresponding buttons. The target words comprised of four-letter long French words that were divided into four groups: words with no orthographic neighbors; words with one orthographic neighbor with no higher frequency than the target; words with one high-frequency neighbor; words with several high-frequency neighbors. The word groups were matched in word frequency, familiarity and positional token bigram frequency. The results showed that words with at least one high-frequency neighbor were responded to significantly more slowly than words with no orthographic neighbor or low-frequency neighbor. The condition with several high-frequency neighbors did not differ from the condition with one high frequency neighbor, suggesting that the higher number of high-frequency neighbors did not further enhance the inhibitory effect on target recognition.

The neighborhood frequency effect is consistent with the lexical inhibition hypothesis. However, as noted by Grainger and Segui (1990), it is also consistent with the Activation-Verification model (Paap, Newsome, McDonald, & Schvaneveldt, 1982) in which word recognition is mediated by a serial verification procedure that searches compatible candidates in order of the candidates' word frequency. Grainger and Segui argued, however, that the two accounts will differ in their predictions of a word frequency effect once neighborhood-frequency is controlled for. They suggested that in the Activation-Verification model word frequency effects could be explained by neighborhood frequency because it is the rank of the frequency among neighbors that controls the duration of a frequency-ordered verification process. The Interactive Activation Model, on the other hand, would predict an effect of word frequency, as it is implemented in the resting levels of the word nodes, with high resting levels assigned to words with high word frequency. In a lexical decision experiment, Grainger and Segui manipulated word frequency by selecting words that had either low or medium frequency and either had no high-frequency neighbor or had at least one high-frequency neighbor. The results showed main effects of both factors. The words with medium frequency were responded to significantly faster than those with low frequency, and words with high-frequency neighbor took significantly longer to process than those without. The authors argued that these results were consistent with the interactive activation framework and the lexical inhibition hypothesis and inconsistent with the Activation-Verification model. In another experiment from the same study, the authors introduced the progressive demasking perceptual identification task with which they continued investigating the same problem. In this paradigm, the presentation of a stimulus is alternated with a presentation of a mask. Initially the mask is presented for a long duration (320 ms) and the stimulus is presented for a short duration (16 ms) but after each cycle the presentation of the mask is decreased, while the presentation of the stimulus is increased by the same amount, and so the total cycle duration kept constant. In this way, the target appears as if it is gradually emerging from the noise. Participants are instructed to press a button once they recognize the word and to enter the word they have seen. Latencies from the target onset to the response as well as error rates are measured. Grainger and Segui replicated the facilitatory word frequency effects and the inhibitory neighborhood frequency effects with the progressive demasking task. An interaction between the two factors was also observed such that the inhibitory neighborhood effect was stronger for low frequency words than for the medium frequency words.

In a similar line of research, Grainger (1990) argued that the stronger facilitatory effect of word frequency on target recognition in lexical decision in comparison to the word frequency effect in naming (e.g. Frederiksen & Kroll, 1976) could be due to uncontrolled inhibitory effect of neighborhood frequency. He suggested that high frequency words are less likely to have a higher frequency neighbor. On the other hand, low frequency words are more likely to have a high-frequency neighbor. Therefore, word frequency effects that have been reported could have been confounded by neighborhood frequency effects. Grainger conducted a study with four-letters-long words in Dutch, which were controlled for bigram frequency and were used as stimuli in word naming and lexical decision tasks. The design consisted of three levels of neighborhood frequency, which differed in terms of the presence of a high-frequency target neighbor and the number of such neighbors (no neighbor, one neighbor, more than one neighbor). In addition, there were two levels of word frequency (low, medium). The results showed no interaction between word frequency and task, which Grainger interpreted as evidence that controlling for neighborhood frequency deflates the word frequency effect in the lexical decision task. The results from the lexical decision performance, however, did not show any interaction between neighborhood frequency and word frequency. An important result was, however, the main effect of neighborhood frequency. Words with no neighbor were faster to respond to than words with one or more than one high-frequent neighbors. These results thus replicated the results of Grainger et al. (1989).

The neighborhood-frequency effect was also investigated in the context of the word superiority effect and the Reicher-Wheeler two-alternative-forced choice (2AFC) perceptual identification task. Grainger and Jacobs (1994) tested participants’ performance when reporting letters embedded in low-frequency French words that either did or did not have a higher-frequency neighbor. Letter report performance in words was compared to another context in which the letters appeared in pseudowords. The letter position and the letter identity across contexts was matched. Unlike in the original paradigm, however, participants were also instructed to report the whole word after their forced-choice response whenever they were capable of doing so. The results showed that in the word context, the accuracy was significantly higher when words did not have a higher frequency neighbor than when they did have one. This result was also present in the word report data. The results also demonstrated a word superiority effect that correlated highly with the word report accuracy. In a subsequent experiment, the authors measured performance of letter perception when the letters appeared in the contexts of high frequency words (with the alternative letter forming another high frequency word), pseudowords and strings of Xs. The results showed that participants were most accurate in the word context condition, followed by the pseudoword context and least accurate in the Xs strings context. The authors suggested that in an interactive-activation framework, the word report accuracy could be a measure of the activity of a word node, while the accuracy in the letter report in the context of the Xs strings reflected the activation of a single letter node. They presented the interactive-activation based Dual Read-Out Model (DROM) which differed from the original model by its modified decision rule. Similar to the Activation-Verification model (Paap et al., 1982), the decision in DROM could be based on activity of a word node or activity of a letter node. A correct choice is made once one of the two activities reaches a certain threshold: the activity of a single target letter node or the activity of a word node containing the correct letter in the correct position. If none of those reaches a threshold, the response is "guessed". The predictions of the DROM successfully captured the neighborhood frequency effect as well as the advantage of word and pseudoword contexts over the context of Xs strings.

The idea of modelling a decision rule based on more than one source was further developed in the multiple Read-Out Model (MROM; Grainger & Jacobs, 1996). Like the dual-read out model (DROM; Grainger & Jacobs, 1994), the MROM had the interactive activation architecture (McClelland & Rumelhart, 1981) with a modified decision rule. Grainger and Jacobs argued that a functional overlap strategy should be followed in visual word recognition modelling. One model should account for the common visual word recognition functions in different tasks that are used for the exploration of this domain (lexical decision, perceptual identification, word naming). However, the model should also be able to explain inconsistencies in results between the different methodologies, resulting from task-specific demands and response strategies. Setting word naming and computation of a phonological code aside for simplification reasons, the authors suggested that MROM could simulate lexical decision task and perceptual identification task results. The decision in the lexical decision task is made once one of the thresholds is reached by any of three possible sources. The first criterion is associated with the local activity of a single word node. The second source is the global activity at the word level, measured by summing the activation levels of all word nodes. The final criterion is set by a time limit threshold. The last two criteria are not a part of the decision computation in the perceptual identification task, in which the overall word-like appearance of the stimuli does not play such a role as in the binary decision in the lexical decision task. The decision in the perceptual identification task (the progressive demasking task, rather than 2AFC perceptual identification) is made once the activity of a single word exceeds a specific threshold.

Grainger and Jacobs (1996) argued that previous findings of inhibitory effects of neighborhood frequency and high frequency neighbors occurred due to lexical competition mechanisms and stated the *lexical inhibition hypothesis* as one of the basic assumptions of the MROM. In their study, they further tested this core assumption by investigating effects of neighborhood density, neighborhood frequency and word frequency in lexical decision and progressive demasking tasks. In a series of experiments, they tested performance on low accuracy words that were divided in four groups. In two of those four groups, the words had a small number of orthographic neighbors (small *N*; group 1 and 2) and in the other half that number was high (high *N*; group 3 and 4). The groups were further divided by the number of high-frequency neighbors, which was: none, one, one, and several for groups 1-4, respectively.

The set of experiments contained one experiment with the progressive demasking task, followed by three lexical decision experiments (LD1, LD2, LD3). LD1 and LD2 differed only by the nature of the nonword stimuli. In LD1 they were more similar to words (difficult nonwords) while in LD2 they were easier to differentiate from a word (easy nonwords). Grainger and Jacobs (1996) suggested that this manipulation reflected the total word activity, with the harder nonwords activating more words and producing a high level of global activity and the easier nonwords producing lower levels of global activity. The authors argued that in the latter case, participants should set a lower threshold of global activity and should be able to produce faster response times without an increase in the error rate. The final experiment (LD3) from the set was identical to the lexical decision task with difficult nonwords (LD1), except for the instruction for the subject to prioritize speed over accuracy.

The results from the progressive demasking task indicated significant inhibitory effect of the presence of one orthographic neighbor, as well as further significant delay in responses to words with more than one high-frequency neighbors. The results from the first lexical decision experiment (LD1) replicated the results from the progressive demasking task regarding the inhibitory effect of an orthographic neighbor but showed no further inhibition when the number of high-frequency neighbors was increased. When the nonwords were easy (LD2), the results indicated an inhibitory effect of one high-frequency neighbor. However, unlike the results in the previous experiments, there was a facilitatory effect of the number of orthographic neighbors. The pattern of results of the last experiment (LD3) resembled the one of LD2, with a smaller effect size of the presence of a high-frequency neighbor and replication of the facilitatory effect of number of orthographic neighbors.

Grainger and Jacobs (1996) demonstrated that the overall pattern of the results could successfully be simulated in MROM by adjusting the number of sources of information on which the decision is made as well as the thresholds of the specific sources (criteria). In the progressive demasking task, only the local activity was taken into account, while in the lexical decision task simulations the global lexical activity and the time deadline were also considered. The argument behind this implementation of the decision in the different tasks was that in the progressive demasking task participants need to identify one word before they respond, therefore isolation of the activity of a single word node is required. In lexical decision, on the other hand, participants might base their response not only on the identification of a word, but also on the overall resemblance of the stimuli to the word category, therefore the global activity was also used as a separate decision source. The inhibitory effect of a high-frequency neighbor that was observed in the progressive demasking task and the first lexical decision experiment was captured by MROM, as was the decrease of the effect of the number of high-frequency neighbors in the lexical decision task in comparison to the progressive task. The authors attributed the correct model prediction to the differences in the decision criteria used in the two tasks.

To accommodate the manipulations in the three lexical decision experiments, the authors decreased the global activity threshold in the simulation of LD2, and both the global activity and time thresholds in the simulation of LD3. The authors argued that the easy nonwords that were easily discernible from words would lead to lower mean global activity, which in turn could make participants adapt and base their response on a lower global activity threshold. The authors suggested that this lower global activity threshold would make more use of this criterion and as the response would be based on the first source in which the threshold has been exceeded, this could lead to different pattern of results. Indeed, the results of the simulations of the three lexical decision experiments captured the empirical data and predicted an inhibitory effect of high-frequency neighbor and facilitatory effects of neighborhood density only when the global activity threshold was reduced. The authors argued that such facilitatory effects are caused by strategies involving the overall word-like appearance of the stimuli, reflected in the high global word activity criterion (increased global activation from stimuli with high *N* in a situation of a decreased global activity threshold). They further suggested that the inhibitory neighborhood frequency effect was mainly driven by the single word activity criterion and it was decreased by the increased use of the global activity criterion (when the global activity threshold is reduced), as words that had high frequency neighbors activated the lexicon globally more strongly than did words with no high-frequency neighbors. Grainger and Jacobs (1996) concluded that the obtained experimental results were in accordance with the lexical inhibition hypothesis. The dynamics of the observed effects was captured by MROM due to its implemented lexical inhibition and multiple decision criteria mechanisms and defensible parameter choices to reflect different settings.

Effects that are consistent with the lexical competition hypothesis have also been obtained with the masked-priming paradigm. Generally, such evidence could be divided into two categories: less priming (decreased facilitatory effects) in a context of competition and inhibitory effects observed with similar to targets competitor primes. Many of the predictions of the lexical competition framework have been tested with the masked-priming paradigm. This paradigm is often used in studies for exploring processes in lexical selection in combination with the lexical decision task (Forster, Davis, Schoknecht, & Carter, 1987). In this task, participants indicate whether a letter string presented on a computer screen forms a genuine word or not by pressing one of two corresponding keys. Participants are typically unaware of the presence of the prime briefly presented after a mask (######) and prior to the target. Nevertheless, they are often faster when the prime is related in form to the target (e.g. bontrast-CONTRAST) in comparison to when it is not (shiuder-CONTRAST). The difference between the two conditions, the priming effect, is usually interpreted as the degree to which the orthographic codes between the related prime and the target overlap. In their study, Forster et al. (1987), however, also provided evidence suggesting that the facilitation produced by a masked prime is not only a function of the similarity between the two strings but also the similarity of the prime-target pair with other words in the lexicon. They demonstrated that the priming effect of nonword primes one-letter different from targets is affected by the neighborhood density (the number of orthographic neighbors) of the prime-target pair. The priming effect in the low neighborhood density pairs was stronger than the priming effect in the high-neighborhood density pairs. Words with many orthographic neighbors are less primable than words with fewer orthographic neighbors.

The idea that the priming effect could be modulated by the similarity of the prime-target pair to other “competitor” words was further supported by Hinton, Liversedge, and Underwood (1998) who demonstrated stronger priming effects with partial primes that provided stronger constraint to the target (bon%-BOND) than primes that were less constraining and resembled a competitor word (e.g., fond, pond; %ond-BOND). Van Heuven, Dijkstra, Grainger, and Schriefers (2001) argued that these results were consistent with the interactive activation framework and pointed out that mutual neighbors of the prime and the target are stronger competitors than neighbors of the target only, as such “shared” neighbors receive activation by both the prime and the target and therefore produce strong inhibitory effects on the target. The authors reported results from an experiment that demonstrated a smaller priming effect was produced by nonword primes that shared a neighbor with the target than by primes that did not share neighbors with the target. These results were captured by a simulation of the Interactive Activation model (McClelland & Rumelhart, 1981), which predicted a slower increase of the activity of the target in the condition in which it shared a neighbor with the prime than in the condition with no shared neighbor.

Other masked-priming evidence in favor of the lexical competition hypothesis comes from reported results of inhibitory effects produced by word primes. As already noted, in the competitive interactive activation framework, words that are very similar to targets, such as their orthographic neighbors, are some of their strongest competitors. This should be particularly true if their frequency is higher than the target’s as high frequency words get activated faster and therefore produce strong inhibition to other units. One prediction of this account is therefore that high-frequency orthographic neighbors should inhibit target’s recognition if they precede its presentation. Segui and Grainger (1990) confirmed this prediction empirically and demonstrated that responses to low-frequency target words in French were significantly delayed after a presentation of a high-frequency word primes in comparison to an unrelated high-frequency word primes. Davis and Lupker (2006) replicated this effect in English and reported a prime-lexicality effect: one-letter-different nonword primes (axue-AXLE) facilitated target recognition while one-letter-different word primes (able-AXLE) inhibited it. The finding that related nonword primes facilitate target recognition had been reported many times before Davis and Lupker (e.g., Forster et al., 1987). However, they demonstrated how the priming effect reverses its direction in the cases of nonword and word primes in one experiment. The prime lexicality effect has been interpreted as further evidence for the lexical competition mechanism: Nonword primes preactivate the target representation and therefore facilitate its recognition, while word primes preactivate a target competitor more than the target itself, therefore an inhibitory effect is observed. The inhibitory word prime effects were also extended to word primes that are a different length from the target (one letter shorter or longer; De Moor & Brysbaert, 2000).

In summary, the orthographic processing literature has provided ample evidence that is consistent with the lexical competition hypothesis. However, it should be noted that there have also been studies providing controversial results, such as failures to replicate some of the findings discussed in this chapter and effects in the opposite direction (e.g. Forster & Veres, 1998; Sears, Campbell, & Lupker, 2006; Sears, Hino, & Lupker, 1995; Sears, Lupker, & Hino, 1999). The lexical competition hypothesis will be further discussed in the next two chapters of the thesis.

Chapter 3

The Sandwich Priming Paradigm Does Not Reduce Lexical Competitor Effects

Effective reading requires the identification by the reader of the words intended by the writer, in a manner that is invariant or tolerant to sources of variation and distortion related to typeface, size, viewing conditions, perceptual noise, or writer error. It therefore seems reasonable that a variety of candidate matches to a stimulus should be considered or activated, and such a selection of candidates has been proposed from some of the earliest models (e.g., Rubenstein, Garfield, & Millikan, 1970) of lexical access. How candidates are considered and selected is thus central to reading, and several aspects of this process have been subject to recent computational and mathematical modeling efforts (e.g., Adelman, 2011; Davis, 2010; Norris & Kinoshita, 2012).

A core range of evidence for evaluating the proposed processes comes from the masked form priming paradigm developed by Forster and Davis (1984) and first used in the context of lexical selection by Forster, Davis, Schoknecht, and Carter (1987). The ongoing task for the participant is lexical decision on clearly visible letter string targets in capital letters, but each target is preceded by a mask (usually of # symbols) and a prime letter string presented in lower case for a duration that is typically between 15 and 70 ms. One major advantage of this procedure is that due to this brief prime duration, primes are usually not perceived consciously and do not allow for development of strategic responses from the participants. An example sequence of stimuli is thus ########—tible—TABLE. Baseline performance is established on unrelated trials where the prime shares no letters with the target. This can be compared with cases in which the prime shares many features in common with the target, and response times (RTs) are typically reduced when prime and target are similar, an RT priming effect. Different manipulations of the letters of the target to produce the prime (prime types) differ in their similarity to the target, and their ability to prime the target, apparently in a graded fashion (see Adelman et al., 2014), suggesting that candidates cannot be simply categorically divided into consistent or inconsistent.

A major result established with the masked priming paradigm, for example, is that the presentation of a nonword prime, constructed by replacing one of the target's letters, such as *tible*, produces significantly faster response times in comparison to the unrelated baseline (e.g.

Adelman et al., 2014; Forster et al., 1987). This effect is decreased and not always significant when two of the letters are replaced (Lupker & Davis, 2009; Perea & Lupker, 2004). Another finding, demonstrated with the masked-priming methodology reflects the letter position tolerance, rather than letter identity tolerance, of the perceptual system. Perea and Lupker (2003) demonstrated that a prime in which two adjacent letters were transposed (*jugde* from target JUDGE) effected shorter response times than one in which the same letter positions contain two replaced letters as in *jupte*(-JUDGE). This finding has been extended to nonadjacent letter transpositions (e.g., caniso - CASINO; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2004). Guerrera and Forster (2008) tested the limits of the letter position tolerance of the visual word recognition system and showed that a priming effect was still observed with primes constructed by adjacent transposition of all the letters in a word except for the external ones (dsiocnut – DISCOUNT). However, the priming was no longer significant when the primes were constructed by even more extreme transpositions, such as transposing all the adjacent letters in a word (T-all or transposed-all letter primes; e.g., avacitno-VACATION).

The magnitude of the effects produced by form-related masked primes have been interpreted as the degree to which the orthographic codes of the prime and the target match. Thus, results produced with the masked priming paradigm have served as a reference point for evaluating models' predictions regarding the similarity between two strings. One major distinction among theories is how they account for these graded patterns. Adelman (2011) suggests that considered candidates are gradually activated, and candidates are eliminated from consideration as inconsistent features of the stimulus are stochastically perceived. Norris and Kinoshita (2012) posit an explicit Bayesian calculation of the likelihood of percepts (the stimulus perceived with noise) given assumptions about the distributions of words and pseudowords. Approaches based on the interactive-activation model (McClelland & Rumelhart, 1981) suggest that the net input to a word unit weighs positive excitatory and negative inhibitory bottom-up influences in a way that is often summarized as a match score[1]. Whether within the interactive-activation framework or not, the predictions and match scores of orthographic encoding models have been compared to empirical results produced with the masked priming methodology that thus served as a validator for the models' credibility.

[1] Match scores may also reflect only the excitatory bottom-up influences and not the inhibitory ones. In many models, they are perfectly complementary; where they are not, the (asymptotic) net input – reflecting both match and mismatch components – is, of course, the relevant factor.

Although the magnitude of form priming is usually interpreted as the extent to which processing during encoding of the prime and the target overlaps, and an approximate string distance is implied, a limit has been shown in the extent to which a masked form priming effect was obtained: As Lupker and Davis (2009) have emphasized, the priming effect is no longer present when a prime includes more extreme deviations from the target. This introduces a limit of the orthographic priming continuum that is not necessarily present in models' predictions and to an extent is also not consistent with commonsense logic. If the effect of a prime produced by a single transposition of adjacent letters from the target is very similar to that from a prime that is identical (except for case) to the target, it is perhaps, then, surprising that a prime with four such transpositions in an eight-letter target produces no significant priming (Guerrera & Forster, 2008); if copmuter is barely different from COMPUTER, why is ocpmture not still quite similar?

And indeed, Lupker and Davis reported high match scores between transposed all-letter primes and their base words from the relative open-bigram model (Grainger & van Heuven, 2003), the SERIOL model (Whitney, 2001) and previous versions of Davis's spatial coding model (Davis, 1999), suggesting that all those predicted facilitation priming effects, which were not significant in the masked-priming studies of Guerrera and Forster and Lupker and Davis. Likewise, it can be seen as surprising that a prime that matches five out of eight letters of a target produced no priming compared to control (Schoonbaert & Grainger, 2004) given these five matching letters must produce more facilitation than no matching letters, and the three mismatching letters must produce less inhibition than eight mismatching letters.

Lupker and Davis (2009) argued that primes that are moderately related to targets, such as transposed all-letter primes and primes containing replacement of more than two letters, were not able to produce facilitation effects not due to the insufficient orthographic similarity between them and the targets, but due to inhibitory processes that could cancel out facilitation. The process they have claimed to be responsible is lexical competition, that is, lateral inhibition among word units. Such an inhibitory process is consistent with evidence that word primes that are orthographic neighbors (words of equal length that differ by only one letter in the same position, such as take – cake or take – tape; Coltheart, Davelaar, Jonasson, & Besner, 1977) of targets can produce inhibitory rather than facilitatory priming (e.g., Davis & Lupker, 2006), that words with orthographic neighbors are typically less primeable (e.g., Forster et al., 1987), and that primes that are neighbors of targets are less effective if prime and target share other common neighbors ("shared neighbors": Van Heuven, Dijkstra, Grainger, & Schriefers, 2001).

An example of a shared-neighbor for the prime-target relationship *azound-ABOUND* is the word *around*, which is a neighbor of both the prime and the target. Davis (2003) argues that nonword primes, such as *azound* are less effective as they not only preactivate the representation of the target due to form similarity, but also representations of the target's neighbor, thus introducing competition on the word level that results in suppression of the target's activation and attenuation of the priming effect.

In the same competitive network framework, Lupker and Davis suggested that primes moderately close to the target were likely to resemble and generate more activation to representations of other lexical units, which once activated would inhibit the target and could cancel out possible facilitation effects which would therefore remain unobserved. In such a lexical competition account, whilst the prime avacitno (in avacitno-VACATION) is reasonably similar to the target VACATION, it is more similar to the task-irrelevant word AVIATION. The closer neighbor AVIATION becomes more activated than VACATION, and thus inhibits the word node for VACATION, eliminating any possible priming for that target. Lupker and Davis thus suggested that if lexical competition effects were filtered out, primes moderately related to targets would be able to produce facilitation.

The conventional masked priming paradigm, according to Lupker and Davis (2009), is thus susceptible to counteractive inhibitory processes and therefore is not an appropriate procedure to directly evaluate orthographic encoding schemes. Thus, they explained the absence of these expected facilitatory priming effects by seeking limitations in the methodology that had been used. They sought to design a paradigm that would allow for evaluation of the matches of stimuli that are more distant from the target, by eliminating or reducing lexical competition effects on the target. One route to achieving this requires preventing the activation of non-target words. Lupker and Davis sought to do so by taking advantage of lexical competition by pre-activating the target, by presenting it for a short duration. The pre-activated target then itself inhibits potential competitors and so is not subject to inhibition itself. That is, a possible stimulus sequence is ########—VACATION—avacitno—VACATION, which was termed a sandwich prime because the prime is sandwiched between two presentations of the target. Simulations of an otherwise unpublished hybrid of spatial coding and interactive activation models gave the prediction that AVIATION would no longer become active, and in the absence of such lexical competition, the target activation of VACATION at the end of the prime stimulus was not at floor. Instead, the target activation was driven by the match score of prime and target so that priming was now predicted for the transposed all-letters prime relative to control.

Lupker and Davis (2009) confirmed this prediction empirically in their first experiment: In the sandwich priming paradigm, the transposed all-letters prime produced shorter response times than an unrelated (sandwiched) prime; in contrast, the non-sandwiched version showed no priming relative to the non-sandwich control. In their second experiment, they extended the finding to the case of primes with several replaced letters, with a parametric manipulation of number of replaced letters from one through five in a seven-letter target. In the standard non-sandwiched case, priming was shown only for one- and two-letter-different primes. In the sandwiched case, priming was greater for one- through three-letter-different primes, so that priming for the three-letter different case was significant. These data patterns were indeed consistent with Lupker and Davis's (2009) lexical inhibition account. The authors interpreted the results as an evidence that the sandwich priming procedure successfully eliminated lexical competition effects and as such it overcame certain limitations of the original masked priming and was a better tool for evaluating orthographic input coding models. For these reasons, the sandwich priming procedure has already been employed in several studies researching orthographic processes so far (e.g., Ktori, Grainger, Dufau, & Holcomb, 2012; Ktori, Kingma, Hannagan, Holcomb, & Grainger, 2014; Lupker, Zhang, Perry, & Davis, 2015).

The present study aimed to test Lupker and Davis's (2009) interpretation that the enhanced form priming effects produced with the sandwich priming paradigm were due to the elimination of lexical competition processes. Although the explanation of Lupker and Davis is consistent with their data, other processes might instead be responsible for the obtained results. A possible alternative explanation is that the results were driven by lower-level bottom-up processes that do not reflect lexical stages and lexical competition in particular. As there is an additional brief presentation of a prime, extra complexity is added in the sandwich priming procedure and the mechanisms that underlie the processing of two masked primes are not entirely transparent. The additional initial letter string – the *preprime* – is another brief visual event that provides additional processing information and its presentation prolongs the time until the presentation of the target. It is not exactly clear what the interaction is between the prime and preprime and whether the same mechanisms are involved and just multiplied by two in a sequential presentation of two brief primes and in a presentation of a single brief prime, immediately followed by the target.

As we consider the data provided by Lupker and Davis (2009) to be inconclusive for the determination of the nature of the responsible processes, we designed several experiments that aimed to provide further evidence of whether the enhanced form priming effects were caused by the modulation of lexical competition mechanisms or not. The way we chose to do that was by following the interactive activation framework and retaining lexical competition by presenting lexical competitor of the target as a preprime, rather than an identical stimulus. If primes can be ineffective due to the role of lexical inhibition – and preprimes can modulate lexical inhibition – as Lupker and Davis propose, then pre-activating a competitive alternative should exacerbate inhibition, which should if anything further attenuate priming effects. In contrast, if a presentation of a stimulus that resembles both the related prime and the target does not produce any particular reduction in the strength of priming or indeed increases it, this would provide some evidence that the results obtained with a sandwich priming were not caused by reduction of lexical competition effects, but rather by some other mechanism, such as prelexical bottom-up processes.

The present work consists of three experiments in total, as well as corresponding simulations of these experiments. The simulations were run with the Spatial Coding Model (Davis, 2010). This model represents a more recent version of the competitive network system used for the simulations in the study of Lupker and Davis (2009). The model is based on the interactive activation model (McClelland & Rumelhart, 1981), but has a different implemented encoding scheme. In the interactive activation's slot-based encoding scheme, two letters with the same letter identity are treated as different letters if they are in different positions and therefore *jugde* is as similar to *judge* as is *jupte*. The Spatial Coding Model, however, could account for transposed-letter effects with its two-dimensional spatial coding scheme, in which letter position and identities are encoded as spatial patterns of values.

The computational modelling methodology could provide an insight as to how the lexical inhibition elimination account of sandwich priming, suggested by Lupker and Davis, fits the specific prediction of the model, regarding the effect of a competitor preprime, based on the properties of the stimuli, such as frequencies and orthographic neighborhoods of the preprimes, primes and targets. The model's predictions and the lexical inhibition account of the sandwich priming effects could then be evaluated by a comparison with the observed empirical data.

The nature of the sandwich priming effects was explored in the context of Lupker and Davis's (2009) Experiment 2 stimuli with replaced-letter primes (Experiment 1), and new stimuli with shared-neighbor primes (Experiment 2) and transposed-all letter primes (Experiment 3).

Experiment 1

Our initial examination of the question was based on the stimuli used in Lupker and Davis's (2009) Experiment 2 to maintain continuity with the original work.

Method

Participants

Ninety students or members of staff from the University of Warwick took part in the experiment. All reported English as their native language. They either received course credit or were paid £3 for their participation.

Design

Three preprime types (none, identity, competitor), that generated three different procedures — conventional masked priming, sandwich masked priming and competitor-modified-sandwich masked priming — were crossed with six prime types (1-, 2-, 3-, 4-, and 5-letters different, and all-letter different control) within-subjects. Counterbalancing was performed by first dividing the items into three equal different preprime type trials for words and nonwords respectively. These comprised of 20 trials per preprime type per target type (each set taken consecutively from the stimulus list of the original paper). The preprime conditions were then counterbalanced in three lists. Each of these lists was transformed into six different versions for the counterbalancing of the prime type conditions. In these lists, the six levels of the prime type were cycled (one-by-one in the order of targets in the original stimulus list). The levels of the two factors appeared equal times in each of the lists. Each of the eighteen resulting conditions appeared either 3 or 4 times in a list for each target type, but the total frequency of the conditions was equalised over all the counterbalancing lists, as every combination of preprime type, prime type and target item appeared exactly once across the eighteen lists. All trials were newly randomly intermixed for each participant[2].

Stimuli

[2] DMDX scripts for all experiments are made available at: http://adelmanlab.org/sandwich/ .

The 60 seven-letter words and 60 matched pseudoword foils were taken from Lupker and Davis's (2009) Experiment 2, along with their primes. The mean frequency reported by the authors was 53.1 per million (CELEX; Baayen, Piepenbrock, & van Rijn, 1993; range 20–145). The mean SUBTLEX-UK Zipf frequency was 4.45 (range 2.79 - 5.2; Van Heuven, Mandera, Keuleers, & Brysbaert, 2014). The mean neighborhood size (number of orthographic neighbors, Coltheart N; Coltheart et al., 1977) was 0.3 (range 0 – 2). These were augmented with the competitor stimulus for each word, which was selected to be the seven-letter word with the least string edit distance (the number or cost of operations to transform one string to another) to the target, using a modified edit distance designed to reflect empirical results from priming[3] (e.g., PROTECT for PROJECT, or HALFWAY for HOLIDAY). The mean CELEX frequency of the competitor words was 9.14 per million (range 0.34 – 216.54). The mean SUBTLEX-UK Zipf frequency was 3.13 (range 1.47 – 5.14). The mean neighborhood size was 0.47 (range 0 – 5). Neighborhood size and CELEX frequency properties were obtained with N-Watch (Davis, 2005). The CELEX frequency of the competitor was higher than the target in only 3 out of the 60 target-competitor pairs, two of which had also a higher SUBTLEX-UK Zipf frequency. A non-identical pseudoword was constructed for each foil by altering one letter to act as a competitor preprime for the nonword trials. The preprime for the sandwich priming condition in the nonword trials was the nonword foil. The prime conditions in the nonword trials matched those in the word trials and comprised of primes that differed from the nonword foils by one, two, three, four, five and seven letters. All stimuli for this experiment are listed in Appendix A.

Procedure

Participants were instructed that their task was to identify whether stimuli presented in capital letters were real English words or nonsense words, indicating the former by pressing the yes key (the right shift key labeled as such) or the no key (the left shift key labeled as such). The experimental trials were preceded by ten practice trials, after which participants were given the opportunity to ask for clarification. On each trial, a ######## mask in 20-point Courier New was presented for 500ms. When the preprime was identity (the original sandwich priming), the target stimulus was then presented at 7.5-point size for 33ms. When the preprime was competitor (the new modified-competitior sandwich priming), the competitor was then presented at 7.5-point size for 33ms. When there was no preprime (conventional masked

[3] In particular: The cost of an internal replacement was 1, the cost of an initial replacement was 6, the cost of a final replacement was 5, and the cost of the first internal transposition was 1.

priming), presentation proceeded immediately from the mask to the prime. The prime was presented for 50ms at 12.5-point size. The target was then presented at 20-point size until the participant responded or 2000ms had elapsed. Feedback was given after every trial.

Results

Response Time

Data analyses were performed with the packages *lme4* (Bates, Maechler, Bolker, & Walker, 2015), *car* (Fox, & Weisberg., 2011) and *phia* (De Rosario-Martinez, 2013) as implemented in R version 3.4.1 (R Core Team, 2017). In this and the subsequent analyses, linear mixed-effects models were initially fitted with their full random structure and were later simplified in the cases in which they failed to converge (Barr, Levy, Scheepers, Tily, 2013).

Mean response times and error rates for word trials in Experiment 1 are shown in Table 3.1. Trials with response times shorter than 150 ms or longer than 1500 ms were excluded from the latency analyses (0.06%)[4], as were incorrect trials (3.41%). A linear mixed-effects model was fitted with preprime type, prime type and their interaction as fixed factors. By-subject and by-items intercepts and slopes for preprime type and prime type were added as random factors. Type II Wald chi-square tests were performed on the fitted model to establish the significance of the fixed main effects as well as their interaction. The results revealed a main effect of prime type, $\chi^2(5) = 80.076$, $p < .001$; and a significant interaction between prime type and preprime type, $\chi^2(10) = 19.957$, $p = .03$. The effect of preprime type was not significant, $\chi^2(2) = 3.47$, $p = .176$. Looking at pairs of preprime types, the preprime by prime interaction was only significant for the comparison of the identity and no preprime conditions, $\chi^2(5) = 15.357$, $p = .009$. Examination of Figure 3.1 clearly shows that this must be driven by greater priming in the identity (sandwich) condition than the no-preprime (conventional) condition. The priming in the competitor condition differed significantly from neither, $\chi^2(5) = 8.937$, $p = .112$, vs. identity, and $\chi^2(5) = 5.616$, $p = .345$, vs. no preprime. To investigate the priming effect further, we constructed post-hoc contrasts for each of the related prime conditions. We used the Benjamini & Yekutieli (2001) adjustment method to control false discovery rate.

One-letter-different primes. Comparing only one-letter-different and control (all-letter-different primes), the interaction with prime type showed differential priming, $\chi^2(2) = 9.433$, $p = .009$.

[4] These data, and analogous data of subsequent experiments, are available at http://adelmanlab.org/sandwich/ .

This priming was 59 ms in the identity condition, 41 ms in the competitor condition, and 24 ms in the no-preprime condition, all of which were significant, $\chi^2(1) = 46.353$, $p < .001$; $\chi^2(1) = 20.702$, $p < .001$; $\chi^2(1) = 7.028$, $p = .015$, respectively. Contrasts between the priming in each two of the preprime conditions showed that the priming in the identity preprime condition differed significantly from the priming in the no preprime condition, $\chi^2(1) = 9.418$, $p = .012$, but not from the priming in the competitor condition, $\chi^2(1) = 2.726$, $p = .271$, which also did not differ significantly from the priming in the no preprime condition, $\chi^2(1) = 1.99$, $p = .29$.

Two-letter-different primes. Priming of 42 ms for the identity condition was significant, $\chi^2(1) = 23.296$, $p < .001$. The 21 ms priming effect in the competitor condition and the 17 ms priming effect in the conventional no-preprime condition were marginally significant, $\chi^2(1) = 5.515$, $p = .052$; $\chi^2(1) = 4.324$, $p = .069$. These priming effects did not differ significantly, interaction $\chi^2(2) = 4.996$, $p = .082$.

Three-letter-different primes. When the prime was three-letter different, it produced significant facilitation relative to the control only in the identity preprime condition: $\chi^2(1) = 16.777$, $p < .001$. It was not significant in the no preprime condition, $\chi^2(1) = 2.59$, $p = .296$, nor in the competitor preprime condition, $\chi^2(1) < 1$.

Four- and five-letter-different primes. The effect of the four-letter and five-letter different primes was not significant in any of the preprime conditions, and there were no interactions between prime type and preprime type.

Accuracy

A generalized linear mixed-effects model with binomial distribution was fitted for the word accuracy analyses with prime type, target type and their interaction as fixed factors and by-subjects and by-items intercepts and slopes for preprime type as random factors. The effect of prime type was significant, $\chi^2(5) = 12.383$, $p = .03$. The accuracy of the participants decreased with the increase of the number of replaced letters in the primes.

Nonword Data

Response Time. Mean response times and error rates for nonword trials in Experiment 1 are shown in Table 3.2. Trials with response times shorter than 150 ms or longer than 1500 ms were excluded from the latency analyses (0.24%), as were incorrect trials (4.48%). A linear mixed-effects model was fitted with preprime type, prime type and their interaction as fixed factors and by-subject and by-items intercepts and slopes for preprime type as random factors. The results showed a main effect of preprime type, $\chi^2(2) = 8.938$, $p = .011$. The effect was driven by the significant difference between the identity preprime condition and the no preprime condition, $\chi^2(1) = 8.96$, $p = .003$. Overall, participants were significantly faster when the target foil was presented as a preprime than when there was no preprime.

Accuracy. A generalized linear mixed-effects model with binomial distribution was fitted with prime type, target type and their interaction as fixed factors and by-subjects and by-items intercepts and slopes for preprime type as random factors. The interaction between preprime type and prime type was significant, $\chi^2(10) = 29.048$, $p = .001$. Post-hoc contrasts with Benjamini & Yekutieli (2001) adjustment for the one-letter-different prime type and the all-letter-different prime type as a control showed a significant facilitation only in the identity preprime condition, $\chi^2(1) = 8.91$, $p = .016$. Contrasts between the priming in each two of the preprime conditions showed that the priming in the identity preprime condition differed significantly from the priming in both competitor preprime condition, $\chi^2(1) = 12.264$, $p = .003$, and no preprime condition, $\chi^2(1) = 5.737$, $p = .046$. As could be observed in Table 3.2, however, the pattern of results did not exhibit a consistent structure that could lead to a straightforward interpretation. A difference in priming between the identity preprime and the competitor and no preprime conditions was also observed in the five-letter-different prime condition, $\chi^2(1) = 9.475$, $p = .006$; $\chi^2(1) = 11.872$, $p = .003$, in which the accuracy of participants in the identity preprime condition increased in comparison to the more related prime conditions.

Table 3. 1 *Mean Response Times (ms) and Error Rates (%) by Condition for Word Trials in Experiment 1*

Preprime	Prime (Different letters)					
	1	2	3	4	5	7
Identity	536 (3)	554 (1)	561 (3)	593 (4)	593 (6)	595 (6)
Competitor	547 (3)	567 (3)	582 (4)	592 (5)	592 (5)	589 (5)
None	555 (3)	562 (2)	565 (2)	577 (3)	583 (4)	579 (2)

Table 3. 2 *Mean Response Times (ms) and Error Rates (%) by Condition for Nonword Trials in Experiment 1*

Preprime	Prime (Different letters)					
	1	2	3	4	5	7
Identity	642 (2)	637 (6)	642 (6)	648 (4)	630 (2)	644 (7)
Competitor	652 (6)	648 (4)	650 (5)	638 (5)	648 (5)	653 (3)
None	644 (3)	659 (7)	662 (5)	652 (5)	651 (6)	661 (2)

Simulation of Experiment 1

Method

Each of the simulations in the present work was run on the same word trials stimuli as the ones in the corresponding experiment. The *easyNet* simulation software (http://adelmanlab.org/easyNet/) was used for all the simulations. A vocabulary of 30606 words from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993) was loaded in the Spatial Coding Model (Davis, 2010). The model was tested with its default parameters.

The procedure of the conventional masked priming included a presentation of the prime for 50 cycles, followed by the presentation of the target. The sandwich priming procedures were identical, except for the 33 cycles presentation of the preprime (either the target itself or the “competitor” word orthographically related to the target) before the prime. As the response time in the model was measured from the onset of the first priming event, the value of 50 was subtracted from the response times in the no preprime trials and the value of 83 was subtracted from the response times in the sandwich priming trials. The resulting value therefore represented the response time from the target onset until the response.

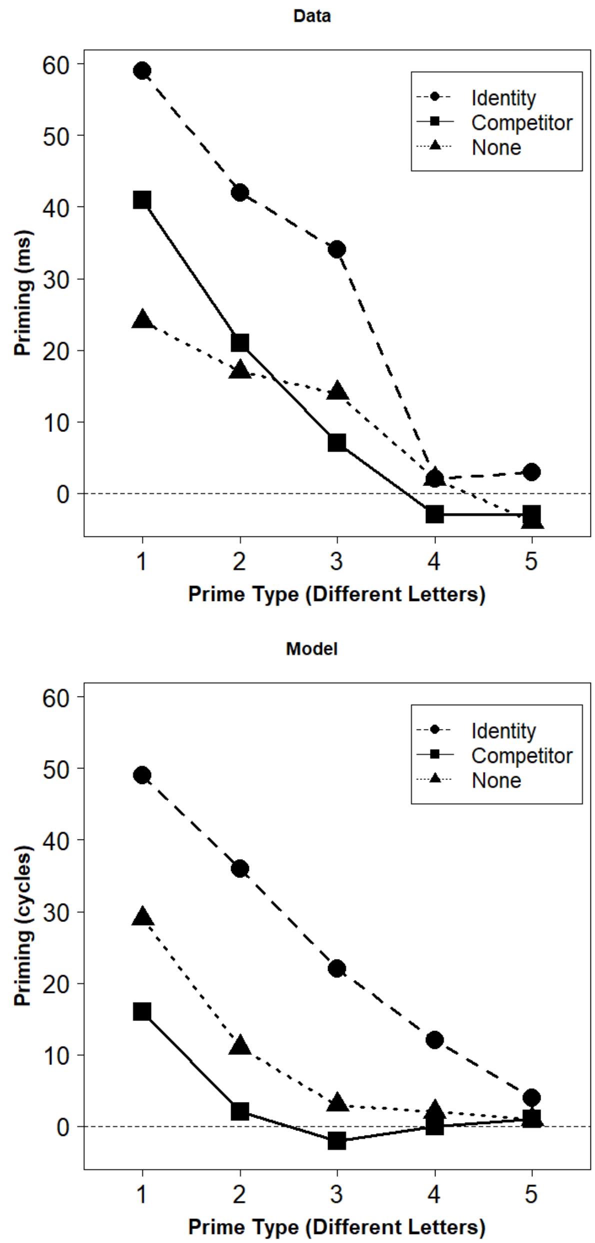

Figure 3. 1 Priming effect (relative to the relevant all-letter-different control) in Experiment 1 (ms; up) and simulation of Experiment 1 (cycles; down), as a function of preprime type and prime type for word trials.

Results

The model correctly recognized all the target stimuli as words. As in the Lupker and Davis (2009) study, we will focus on the pattern predicted by the model, rather than on the results of statistical analyses as the model's response times do not include participant variability and therefore numerically small differences produce statistically significant results. Following Davis's (2010) calibration of parameters, we consider one cycle priming effect to be comparable to 1 ms priming.

As previously, the model predicted a priming boost in the identity preprime (original sandwich priming) condition in which the target was presented before the prime, relative to the no preprime condition. In the one, two and three -letter different priming conditions, the model predicted a priming effect of 49, 36 and 22 cycles, respectively. In the no preprime condition, the predicted priming effect for the same priming conditions was 29, 11 and 3 cycles, respectively. Thus, the model fitted the portion of the experiment that was a (within-subject mixed-list) replication well. However, as can be observed in the right panel of Figure 3.1, the presentation of a competitor preprime attenuated the priming effect, relative to the no preprime condition. The predicted priming after the presentation of a competitor preprime was consistently smaller than the priming effect in the no preprime condition. In the one, two and three-letter different priming conditions, the effect was decresed to the values 16, 2 and -2 cycles.

Discussion

The response time results of Experiment 1 demonstrated the expected sandwich priming boost of the orthographic priming effect evident in the significantly larger priming that was observed when the target was presented before as a preprime, than when the original masked priming paradigm was employed. Apart from producing a bigger size of the effect, the presentation of the target before the prime led to a significant priming effect in the three-letter different prime condition that was not observed in the no preprime condition. These results replicated those reported by Lupker and Davis (2009) and matched the prediction of the Spatial Coding Model. However, contrary to the model's predictions and the hypothesis that a preprime presentation addresses lexical competition effects, the presentation of the competitor preprime did not attenuate the priming effect relative to the one observed in the no preprime condition. As the priming effect of the one-letter different condition did not differ significantly between the identity and the competitor conditions, but only between the identity and the no preprime conditions, if anything, there was a trend of the competitor preprime towards producing a slight boost, rather than attenuating the priming effect.

Experiment 1 gave no evidence that lexical competition could eliminate priming when an attempt was made to inject lexical competition with an initial prime that was the closest competitor of the target. However, the absence of inhibitory effect might be attributed to the distance of preprimes to targets, because Lupker and Davis (2009) chose many targets that had no one-letter-different neighbors. Therefore, as potential competitors, they might have been ineffective because they were not sufficiently supported by the subsequent presentations of the prime and the target or because only near neighbors have inhibitory links (cf. Davis & Lupker, 2006). In interactive-activation-based models (McClelland & Rumelhart, 1981), such as the Spatial Coding Model (Davis, 2010), nodes representating words very similar to targets, such as target's orthographic neighbors, receive more activation upon target's presentation as more letter nodes consistent with the input receive excitation and feedforward to competitor word nodes. The higher the activity level of a word node, the stronger the inhibitory effects it produces on other word nodes. As the primes in Experiment 1 were constructed by replacing letters from targets and targets were in most of the cases more than one-letter-different from the competitors, the activity of the competitor word node could have dropped after the presentation of the prime and subsequently of the target, resulting in a weaker influence of the competitor preprimes. Figure 3.2 confirms this concern and illustrates how the activity of the competitor word node could not be sustained by the prime and dropped with its presentation after the 33th cycle in a trial example from the simulation of Experiment 1. Conversely, as the prime was a target-only neighbor, the activity of the target node rapidly increased with the prime presentation. The time the target needed to reach a recognition threshold was thus not dramatically delayed by the preprime presentation of the competitor. This example indicates that the distance between the competitor and the prime and between the competitor and the target could partially explain the preserved facilitation pattern in the competitor preprime condition in Experiment 1 and the lack of a reversed priming effect in the simulation of Experiment 1.

Another reason of the lack of inhibitory effects in the competitor preprime condition might concern the relative frequency of competitors and targets. As Lupker and Davis's (2009) stimuli included high frequency targets, only in 5% of the competitor-target pairs was the competitor a more frequent word than the target. In interactive-activation terms, higher frequency words have higher resting levels, therefore reach positive activation levels sooner, and therefore produce more inhibition to other word nodes. This hypothesis has been supported by evidence from previous studies demonstrating that higher frequency target neighbor word primes produce stronger inhibitory effects than lower frequency ones (Davis & Lupker, 2006; Segui & Grainger, 1990).

The results of Experiment 1 showed no signs of inhibitory effects produced by the competitor preprime. There is a possibility that these results could be attributed to the properties of the stimuli and the low competitiveness of the competitors. Partially, this interpretation is supported by the results of the simulation, which demonstrated inhibitory influence and attenuated facilitation effect in the competitor preprime condition, however, did not indicate a reversal of the priming effect as a prediction of the model. An important question arises at this moment. If we accept that words closest in form to targets are their strongest competitors, and that the competitors in Experiment 1 are not inhibitory enough, then we should accept that the targets in Experiment 1, with their low neighborhood density properties, high word frequencies and lack of high frequency neighbors, are not prone to the influence of a strong lexical competition. If this is the case, why would the large priming boost produced with the original sandwich priming paradigm with these stimuli be attributed to a decreased lexical competition? We continue our investigation of the nature of the sandwich priming effects with a selection of new stimuli.

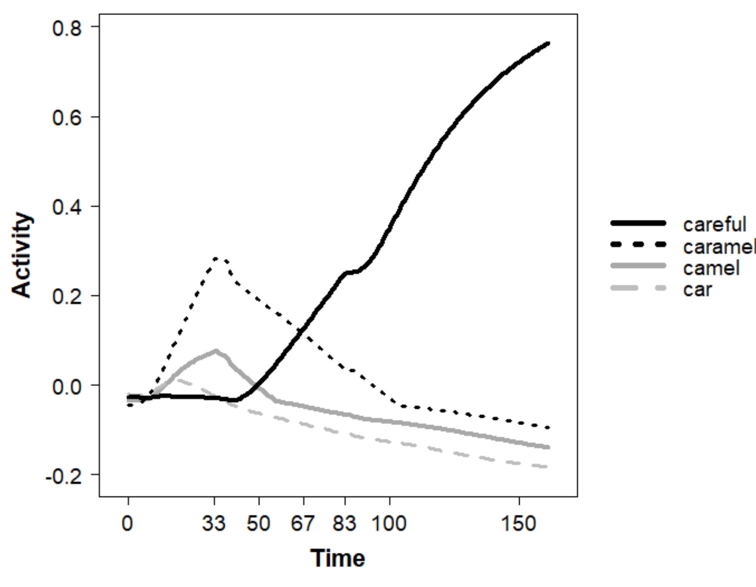

Figure 3. 2 Words activity over time in the trial CARAMEL-cvreful-CAREFUL from the simulation of Experiment 1.

Experiment 2

Experiment 2 addressed the aforementioned concerns regarding the similarity among stimuli by using only stimuli that were one letter different from each other. That is, primes were Coltheart neighbors of targets (e.g., azound - ABOUND) and potential competitors were Coltheart neighbors of both, that is, shared neighbors (e.g., AROUND-azound-ABOUND). Prior research has found that prime-target combinations for which such shared neighbors exist are less effective (Davis & Lupker, 2006; Van Heuven et al., 2001). Moreover, to enhance the scope for inhibition, the potential competitor was chosen to be of higher frequency than the target (Davis & Lupker; Segui & Grainger, 1990). In the interactive-activation framework (McClelland & Rumelhart, 1981), the high-frequency neighbor competitor should get activated more rapidly than a low frequency word due to its higher resting level and its activation levels should increase dramatically after the presentation of the neighbor prime and the neighbor target, eventually resulting in suppressing the target's activity through inhibitory lateral connections. The expectation is, that if the preprime presentation in a sandwich priming paradigm affects lexical competition, such a strong competitor should reverse or at least decrease the facilitation effect that would be observed with the conventional masked priming paradigm.

Method

Participants

One hundred eighteen native English speakers took part in this experiment. They were undergraduate students at the University of Warwick and received course credit for their participation. The last four participants were replacements for those with low accuracy scores (correct on less than 75% of the trials), leaving data from 114 for analysis.

Design

The three types of preprime type (identity, competitor, none) were crossed within-subjects with prime relatedness, with the related prime type being shared neighbor. The six conditions were rotated over the targets to produce six counterbalancing lists. All trials were randomly intermixed anew for each participant.

Stimuli

Seventy-eight six-letter words with higher frequency neighbors were chosen as word targets. They had a mean CELEX frequency of 3.69 per million (range 0.56 - 15.87), mean SUBTLEX log frequency Zipf 3.18 (range 1.47 – 4.22) and only one Coltheart neighbor that was used as a competitor preprime. The targets' neighbors had higher frequencies than the targets. Their mean CELEX frequency was 26.751 per million (range 1.01 - 503.41), mean SUBTLEX log frequency Zipf 3.83 (range 2.11 – 5.86); mean neighborhood size 2.27 (range 1 – 9). A shared neighbor pseudoword was constructed for each preprime condition to be the related prime for these stimuli.

Seventy-eight further six-letter words were chosen to be the "competitor" preprimes of the nonword foils; nonword foils were constructed by changing one letter of these; and shared neighbor primes were constructed by changing that letter again. Unrelated primes were constructed for each preprime condition by randomly selecting six letters without replacement that were in neither competitor nor target. The nonword foils served as preprimes in the identity preprime condition, nonword trials. All stimuli for this experiment are listed in Appendix B.

Procedure

The procedure was identical to that of Experiment 1.

Results

Response Time

Trials in which the response took less than 150 ms or longer than 1500 ms (0.76%) or were incorrect (12.87%) were excluded from the response time analyses.[5] Mean response times and error rates by condition for word trials are displayed in Table 3.3. A linear mixed-effects model was fitted with preprime type, prime type and their interaction as fixed factors. The random effects ultimately included in the model were the by-subject and by-items intercepts and slopes for preprime type and prime type, as well as the by-items slopes for their interaction. The effect of prime type was significant $\chi^2(1) = 62.404$, $p < .001$. The effect of preprime type was not significant, $\chi^2(2) = 3.74$, $p = .154$, nor was the interaction between preprime type and prime

[5] In addition, data from the words *navels*, *quotas*, *usable*, *rectal*, *sulked*, *convex* in Experiment 2 and *navels* and *portly* in Experiment 3 were excluded from the analyses as the accuracy of those items was less than 60%.

type, $\chi^2(2) = 1.59$, $p = .451$. The difference between the unrelated and related primes was significant in all preprime conditions: identity, $\chi^2(1) = 25.923$, $p < .001$; competitor, $\chi^2(1) = 28.888$, $p < .001$; no preprime, $\chi^2(1) = 15.34$, $p < .001$.

Accuracy

A generalized linear mixed-effects model with binomial distribution was fitted for the word accuracy analyses with preprime type, prime type and their interaction as fixed factors and by-subjects and by-items intercepts and slopes for preprime type, prime type and their interaction as random factors. The effects of preprime type and prime type were both significant, $\chi^2(2) = 8.402$, $p = .015$; $\chi^2(1) = 8.498$, $p = .004$. The interaction between the two factors was not significant, $\chi^2(2) = 3.389$, $p = .183$. In general, participants made significantly fewer errors in the no preprime condition than in the identity preprime, $\chi^2(1) = 5.496$, $p = .019$, and in the competitor preprime conditions, $\chi^2(1) = 6.14$, $p = .013$. They were also significantly more accurate when the prime was related than when it was unrelated, $\chi^2(1) = 7.957$, $p = .005$.

Table 3. 3 *Mean Response Times (ms) and Error Rates (%) by Condition for Word Trials in Experiment 2 and Response Times (cycles) by Condition in Simulation of Experiment 2*

	Preprime					
	Identity		Competitor		None	
Prime	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation
One-letter different	623 (9)	76	634 (10)	157	631 (7)	111
Unrelated	659 (14)	113	667 (13)	115	656 (10)	114
Priming	36 (5)	37	33 (3)	-42	25 (3)	3

Nonword Data

Response Time. Mean response times and error rates for nonword trials in Experiment 2 are displayed in Table 3.4. Trials with response times shorter than 150 ms or longer than 1500 ms were excluded from the latency analyses (1.05%), as were trials with incorrect response (11.54%). In addition, items with accuracy less than 60% were not included in the analyses. A linear mixed-effects model was fitted with preprime type, prime type and their interaction as fixed factors and by-subject and by-items intercepts and slopes for preprime type and prime types as random factors. The results revealed a main effect of preprime type, $\chi^2(2) = 9.037$, $p = .011$. The effect was driven by the significant difference between the identity preprime condition and the condition with no preprime, $\chi^2(1) = 9.012$, $p = .003$. Participants were faster to reject nonword foils when the foils were presented as preprimes than when there were no preprimes.

Accuracy. A generalized linear mixed-effects model with binomial distribution was fitted with preprime type, prime type and their interaction as fixed factors and by-subjects and by-items intercepts and slopes for preprime type, prime type and their interaction as random factors. The results revealed a significant interaction between preprime type and prime type, $\chi^2(2) = 8.891$, $p = .012$. The difference between the unrelated and related prime conditions was significant only when there was no preprime, $\chi^2(1) = 8.655$, $p = .003$. In this preprime condition, participants were significantly more accurate after a related prime, than after an unrelated one.

Table 3. 4 *Mean Response Times (ms) and Error Rates (%) by Condition for Nonword Trials in Experiment 2*

Prime	Preprime		
	Identity	Competitor	None
One-letter different	696 (10)	701 (10)	707(8)
Unrelated	701 (8)	708 (9)	718 (9)
Priming	5 (-2)	7 (-1)	11(1)

Simulation of Experiment 2

Experiment 2 was simulated with the same method as for Experiment 1. The model recognized correctly all the target stimuli as words. Mean predicted response times (cycles) are included in Table 3.3. The model predicted a small facilitation priming of 3 cycles in the no preprime condition, thus underestimating the effect in comparison to the empirical results. This priming effect was enhanced significantly in the identity preprime, in which it was 37 cycles, matching the size of the one observed in the human data. Critically, the model predicted a strong inhibitory effect (-42 cycles) in the competitor preprime condition.

Discussion

The results from Experiment 2 showed no sign of inhibitory effect as a result of the high frequency neighbor presentation before the prime. There was a significant facilitatory priming effect in the competitor preprime condition that was numerically bigger than the priming effect in the no preprime condition. These results contrasted the prediction of the Spatial Coding Model (2010) of a strong inhibitory effect in the competitor preprime condition and the claim that the preprime presentation addresses counteractive inhibitory effects produced by lexical competition (Lupker & Davis, 2009). As the prediction of the model in the simulation of Experiment 2 was specific to the stimuli of Experiment 2, it verified the strong competitive environment with these items in the competitor preprime condition, according to the interactive-activation account.

Experiment 3

In Experiment 3, we sought to extend the results of Experiment 2 to the case of transposed-all primes, which were the other motivating case for the development of sandwich priming. As previous studies have shown no significant priming effect of transposed-all letter primes relative to control when the conventional masked priming paradigm was used (Guerrera & Forster, 2008) and significant facilitation effect with the sandwich priming paradigm (Lupker & Davis's, 2009, Experiment 1), a comparison between these two procedures and a competitor sandwich would be informative about the mechanisms triggered by the additional presentation of a preprime. If a significant facilitation effect could be obtained with transposed-all primes and a competitor preprime, that could be considered as evidence that a preprime related to the target acted as an attenuated version of a sandwich prime and did not affect lexical competition processes. If, on the contrary, such a presentation reversed the direction of the effect and led to inhibitory effect on the target recognition, that would provide a strong evidence towards a lexical competition account of sandwich priming.

Method

Participants

Sixty-five undergraduate students from the University of Warwick took part in the experiment for course credit. All of them reported English as their native language. Participants who were accurate in less than 75% of the trials (5 people) were replaced, so data from 60 were analysed.

Stimuli

The stimuli were the same as those in Experiment 2, except the shared neighbor prime was replaced with the transposed-all prime (e.g., lbaehc-BLEACH) and the randomly generated unrelated primes were resampled. All stimuli for this experiment are listed in Appendix C.

Procedure

The procedure was the same as Experiments 1 and 2.

Results

Response Time

Word trials with response times shorter than 150 ms or longer than 1500 ms (0.38%) or with incorrect responses (11.82%) were excluded from the RT analysis. Mean response times and error rates by condition are shown in Table 3.5. A linear mixed-effects model was fitted with preprime type, prime type and their interaction as fixed factors. The full random structure was successfully included in the model. The random effects were the by-subject and by-items intercepts and slopes for preprime type, prime type and their interaction. The effect of prime type was significant $\chi^2(1) = 23.759$, $p < .001$. The interaction between preprime type and prime type was also significant $\chi^2(2) = 13.042$, $p = .001$. The effect of preprime type was not significant, $\chi^2(2) = 2.731$, $p = .255$. The interaction was driven by the significantly greater facilitatory priming effect produced in the two sandwich conditions in comparison to the one produced in the no preprime condition. Contrasts between the preprime conditions showed that the difference between the priming in the identity preprime condition and the no preprime condition was significant, $\chi^2(1) = 4.965$, $p = .026$, as was the difference between the competitor preprime and the no preprime condition $\chi^2(1) = 12.93$, $p < .001$. The difference between the identity preprime condition and the competitor preprime condition was not significant $\chi^2(1) = 1.673$, $p = .196$. Pairwise comparisons between the two priming conditions for each of the preprime conditions showed that the difference between the unrelated and related primes was significant in the identity preprime condition, $\chi^2(1) = 13.272$, $p < .001$; and in the competitor preprime condition, $\chi^2(1) = 31.201$, $p < .001$; but not in the no preprime condition, $\chi^2(1) < 1$.

Table 3. 5 *Mean Response Times (ms) and Error Rates (%) by Condition for Word Trials in Experiment 3 and Response Times (cycles) by Condition in Simulation of Experiment 3*

	Preprime					
	Identity		Competitor		None	
Prime	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation
Transposed-all	614 (10)	99	617 (9)	116	630 (9)	113
Unrelated	640 (14)	113	657 (13)	115	633 (12)	114
Priming	26 (4)	14	40 (4)	-1	3 (3)	1

Accuracy

A generalized linear mixed-effects model with binomial distribution was fitted for the word accuracy analyses with preprime type, prime type and their interaction as fixed factors and by-subjects and by-items intercepts and slopes for preprime type as random factors. The effect of prime type was significant, $\chi^2(1) = 16.89$, $p < .001$. Participants were significantly more accurate when the prime was related than when it was unrelated.

Nonword Data

Response Time. Mean response times and error rates for nonword trials in Experiment 3 are displayed in Table 3.6. Trials with response times shorter than 150 ms or longer than 1500 ms were excluded from the latency analyses (0.6%), as were trials with incorrect reponses (12.54%). In addition, items with accuracy less than 60% were not included in the analyses. A linear mixed-effects model was fitted with preprime type, prime type and their interaction as fixed factors and by-subject and by-items intercepts and slopes for preprime type, prime types and their interaction as random factors. The effect of prime type was significant, $\chi^2(1) = 4.097$, $p = .043$. Participants were faster to reject nonword foils when the primes were related, than when the primes were not related.

Accuracy. A generalized linear mixed-effects model with binomial distribution was fitted for the nonword accuracy analyses with the same structure as the one in the nonword latency analyses. The results did not reveal any significant effects.

Table 3. 6 *Mean Response Times (ms) and Error Rates (%) by Condition for Nonword Trials in Experiment 3*

Prime	Preprime		
	Identity	Competitor	None
Transposed-all	698 (13)	701 (11)	701(10)
Unrelated	711 (12)	708 (11)	708 (11)
Priming	13 (-1)	7 (0)	7(1)

Simulation of Experiment 3

Experiment 3 was simulated with the same method as for Experiments 1 and 2. The model recognized correctly all the target stimuli as words. Mean predicted response times (cycles) are included in Table 3.5. The model predicted a 1 cycle facilitation effect in the no preprime condition, which was enhanced to 14 cycles in the identity preprime condition. Crucially, contrary to the observed results in the competitor preprime condition in Experiment 3, the model predicted a 1 cycle inhibitory effect in this condition, rather than a priming boost relative to the no preprime condition.

Discussion

The results in Experiment 3 showed a significant facilitation priming effect when the preprime was a high frequency neighbor and this effect was not only in the same direction as the identity preprime condition, but also numerically greater. The model's prediction did not match the empirical results as it included a priming boost relative to the conventional masked-priming paradigm only in the identity preprime condition. The evidence again ran in the opposite direction to that predicted by the idea that activation of lexical competitors eliminates or attenuates priming. These results suggested that the advantage of the sandwich priming paradigm over the conventional one could also be obtained by a preprime presentation of a similar to the target word, rather than the target itself and thus could not be attributed to the elimination of lexical competition effects.

General Discussion

The results from the present study showed that the masked form priming effect was increased not only after a brief preprime presentation of the target itself, but also after a presentation of a word orthographically related to the target. These results contradicted the predictions of the Spatial Coding Model (Davis, 2010), which predicted an increase of the priming effect only after a presentation of the target and an inhibitory influence of the presentation of a related word. In the interactive activation framework, the activation of such closely related candidates leads to inhibition of the target word and they are therefore considered to be target's competitors. Our study replicated the results of Lupker and Davis (2009) that the presentation of the target before the prime, as in the sandwich priming paradigm, produced priming effects that were not present when the original masked priming was employed. Crucially, however, we extended their findings and demonstrated that this effect could also be achieved with a preprime presentation of a *competitor* word. As a presentation of a competitor should increase lexical competition, the results presented here thus contradict Lupker and Davis's interpretation that the sandwich priming procedure enchances priming by attentuating lexical competition processes. More specifically, the present results provided evidence that the brief presentation of the target as a preprime was not linked to mechanisms of suppression of targets' competitors. These findings suggested that the sandwich priming methodology could not be considered as a method overcoming the limitations of the conventional masked priming paradigm *by eliminating lexical competition effects*.

In the present study, we addressed the question of why the primes that failed to produce facilitation effects with the conventional masked priming paradigm did so with the sandwich priming. As we considered the evidence provided by Lupker and Davis (2009) to be inconclusive for determining the nature of the sandwich priming effects, we tested their claim that a preprime presentation affected lexical competition processes. We followed the interactive activation and competition framework and aimed to provide more evidence by keeping lexical competition present. What is more, we aimed to enhance it. We did so by manipulating what and whether anything was presented before the prime. If the presentation of the target would activate the target's lexical representation and by doing that this advantage will lead to the elimination of lexical competition effects, then it should follow from that, that a presentation of a target's competitor before the prime would preactivate the target's competitor lexical representation, which would keep and even augment lexical competition effects. The claim of Lupker and Davis was that moderately related primes could produce facilitation if lexical competition effects were filtered out. We explored whether moderately related primes could also produce priming with preprimes that clearly could not filter out lexical competition (and indeed should have the opposite effect).

In three different lexical decision experiments, we explored the priming effects of related primes by comparing them to unrelated primes conditions. We did that comparison with three different procedures. We used the conventional masked priming procedure in which we presented only one brief prime, that was immediately followed by a target. We also used the procedure, suggested by Lupker and Davis (2009), in which we inserted the target's brief presentation before the prime. In the third procedure, we inserted a target's competitor before the presentation of the prime. We compared the obtained empirical results with the predictions of the Spatial Coding Model (Davis, 2010) that were specific to the used stimulus materials.

In our first experiment, we used the original Lupker and Davis (2009, Experiment 2) stimuli and chose the closest possible competitor for each target. The results showed that the priming effects in the competitor preprime conditions for the one and two-letter different primes was numerically larger, but not significantly different from the ones that were obtained when there was no preprime (conventional masked priming). These results did not accord with the prediction of the model of an attenuation of the priming effect in the competitor preprime condition, relative to the no preprime condition. Consistent with the model's predictions, however, and with the reported results by Lupker and Davis, a form priming boost was replicated in the identity preprime (original sandwich priming) condition. After such a target preprime presentation, the priming effect in the one-letter different prime condition reached 59 ms. This effect was statistically different from the no preprime condition, but not from the competitor condition, suggesting a tendency of the competitor preprime towards producing a form priming boost. With an identity preprime, a significant facilitation effect was observed when the related primes were up to three-letter different from the target, thus differing from the competitor and the no preprime conditions.

In Experiment 2, we chose different targets that have orthographic neighbors and constructed stronger competitors for them. We chose high frequency words that differ by only one letter from the target. We expected that such a manipulation should afford strong inhibitory effects if indeed lexical competition was affecting priming results. In this experiment, all primes were one-letter different from the target as well as one-letter different from the competitor preprimes. All three preprime conditions produced significant facilitation. No trace of inhibition was introduced by the high-frequency target neighbors. These results stood in sharp contrast with the Spatial Coding Model's (Davis, 2010) prediction of a strong inhibitory priming effect in the competitor preprime condition. The model's prediction suggested that in an interactive-activation framework, the selected items were highly effective in triggering lexical competition processes in the context of the shared-neighbor primes and the lower frequency neighbor targets. Despite that, however, the priming effect in the competitor preprime condition in Experiment 2 remained in the opposite direction and did not differ significantly from the priming effect in the identity preprime condition.

With competitor preprime manipulation left aside, the results from the second experiment also showed that, although numerically 11 ms bigger, the 36 ms priming effect in the identity condition was also not statistically different from the one in the conventional masked priming condition. Unlike the sandwich priming boost in the one-letter different prime condition in

Experiment 1, such a robust boost was not observed with the stimuli in Experiment 2. The priming effect was increased with 35 ms relative to the no preprime condition in Experiment 1 and with only 11 ms in Experiment 2. Apart from being one letter shorter, the targets in Experiment 2 differed from those in Experiment 1 by having a high frequency neighbor. In addition, related primes were constructed to be neighbors of both the target and the target's word neighbor. Previous studies have demonstrated that the size of the priming effect is reduced when target neighbor nonword primes and targets share a word neighbor (Van Heuven, Dijkstra, Grainger, & Schriefers, 2001). These findings have been interpreted in just this kind of the lexical competition framework: The explanation has been that when the prime is related to both the targer and a competitor, this competitor becomes highly active and therefore influences the target negatively through the lateral inhibition mechanism in the related condition. If shared neighbors reduce the size of the priming effect even after the sandwich priming manipulation, then lexical competition, stated as a cause for decreased priming effects, is not eliminated by the preprime presentation of the target. The fact that the size of the sandwich priming boost was greater with targets that had no close competitors (Experiment 1) than with targets that had high frequency neighbors and were primed by shared-neighbor primes (Experiment 2) is consistent with the interpretation that sandwich priming does not address counteractive lexical competition effects. However, further investigation is needed before drawing strong conclusions regarding the sandwich priming boost dependency on effects such as shared neighborhood, frequency and neighborhood size relationships between targets and competitors, and possibly target length.

Some evidence that the sandwich priming boost might be dependent on word length in a shared neighbor priming context comes from the obtained robust priming effect in the conventional masked priming condition in Experiment 2. This condition served as a baseline for evaluating the sandwich priming boost and was not significantly different from the identity preprime condition. One apparent difference between the current study and a previous study, that had demonstrated that shared neighbor primes were not effective (Van Heuven, Dijkstra, Grainger, & Schriefers, 2001), was the length of the stimuli. The stimuli in Experiment 2 were six-letters long, while the items in Van Heuven et al. (2001) were four-letters long.

In Experiment 3, we sought to extend the findings with the three preprime manipulations and constructed the related prime condition by transposing all adjacent letters in the targets. Previous studies have shown that such primes do not differ from an unrelated condition when the original masked priming is used (Guerrera & Forster, 2008; Lupker & Davis, 2009). Our results were in accordance with those studies as we failed to establish a significant priming effect when there was no preprime. We also managed to replicate the significant difference between the related condition and the unrelated condition when the target was presented as a preprime that was found by Lupker and Davis (2009, Experiment 1). More important, though, we found that higher-frequency neighbors of the target enabled the same facilitation effect as the target words themselves (in fact, even numerically bigger) when they were presented as preprimes. These results were again not in accordance with the Spatial Coding Model's (Davis, 2010) predictions.

These findings imply that the competitor preprimes did not inhibit the targets' recognition and could not be linked to lexical competition processes. On the contrary, the results from Experiments 2 and 3, in which the competitors highly resembled the targets and differed by only one letter from them, the cases in which they should produce most inhibition, they produced as much facilitation as the target preprimes did.

Like Lupker and Davis (2009), we found that the brief presentation of the target before the primes boosted masked form priming facilitation effects and even produced facilitatory priming in cases in which the traditional masked priming procedure could not. Our results were not however consistent with an interpretation that the obtained facilitatory orthographic priming effects were evidence that prime sandwiching was a manipulation that operated by reducing lexical competition effects. Considering the evidence presented here, one should not view a dual-prime paradigm, such as the sandwich priming paradigm, as a superior to the conventional masked-priming paradigm by virtue of reduction of competition. Such an interpretation is ruled out by our demonstration that the orthographic effects were not reversed and followed the same sandwich pattern when orthographic neighbors of the targets were presented as a preprime.

It appeared from the data presented here that the priming effect was boosted when both the preprimes and primes reached a high degree of similarity with the targets. In Experiment 1, when the competitor preprimes were more often more than one-letter different from the target, the facilitation in the competitor preprime condition was evident only when the related primes were no more than two-letters different. Thus, the results in this preprime condition matched those in the no preprime condition. In Experiment 3, however, when the competitor preprimes differed by only one-letter from the target, the priming effect produced by transposed-all letter primes reached significance and was highly boosted by the presence of a preprime, regardless of whether the preprime was the competitor word or the target. We could thus infer that the orthographic priming effect produced in a sandwich priming paradigm was not a function of the similarity between the prime and the target, with lexical competition being filtered out, but rather of the joint similarity of the two primes with the target.

Such an interpretation is consistent with evidence provided by Forster (2009, 2013) that masked form primes did not produce significant priming effects when they were followed by another unrelated prime, rather than directly by the target. In his studies, Forster used a procedure that resembled the sandwich priming paradigm as it also included an additional processing event which was inserted in the conventional mask-prime-target sequence. As he explored the limits of obtaining a priming effect, his study contained different manipulations than those in the present study. Such differences include: order of presentation of the two primes, prime visibility (masked, unmasked) and prime type levels. An additional unrelated preprime served as a control for establishing the effect of an identity preprime and a one-letter different nonword form prime. When both primes were masked (both presented for 50 ms), an identity preprime produced a significant facilitation effect relative to the control when followed by an unrelated prime, but form prime did not. Forster concluded that identity priming operated on two levels: meaning and form, with only the processes taking place on the level of meaning being unsusceptible to the effects of the dissimilar in form unrelated “intervenor”. These results, and the interactive nature of the sandwich priming boost observed in the present study, suggest that a masked orthographic priming effect requires a degree of consistency in the information provided by subsequent brief perceptual events.

A possible explanation of these observations could be that the presentation of the preprime in the present study enhanced the form priming effect by providing additional perceptual evidence that was consistent with the characteristics of the target. The priming effect is a function of the total amount of information consistent with the target that could be processed in such conditions from both the prime and preprime. It follows from the preprime and prime interaction that the accumulated evidence towards the target from the preprime alone is insufficient when there are two sequential priming visual events and an additional supporting evidence from the prime is needed to produce the facilitation effect. When the prime is related to the target (and the preprime), the total amount of inconsistent information is much less (in terms of wrong letter identities, and letter positions or both) and possibly the probability that it is detected is much lower in comparison to the unrelated prime condition. Thus, the difference between the related and unrelated prime conditions becomes significant. Interpretations of priming effects in terms of accumulating perceptual evidence from successive perceptual events are also made by proponents of the Bayesian Reader framework (Norris & Kinoshita, 2008).

Another interpretation of the results, and particularly the consistent sandwich priming boost with moderately related primes, could be described in the framework of the interactive-activation model (McClelland & Rumelhart, 1981) with mechanisms different from lexical competition. As the name suggests, this account models the process of word recognition by the means of accumulation of activation of individual lexical units (word nodes), and higher levels of activation are associated with recognition. Facilitatory priming is therefore observed when the target word's node is more active at related prime offset than at control prime offset.

A word node's activation starts from a resting level, a negative number that is specific for each word node and is a function of the word's frequency but is typically higher than the minimum (floor) activation associated with all nodes. When an input is presented that is sufficiently consistent with the node, the node's activity increases, while with a net inconsistent input the activity decreases. Therefore, the presentation of an unrelated prime will decrease the target's activation below its resting level, eventually pushing it towards the floor.

A prime, insufficiently consistent with the target, such as a transposed-all prime, could produce a similar effect. Although more slowly than with an unrelated prime presentaiton, the target's activation will also decrease due to a transposed-all prime and could reach the floor level by the time of the prime's offset. In this scenario, at the time of the target's onset, the activitation of the target node will be at the same starting point, the floor level, in both the unrelated prime and the related transposed-all prime conditions. Therefore, in both conditions, the target node will need the same amount of time to raise its activity to the recognition threshold. Since there will be no difference between the two priming conditions, a priming effect, measured by that difference, would not be observed.

In sandwich priming scenarios, the first event is the preprime that is consistent with the target, rather than the prime that is not. Therefore, the target's activation will first increase above the resting level, rather than decrease to the floor level (as in the no preprime condition). This increase could be achieved with both a target preprime and a one-letter-different from the target preprime (i.e., the competitor preprime condition). When the prime is presented as a second event, the level of the target's activation is sufficiently high to remain above the floor level until the offset of the inconsistent prime, at least in the transposed-all prime condition. In this condition, the activity decreases at a slower rate than the control due to this related prime's moderate similarity to the target. As the activity of the target will not drop to the floor level, or at least not in both priming conditions, it will be different for the two conditions at the time of the target's onset. The crucial difference between the conventional priming and the sandwich priming, therefore, is that a floor effect is observed in the former, while in the latter it is not. In conventional priming, at the time of the target's onset, the activation of the target node is at the same (floor) level in both priming conditions, while in sandwich priming, it is higher in the related transposed-all prime condition than in the unrelated one, allowing for a priming effect to occur.

An interpretation as the one in the interactive activation framework, however, considers all features of the stimuli and assumes that all information is processed in both the conventional masked priming and the sandwich masked priming conditions. Due to the additional visual event and the further processing time, however, the mechanisms involved might differ between the two masked priming paradigms and a straight comparison between the orthographic priming effects produced by both might not be absolutely informative, until more evidence is gathered about the perceptual processes that take place when two primes are briefly displayed. Interesting outstanding questions include the extent to which the preprime information is processed, and in particular, when such information is inconsistent with the other two visual events (prime and target). Such information was, for example, the inconsistent one different letter in the competitor preprime in Experiment 3. Although the sandwich priming paradigm may not be superior to the original masked priming paradigm for the reasons stated by Lupker and Davis (2009), it may nevertheless be informative in the exploration of bottom up processes, early processing stages in visual recognition and capacity limitations of the processing system. A similar technique has already been employed for investigation of capacity limitations in several studies (Forster, 2009, 2013). A task that could be used as an alternative to the conventional masked-primed lexical decision for measuring orthographic similarity is the same-different task, which has been proposed as less susceptible to lexical effects and more sensitive for detecting small differences in priming effects (e.g. Kinoshita & Norris, 2009; Norris, Kinoshita, & van Casteren, 2010).

In conclusion, the present study provided evidence that the enhancement of the form priming effect produced in the sandwich priming paradigm in comparison to the conventional masked priming paradigm could not be attributed to the elimination of lexical competition processes. Rather, the results from the present study suggest that this effect have a different locus, such as bottom-up processes that operate on a prelexical level. The results from the present study thus not only question the mechanisms underlying the sandwich priming procedure, but they also provide more information about the nature and the boundaries of orthographic processing.

Chapter 4

More Sandwich Priming and Lexical Competition

The process of reading, and more specifically, recognizing an individual word, requires encoding of the identity and position of the letters within a word and mapping a visual stimulus to an individual unit from the lexicon. It is plausible to assume that the access of a lexical unit requires evaluation of possible candidates. The implementation of this lexical selection process differs across models of visual word recognition.

Localist hierarchical models such as the Interactive Activation (IA) model (McClelland & Rumelhart, 1981) and its successors (e.g., Davis, 2010; Grainger & van Heuven, 2003) consist of nodes corresponding to meaningful unit representations of various cognitive complexity: from nodes of low-level perceptual features in letters to nodes for word representations. The levels within these hierarchical structures are connected by excitatory and inhibitory links. Units that are consistent with a visual stimulus receive activation and those that are not are inhibited. It follows from this mechanism that the representations of words that are similar in form and contain the same features and letters (e.g. *cost* - *host*) are simultaneously activated once stimuli related to them are presented. The presentation of the word *cost* will activate *cost*, *most*, *post* and so on. As the nodes in the level are connected (only) with lexical inhibitory links, activated word units send inhibition to other words, a mechanism known as lateral inhibition. Thus, in these models, the process of lexical selection (recognizing a letter string as a word) is mediated by competition between related words that is explicitly implemented within the model. The competition ends once the activity of one of the lexical candidates exceeds a certain threshold.

The prediction of the IA model with typical parameters is such that if two words differing by a single letter (orthographic word neighbors) are perceived in a brief time interval and in an immediate succession, the recognition of the second word will be delayed (Davis, 2003), relative to an unrelated control condition. This prediction was tested and confirmed by Davis and Lupker (2006), who reported a lexicality effect on priming in the form of an interaction such that the presentation of an orthographic word neighbor prior to a target word produces inhibitory effects on the target recognition while the presentation of nonword neighbor produces facilitation effects. Davis and Lupker explained those results by pointing out that one-letter-different word primes increased the activation of a competitor word which in turn produced inhibitory effects on the target word. The direction of the effect is reversed in the nonword related primes condition, which facilitate word recognition, as non-words do not have lexical representation in the mental lexicon and instead of strongly activating a competitor word, they only increase the activation of the target prior to the target presentation thus facilitating its recognition.

As already discussed in the previous chapter, the leading technique for studying orthographic processing has been the masked priming paradigm, most often combined with the lexical decision task. The magnitude of the (facilitatory) priming effects has often been interpreted as the degree to which the processes involved in encoding the prime and the target overlap. This paradigm has been criticized by authors advocating the lexical competition account with the argument that the priming results are not only a function of the similarity between the orthographic codes between the prime and the target, but also of counteractive inhibitory processes that might cancel out facilitation, thus making it difficult to link obtained empirical results with the orthographic similarity between two letter strings (Lupker and Davis, 2009). This criticism was motivated by the null priming effects obtained with primes moderately related to the target. As a solution, Lupker and Davis suggested an alternative procedure in which two primes were presented, the target itself being the first prime, thus sandwiching the prime with its two presentations, a sandwich priming. The reasoning behind this procedure was that such an initial presentation would activate the target's representation and would therefore give it an initial advantage over its competitors. With sandwich priming, they succeeded in obtaining facilitation effects with primes moderately related to the target and attributed this form priming boost to the successful elimination of lexical competition and simplifying the interpretation of the relation between the orthographic codes of the prime and the target.

In the previous chapter of this thesis, evidence was provided against this argument, as it was demonstrated that the presentation of a related word rather than the target as a first prime, which in this IA account should increase lexical competition or at least decrease facilitation, also resulted in a form priming boost. A possible interpretation of these results is that the processing of the preprime did not reach a stage of accessing the lexical unit of the preprime, thus degrading it to a related nonword and producing facilitation, rather than inhibition effects. Another explanation could generally question the necessity of lexical competition processes in word recognition, possibly because inhibitory findings are due to task-specific decision processes, not lexical access.

It is difficult to infer what mechanisms are involved in a paradigm with two primes with only the evidence presented so far. Key conditions that are missing from the design of all those experiments are related and unrelated word primes, rather than preprimes or nonword primes and the crucial comparison of the priming effect as a function of prime relatedness in both conventional (prime-target) and sandwich priming (target-prime-target) conditions. Word priming conditions are important, because they are hypothesized to show inhibitory priming effects, thus implying lexical competition. In fact, in their study, Lupker and Davis (2009) showed that primes constructed by transposing all target letters or replacing three target letters produced facilitation relative to control with the sandwich priming paradigm and only assumed that these primes did not produce the same results with the conventional priming due to counteractive lexical competition. Their experiments did not explicitly demonstrate the presence of an inhibitory effect produced by related word primes and a removal of this effect under the conditions of a sandwich priming. They did not explicitly show that sandwich priming eliminated lexical competition, as there was no inhibitory effect of a related word prime at the first place that needed to be reduced or eliminated by a preprime presentation of the target.

One could argue that even a demonstration of an inhibitory effect produced by a related to the target word prime with a conventional priming but not with sandwich priming will also not necessarily provide evidence for the mechanisms that Lupker and Davis (2009) hold responsible for the sandwich priming results. A possible change of the lexical inhibition effect could simply be attributed to the difficult processing conditions in a dual priming paradigm. A more convincing demonstration will be one in which it is shown that a related word prime produces inhibition relative to an unrelated control after a presentation of a preprime and only stops inhibiting the target when the preprime is the target. Therefore, a design more informative for the mechanisms in sandwich priming would be one in which a condition of an unrelated word is also included at the position of a preprime. Such a word will not activate the target's representation as it will not be related to it. Therefore, any effect produced by this preprime will provide evidence of the extent to which the (related) prime is processed when sandwiched between a preprime and a target. If the presentation of an unrelated word affects the produced priming effect, that would suggest that the conditions of the sandwich priming paradigm simply block the effective processing of the prime.

This condition and the research question behind it relates to another study that included two primes, which were included for studying the capacity of the lexical processor (Forster, 2009). In this study, Forster presented an unrelated word that either preceded or succeeded the presentation of another prime and was either visible or masked (presented for 50 ms). The focus was on exploring whether the priming effect could 'survive' across 'an intervenor', an unrelated word. The related priming conditions were either identity (the target) or one-letter different nonword and were compared to an unrelated word control conditions. In the masked conditions, which are the relevant ones to the present study, the results indicated that only identity priming produced significant priming effect when the unrelated word succeeded the prime (and acted as an intervenor) but when the unrelated word preceded the primes both identity and one-letter different nonword produced significant priming, with the identity priming producing larger effect (53ms and 27 ms).

Crucial differences between the conditions proposed here and those in Forster (2009) are, however, the lexicality of the one-letter different prime, which was a nonword in Forster's study as well as the longer presentation of the first priming event (50 ms vs. 33 ms in the sandwich priming paradigm). Therefore, although relevant to the present study as also including two primes before the target, Forster's results cannot predict whether a possible inhibitory effect could be blocked if an unrelated word is presented for 33 ms as a first prime.

The present study aimed to address the questions discussed so far and to provide more evidence regarding the mechanisms involved in a paradigm with two primes by designing an experiment with the aforementioned conditions. More specifically, it directly tested the assumption of the presence of lexical competition by presenting a competitor word as a prime (rather than as a preprime as in the design of the experiments in Chapter 3) and compared its effect on the target in conditions with conventional masked priming, sandwich masked priming with a target preprime and sandwich priming with an unrelated word preprime. The last-named condition was included to test whether the priming effect produced by the 'competitor' word could still affect the target recognition if the lexical processor is forced to initially process another lexical unit unrelated in form or is just perceptually blocked by the preceding visual event. The results from the experiments in Chapter 3 showed that the priming effect survived only when a considerable form overlap was observed between the preprime and prime (and target) but did not include a condition in which the presentation of the target is immediately preceded by a competitor prime, which is itself preceded by a preprime.

The expectation was that a related prime word would produce an inhibitory effect related to the unrelated condition when no preprime was presented (conventional masked priming). This expectation was motivated by the prime lexicality effect, demonstrated by Davis and Lupker (2006): Related nonwords facilitated target recognition, but related words inhibited it relative to an unrelated prime condition. Such a result would also be in accordance with Lupker and Davis's claim that the relatedness of the orthographic codes is not sufficient to predict the size of the priming effect and sometimes not even the direction of the effect.

Furthermore, if the related word was recognized by the system as a legal lexical unit, the related word should still produce inhibitory effects on the target in the nonword preprime condition. In such a scenario, the lexical inhibition effect could serve as a marker of successful lexical access and processing on the stage of a lexical level. If on the other hand, the effect of the related word was blocked after a presentation of the unrelated preprime, that would suggest that the prime was not processed effectively, and sandwich priming results could not be attributed to preactivation of the target, but rather to blocking the processing of the prime and its effect on the target. If this was the case, the related word prime could be processed only at prelexical level as a related nonword, thus possibly producing facilitation effects on the target as in Forster (2009).

Finally, all the aforementioned conditions and effects would also be compared to a sandwich priming condition with a target preprime, for which the results of Lupker and Davis (2009) and those of the experiments in Chapter 3 suggest that a facilitatory form priming boost should be observed.

Experiment 1

The aim of the first experiment was to replicate the lexical inhibition effect, previously demonstrated by Davis and Lupker (2006), produced by an orthographic neighbor on the target recognition and to test whether this effect could survive if the prime is preceded by another prime (an unrelated word or the target). The purpose of this test was to explore whether the lexical status of a prime could be determined by the lexical processor which would suggest that the (second) prime was processed lexically in a paradigm with two primes.

Method

Participants

Fifty-four native English speakers participated in the experiment in exchange for course credit.

Stimuli and Design

Ninety pairs of 5-letter orthographic neighbour words (store-STORM) were selected for the word target trials (mean *N* = 4.6). The more frequent word of each pair served as a prime and the less frequent one served as a target. Both words shared one more orthographic neighbour differing in the same letter position (story). Another 90 pairs of orthographic neighbours were selected for the nonword target trials. Nonword targets were constructed by changing the letter in the position in which the orthographic neighbours in the pairs differed (e.g., never-fever-TEVER).

The design of this experiment included three different preprime (first prime) conditions: (none/unrelated word/identity) and two prime conditions: related word (orthographic neighbour)/unrelated word. The unrelated word in the preprime condition and the unrelated word in the prime condition were related words for other targets from the same set. They were matched so that they did not share more than two letters with the target and the shared letters did not appear in the same positions. An example of unrelated preprime, unrelated prime condition is STORY-chefs-QUILT. The unrelated preprimes were the third neighbor of a matched orthographic pair (e.g., STORY from the pair store-storm). Each participant saw all six conditions, but they saw each target in only one of the six conditions. Six different counterbalancing lists were created for that purpose.

Procedure

Each trial began with a fixation cross, presented for 300 ms, followed by a 200 ms blank screen after which a forward mask (########) appeared for 500ms. The mask was followed by a presentation in uppercase of a preprime (except for in the no-preprime condition) for 33 ms and a presentation in lowercase of a prime for 50ms. The target was then presented in uppercase and stayed on the computer screen until response. The preprimes, primes and the targets were all presented in Courier New font, sizes 7.5, 12.5 and 20 respectively. The purpose of the case and size manipulations were to minimize visual overlap between the stimuli. The stimuli were presented in black on a white background. The task was lexical decision. Participants were instructed to indicate their decision regarding the lexicality of the target string (real word or not a real word) as quickly and as accurately as possible by pressing one of two corresponding keys. Feedback was given after each trial. The DMDX software (Forster & Forster, 2003) was used for stimuli presentation and data collection.

Results

Response Time

Prior to the word latencies analysis, trials with latencies that were less than 150 ms or greater than 1500 ms (0.47%) or had an incorrect response (9.28%) were removed. Mean reaction times and accuracy by condition are reported in Table 4.1. A linear mixed-effects model was fitted with preprime type, prime type and their interaction as fixed factors and by-subjects and by-items intercepts, by-subjects slopes for preprime type and prime type and by-items slops for preprime type, prime type and their interaction as random factors using the *lme4* package in R (Bates, Maechler, Bolker, & Walker, 2015). The by-subject slope for the preprime type by prime type interaction was removed from the model, as it did not converge. Type II Wald chi-square tests were performed on the fitted model to establish the significance of the fixed main effects as well as their interaction. The effect of prime type was significant $\chi^2(1) = 4.552$, p = .033. The effect of preprime, $\chi^2(2) = 2.359$, p = .307, and the interaction between the two factors were not significant, $\chi^2(2) = 1.41$, p = .494.

Table 4. 1 *Mean Reaction Times (ms) in Experiment 1 for Word Targets and Error Rates (in Percentages, in parentheses) as a Function of Preprime Type and Prime Type*

		Preprime		
		-	*guilt*	*storm*
		None	Unrelated	Identity
Prime				
store	Related	646 (8.3)	655 (9.6)	641 (8.3)
fudge	Unrelated	653 (9.1)	657 (10.9)	659 (11)
	Priming	7 (0.8)	2 (1.3)	18 (2.7)

Accuracy

A generalized mixed effects model with binomial distribution was fitted for the word accuracy analyses with preprime type, prime type and their interaction as fixed factors and by-subjects and by-items intercepts as random factors. The by-subjects and by-items slopes were excluded as the model could not converge. The results revealed a main effect of prime type $\chi^2(1) = 4.865$, $p = .027$. The effect of preprime was not significant, $\chi^2(2) = 2.511$, $p = .285$; nor was the interaction between the two factors, $\chi^2(2) = 1.035$, $p = .6$. Participants were significantly more accurate when the prime was related, than when the prime was not related.

Discussion

The most surprising result of this experiment was the lack of inhibitory effect of relatedness which was expected to be obtained at least in the no preprime condition. The related word primes were numerically (but not significantly) even facilitating target recognition in comparison to the unrelated primes by 7 ms. This result contradicts the results reported in the Davis and Lupker (2006) study and do not provide strong support for the lexical competition hypothesis. There was a trend of increasing the priming effect in the identity preprime condition, but the results did not provide evidence of significant difference in that condition, as the interaction between preprime type and prime type was not significant. The lack of a lexical inhibition effect is further addressed in Experiment 2.

Experiment 2

The aim of this experiment was to replicate the lexical inhibition effect reported by Davis and Lupker (2006) using their stimuli as well as the stimuli from Experiment 1. The purpose of using both sets of stimuli was to test whether the lack of inhibition effect in Experiment 1 was due to some idiosyncrasies of the stimulus material.

Method

Participants

Thirty-six native English speakers participated in the experiment in exchange for course credit.

Stimuli and Design

Seventy-six of the orthographic pairs from the Experiment 1 were used[6] in addition to the stimuli from the first experiment in the Davis and Lupker (2006) study. As Davis and Lupker obtained stronger inhibitory effects when the higher frequency words from the orthographic neighbor pairs served as primes and the lower frequency words served as targets, the higher frequency words from each pair served as a related prime in this experiment. There were four priming conditions, which were formed by crossing the factors prime lexicality (word/ nonword) and prime relatedness (related/ unrelated). The related nonword primes for the Experiment 1 set were constructed by changing one letter from the related word primes. This letter was in the position in which the related word prime and the target differed. Due to an error, the related nonword primes in the Davis and Lupker subset were two-letter different, rather than one-letter different from the targets.

Procedure

The procedure was identical to that in Experiment 1, except for the lack of a preprime presentation.

Results

Response Time

Prior to the latency analysis, latencies that were less than 150 ms or greater than 1500 ms (1.10%) and incorrect trials (11.19%) were removed.[7] Mean reaction times and accuracy by condition are reported in Table 4.2. A linear mixed-effects model was fitted with relatedness, lexicality and their interaction as fixed factors and by-subjects and by-items intercepts as random factors. Neither of the main effects was significant, nor was the interaction between the two factors (all χ^2 <1). There were similarly no significant results when the two sets of stimuli were analyzed separately; the relevant means are presented in Table 4.3.

[6] The number of pairs decreased as the same items were already included in the Davis and Lupker (2006) stimuli.

[7] In addition, as 10 items out of 64 from the Davis and Lupker (2006) stimuli and 3 items out of 76 carried over from Experiment 1 had an accuracy below chance level, data from those items were not included in the latency and accuracy analyses.

Table 4. 2 *Mean Reaction Times (ms) in Experiment 2 for Word Targets and Error Rates (in Percentages, in parentheses) as a Function of Lexicality and Relatedness*

	Nonword prime	Word prime
Related	647 (8.1)	648 (8)
Unrelated	649 (8.2)	650 (7.7)
Priming	2 (0.1)	2 (0.3)

Accuracy

A generalized mixed effects model with binomial distribution was fitted for the word accuracy analyses with preprime type, prime type and their interaction as fixed factors and by-subjects and by-items intercepts as random factors. The by-subjects and by-items slopes were excluded as the model could not converge. As in the latency analysis, the factors and the interaction between them were not significant (all χ^2 <1).

Table 4. 3 *Mean Reaction Times (ms) in Experiment 2 for Word Targets and Error Rates (in Percentages, in parentheses) by condition for the two separate datasets*

	Stimuli: Exp 1		**Stimuli: D&L (2006)**	
	Nonword prime	Word prime	Nonword prime	Word prime
Related	643 (6.9)	643 (7.9)	653 (9.9)	654 (8.2)
Unrelated	659 (6.9)	640 (7)	649 (10)	663 (8.6)
Priming	6 (0)	-3 (-0.9)	-4 (0.1)	9 (0.4)

Discussion

The results from Experiment 2 also failed to replicate the lexical inhibition effect produced by related word primes that was reported by Davis and Lupker (2006). As the sample size did not differ between the two studies (32 participants in the Davis and Lupker study) and the stimulus materials were the same, the different pattern of results could not be attributed to these two reasons.

General Discussion

The results from the two experiments described above did not show a significant inhibitory effect produced by primes that were word neighbors of the targets relative to unrelated control word prime conditions. These data thus failed to provide explicit evidence for emerging lexical competition processes under masked priming conditions. The results from the present study failed to replicate those reported by Davis and Lupker (2006) even when the same stimulus material was used.

The present study, however, is not the first one to report null effects produced by such primes. In another study using the lexical decision task, Forster and Veres (1998) reported facilitatory effects produced by word neighbor primes when the nonwords in the task did not resemble words and a null effect when they strongly resembled words, suggesting that the priming effect produced by word primes was a function of the difficulty of the task. The results from Experiment 1 and Experiment 2 were in accordance with those of Forster and Veres, as again a null effect was observed with nonwords that were one-letter different from words, strongly resembling real words.

In their paper, Davis and Lupker (2006) also addressed the discrepancy in the literature regarding the effect of related word primes. They stated several possible reasons for the observed different results. The first reason that was stated was language, with more evidence towards inhibitory effects being presented by studies in languages different from English (e.g. in French, Segui and Grainger, 1990). The second reason was the neighborhood density of the targets. This expectation was related to previous evidence, suggesting that words with many orthographic neighbors were more difficult to be primed by related nonwords than words with fewer orthographic neighbors (e.g., Forster, Davis, Schoknecht, and Carter, 1987). This evidence was attributed to lexical competition and led to the hypothesis that inhibitory effects should be larger for words with many neighbors. This hypothesis was tested by Davis and

Lupker in Experiment 3 of their study and they did not find a significant difference on the inhibitory priming effect between low-*N* targets (mean $N = 2.8$) and high-N targets (mean $N = 13.1$). Therefore, they considered this reason to be unlikely for the discrepancy between their results and those reported by Forster and Veres (1998). Instead, they emphasized the importance of the prime and the target sharing a neighbor. In the same study, they demonstrated that the inhibitory effect was greater when the prime and the target shared a neighbor. The explanation given was that the activation of the shared neighbor was supported by both the prime and the target, thus introducing even more inhibition to the target.

The stimuli from Experiment 1 were all selected so that the primes and the targets share a neighbor. What is more, both the shared neighbor and the prime were more frequent words than the target, suggesting that the prime should be more easily activated and should produce more inhibition to the target, a prediction confirmed by Segui and Grainger (1990). The fact that the related nonword primes and the target also shared a neighbor (the related word prime) could explain the lack of significant facilitation effect produced by the nonword primes in Experiment 2 when nonword primes were one-letter different from the target (the Experiment 1 stimuli). Such an interpretation is in accordance with results presented by van Heuven, Dijkstra, Grainger, & Schriefers (2001) who reported smaller priming effect produced by nonword primes that shared a neighbor with the target than by primes that did not share neighbors with the target. As an inhibitory effect produced by orthographic primes has already been observed with part of the stimuli from this study and the rest of the stimulus material was selected so that it maximized lexical competition and the likelihood of establishing inhibitory effects, we consider highly unlikely that this effect was not observed due to idiosyncrasies of the stimuli that were used in the two experiments.

Another reason for not replicating the results of Davis and Lupker (2006) could be the small difference between the procedure in the two experiments described here and the procedure in Davis and Lupker. The duration of the prime in Experiment 1 and 2 was slightly shorter (50 ms) than that in their experiments (57 ms). As the main purpose of this study was to explore the mechanisms in a sandwich priming, a duration of 50 ms was chosen to match that of the prime duration in the sandwich priming paradigm, proposed by Lupker and Davis (2009). And indeed, the pattern of results in the literature suggests that one is more likely to observe significant inhibitory effects with word primes when a longer than 50 ms prime duration is used. The present study and that of Forster and Veres (1998) used a 50 ms prime duration and obtained null results while Davis and Lupker, and Segui and Grainger (57 and 60 ms) did report inhibitory effects. In another study, Andrews and Hersch (2010) also presented neighbor word primes for 50 ms and demonstrated that spelling ability was associated with the magnitude of the produced inhibitory effects with large inhibitory effects produced by better spellers only. All this evidence suggests that lexical competition processes might be triggered at a relatively later stage and enough processing time for the prime needs to be provided for an inhibitory effect to be observed in an average population of participants.

The results from the present study could not demonstrate whether an inhibitory effect produced by an orthographic neighbor of the target could be eliminated by the presentation of an unrelated word preprime, as the effect was not replicated in the condition in which no preprime was presented. Thus, this effect could not serve as a marker for the lexical access of the word prime. More importantly, the fact that the inhibition effect was not replicated suggested that a 50 ms duration of the prime might have been insufficient for a strong lexical competition to be possible. It might be the case that in a paradigm with the same prime duration, such as the sandwich priming, inhibitory processes are not present even without the preprime presentation of the target. Therefore, the observed priming boost after the additional preprime presentation of the target in the experiments of Lupker and Davis (2009), those presented in Chapter 3 and Experiment 1 in this chapter, could not be attributed to elimination of lexical competition as lexical competition might have already been eliminated and not present even without a preprime presentation of the target.

Chapter 5

Letter Processing

The process of reading is mediated by the identification of letters and their position in a word. Most researchers agree that letter identification is achieved through assembling features into letters (e.g., Finkbeiner & Coltheart, 2009; Grainger, Rey, & Dufau, 2008; Pelli, Burns, Farell, & Moore-Page, 2006). Finkbeiner and Coltheart argue that this process has been overlooked within the visual word recognition literature. They give an example with the unquestioned assumptions for the presence of the feature level in the interactive activation model (McClelland & Rumelhart, 1981) and models based on it (dual route cascaded, DRC model, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; spatial coding model, SCM, Davis, 2010). The processes underlying letter identification have not been in focus and these models do not question how the featural information is processed with the aim of recognizing abstract letter identities. Some of the assumptions that could be challenged, for example, concern the nature of the links between and within the feature and letter levels in these models (excitatory or inhibitory; Rey, Dufau, Massol, & Grainger, 2009) as well as the relative importance and the speed of extraction of the individual features in the identification of letters (Fiset et al., 2009).

Orthographic processing research typically proceeds from the finding that in serial presentations of visual events, such as in the masked-priming paradigm, the activation of abstract letter representations is not affected by differences in font, case and size. In the masked priming literature, the primes and targets usually appear across case and the priming effect is not disrupted by that difference. Bowers, Vigliocco and Haan (1998) focused on visual similarity effects and demonstrated that word identification was facilitated by an identity prime presented in lower case both when the uppercase targets were similar and dissimilar to the primes (kiss-KISS and able-ABLE). Kinoshita and Kaplan (2008) extended these findings for letters in isolation. With a cross-case same-difference task, they demonstrated a robust priming effect with identity letter primes that did not differ for similar (c/C) and dissimilar (a/A) letters. The literature has also provided evidence that even nonalphabetic characters can activate abstract letter representations due to visual similarity. Primes with embedded digits facilitated target recognition when the digits resembled the base letters (M4T3R14L-MATERIAL) than when they did not (M6T2R76L-MATERIAL; leet priming; Carreiras, Duñabeitia, & Perea, 2007; Perea, Duñabeitia, & Carreiras, 2008). As already discussed, however, the mechanisms by which different shapes and forms are mapped into the same letter identities have not been the focus of visual word recognition modeling. Finkbeiner and Coltheart (2009) gave an example with two different instances of the same letter (D/d) that would have mutually exclusive features for models based on the interactive activation model and therefore could not activate the same letter. Another example for oversimplifications in visual word recognition models is the assumed successful letter identification independent on font and size in the *alphabetic array* of the open-bigram model by Grainger and van Heuven (2003).

A central topic in the orthographic processing research relates to the way in which letters are perceived when they are embedded in strings. This problem is important for the understanding of the processes involved in reading. Questions related to this topic include functional specialization for the processing of letter strings as well as the manner at which letter information is extracted: serial or parallel. The question of parallel vs serial possessing has important implications for modelling visual word recognition. The question of whether letter identification is obtained serially or in parallel is essential for the understanding of letter position and identity encoding. As noted by Tydgat and Grainger (2009) most researchers agree that processing of letter identities is performed in parallel. One of the basic assumptions of the interactive activation model (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982) is that visual perceptual information (or at least one involving four-letter long words) is processed simultaneously for each of the spatial positions (letter slots) but also at several levels in parallel (feature, letter, word). The parallel assumption has been inherited by some of the models based on the interactive activation model (e.g. DRC, Coltheart et al. 2001; relative position open-bigram model, Grainger, van Heuven, 2003), although some have implemented rapid serial left-to-right scanning mechanism (SCM, Davis, 2010) for processing letter identity information and establishing the order code. A problem related to the parallel vs. serial debate is whether letters in strings are perceived equally well or some have a perceptual advantage over others depending on their position.

Evidence supporting the parallel processing of letter strings was provided by Adelman, Marquis and Sabatos-DeVito (2010). In their study, four-letter words were presented for durations from 12 ms to 54 ms with a time resolution of 6 ms between duration conditions. The authors explored letter processing at all four possible letter positions. The target was followed by two response options, which comprised of words differing by a single letter in one of the four positions (e.g. lung – sung for position 1, fish – fist for position 4). The results showed that at 18 ms the accuracy of the participants was at chance level for all four positions. In the next duration step (24 ms), however, performance was above chance again for all possible positions. The authors ruled out left-to-right serial scan and concluded that letter identities are processed in parallel. They attributed the trend of slight left to right decrease in accuracy to differences in efficiency of extraction of identity information. The results of this study motivated the parallel processing assumption of LTRS model (Letters in Time and Retinotopic Space; Adelman, 2011). In this model the processing of all letters starts at the same time and letter information is randomly extracted at different rates and in different moments in time.

Tydgat and Grainger (2009) investigated letter position effects in string processing and explored whether these effects apply to processing of other domains. They reviewed previous literature suggesting a W-shaped serial position function for letter identification accuracy in strings and an M-shaped function for letter detection speed. They argued that those shapes reflect more than one process. They suggested that both visual acuity as a function of distance from fixation and crowding mechanisms play a role. The visual acuity factor suggests that letters that are closer to fixation are easier to perceive than those further from fixation. The crowding affect reflects lateral interferences in terms of flanking of letters. As exterior letters are flanked by only one letter (to the right and to the left, respectively) they are more visually salient than interior letters, which are surrounded by two. However, the authors argued that these two factors could not explain further evidence from the literature demonstrating differential serial position function for symbols (e.g., Mason, 1982).

In a series of experiments, Tydgat and Grainger (2009) investigated whether the same mechanisms were involved in the processing of letter strings as the ones in the processing of digits and symbols. Their letter stimuli constituted by random five-letter-long consonant strings, they used the digits from 1 to 9 and symbols such as (%, /, ?, @, }, <, µ, £, §). The nature of the language stimuli was chosen so as to decrease influence of higher level phonological or semantic processes. In the first four experiments of their study, they used the two-alternative forced choice (2AFC) perceptual identification task. Fixation position was controlled by the presentation of two vertical bars which were placed at a central position above and below a forward mask. They presented their stimuli for 100 ms, sandwiched between forward and backward masks. Two options were presented at the end of each trial. These constituted of two single units, presented above and below the backward mask at one of the five corresponding positions. To minimize positional uncertainty errors, the incorrect response in these experiments was always not present in the strings. In the last two experiments, the authors changed the procedure and used free report instead of giving a choice between two units. Horizontal bars were presented above and below the probed position (bar-probe identification procedure), and participants had to report the stimulus at the probed position. In Experiment 1, the different target types (letters, digits, symbols) were presented in separate blocks. The results of the experiment showed differential functions for letters and digits in comparison to symbols, mainly expressed by an initial position advantage for letters and digits that was absent in the case of symbols stimuli. The same pattern of results was observed in Experiments 2 – 4, when stimulus type trials were intermixed, rather than presented in blocks (Experiment 2), and when target letters were embedded in symbols and vice versa (Experiment 3).

These results suggested that alphanumeric strings are processed in a specialized manner that is different from the one associated with symbol strings. The findings from the second and third experiments in Tydgat and Grainger's study (2009) ruled out the possibility that endogenous or exogenous attentional mechanisms are responsible for the different pattern of results for alphanumeric and symbol characters. Such mechanisms could be, for example, orienting attention at the beginning of the string in the cases of letters and digits, but not in symbols. In Experiment 4, when the unit at position 3 was removed, the performance at position 4 increased significantly for both letters and symbols, suggesting that crowding affects the pattern of the results. However, the initial position advantage was again only present in the case of letters, and not in symbols. In the symbol strings, the second unit was reported with significantly higher accuracy than the first one, again demonstrating that different mechanisms are involved in the processing of the two domains. When the 2AFC task was replaced with the bar-probe identification procedure (Experiments 5 and 6), a final unit advantage was also observed along with the initial unit one in the cases of letters and digits, but not symbols. Tydgat and Grainger explained the difference in the results of the final position between the two tasks with the larger number of location errors in position 4 than in position 5. As the alternative response in the 2AFC was not present in the target string, such a difference could not be observed with that task. The advantage of the final position over the penultimate one was explained with the difference in the number of flanking characters, with the final position having one, and the penultimate position having two. Based on these findings, Tydgat and Grainger argued for a specialized system for processing alphanumeric strings. They suggested that the reading system had evolved to compensate for effects of crowding by modifying the size and the shape of its receptive field detectors. In the cases of systems processing letters and digits, the receptive field detectors are smaller so that interference of surrounding units is reduced, as are crowding effects. According to these authors, the size of the detectors for symbols is larger and so strong crowding effects occur even with a single flanker.

Although the first position advantage could suggest a serial processing mechanism for letters and words, Tydgat and Grainger (2009) argued against such an explanation. They suggested that a serial processing should suggest a gradient in the processing of the serial strings, while the results indicated that the serial effect was driven entirely by the first position. They reported similar results for positions 2 and 4, and further suggested that a serial processing mechanism could not accommodate the final position advantage observed in Experiments 5 and 6. The authors explained the first position advantage with a modified shape of the receptive fields (elongated in the direction of the initial position) to accommodate for the special function of the initial position. They argued that the first position is important as it provides more constraint on lexical identity than other positions, and also pointed out to mechanisms of translation of an orthographic code into phonological, which rely on precise information of letter order and initial position.

Scaltritti and Balota (2013) further investigated the first letter position advantage with a 2AFC perceptual identification task. They demonstrated that initial letters were perceived with higher accuracy in words with various length (from 3 to 6 letters). They replicated this effect with 5-letter-long pseudowords and random consonant strings, but not with symbol strings, further suggesting functional specialization of the visual system for processing alphanumeric strings. The authors also argued that the pattern of their results is inconsistent with the assumption that letters are processed in parallel and independent of their position. It should be noted that unlike Tydgat and Grainger (2009), Scaltritti and Balota did not find any advantage of middle letter position. This could be due to methodological differences between the studies, such as lack of fixation bars in the case of Scaltritti and Balota's study, as well as presentation of string response options, rather than single letters, as in the case of Tydgat and Grainger's study.

Recently, the locus of the initial letter advantage was further investigated by Aschenbrenner, Balota, Weigand, Scaltritti and Besner (2017) who challenged the modified receptive field explanation proposed by Tydgat and Grainger (2009). This explanation suggested that the first letter advantage is due to receptive fields that are elongated to the left (for languages read from left to right) as an adaptation of the visual system to improve performance of initial letter detection due to their special function in reading. Aschenbrenner et al. demonstrated a first letter advantage with the word stimuli of Scaltritti and Balota (2013) even when the items were displayed vertically, rather than horizontally. Based on these results, they argued that rapid adaptive attentional mechanisms play a role in the initial letter advantage effect and attentional dynamics should be implemented in models of visual word recognition. In a follow-up study, Scaltritti, Dufau, and Grainger (2018) used random five-letter consonant strings and symbol strings and also manipulated orientation (horizontal and vertical). They demonstrated an initial unit advantage only in the letter strings and not in the symbols. The first letter advantage over the other letters was larger in the horizontal orientation than in vertical one. The authors concluded that the results are in accordance with the modified receptive field hypothesis, but since the first letter advantage was also present in the vertical orientation, they suggested that additional mechanisms in which attention is allocated to initial letters in a letter string operate regardless of orientation.

The special role of external letters was also demonstrated in studies showing that the rate of reading sentences is slowed most in a condition with degraded exterior letter pairs than in degrading the initial two letters or interior letters (Jordan, Thomas, Patching, & Scott-Brown, 2003). It is also supported by evidence from the masked-priming literature, suggesting that transposed-letter primes are less effective when the transposition involves external letters than when it involves middle letters (e.g., Schoonbaert & Grainger, 2004). As noted by Aschenbrenner et al. (2017), the special role of initial and final letter position has been implemented by different means in the current models of visual word recognition. In LTRS (Adelman, 2011), this is achieved by different processing rates as well as additional mechanisms that privilege the exterior letters once the lack of adjacent letter has been perceived. The overlap model (Gomez, Ratcliff, & Perea, 2008) encodes letter identities as normal distributions over positions. The standard deviations of the distributions are associated with the positional uncertainty of the letter. The model has different standard deviations for each of the positions. As for the initial position the standard deviation is smaller, the model thus successfully accommodates findings for initial position advantage. The spatial coding model (SCM, Davis, 2010) has a separate architectural component that ultimately enhances the weight of the letters in exterior positions.

Another important question related to letter processing in strings is whether repetitions affect the processing of the individual letter units. Models of visual word recognition have dealt with the repetition problem either by including explicit mechanisms (e.g. SCM, Davis, 2010), or generate predictions as a result of their architecture (open bigram model, Grainger & van Heuven, 2003). The orthographic research literature, however, does not provide convincing evidence for repeated letter effects. The results appear to be mixed. There are findings of inhibitory effects, evident in slower response times to targets with repeated nonadjacent letters than targets with no repetition (Schoonbaert & Grainger, 2004). However, evidence for nonadjacent repetition effect was not provided by masked-priming manipulations in some studies (Schoonbaert & Grainger, 2004; Van Assche & Grainger, 2006) and was provided by another study only for cases of adjacent repetition (Norris, Kinoshita, & van Casteren, 2010).

Letter repetitions occur quite often in many languages, especially in words with more than one syllable. Understanding how strings with repetitions are processed is therefore vital for understanding reading. The problem of repeated letter units is related to letter identity and letter position encoding in strings and could be informative for investigating contextual effect in letter processing, i.e. the problem of whether letters are processed in a different manner dependent on the other letters in the string. There is a general debate of whether letter position and identity encoding should be local-context-specific or not. Davis (2010) advocates context independent letter identity encoding and suggests that the same representation units should be involved regardless of the other letters in the string. His spatial coding model has a dedicated mechanism that assures that repeated letters are treated in the same way as two different letters, also suggesting that the same mechanisms are involved in the processing of the letter A in a string in which there is only one occurrence of A and in a string in which there are several. The relative position open bigram model (Grainger, & van Heuven, 2003) has an implemented level of representations whose function is to encode the location of the identified letters relative to each other (to the left or to the right). The example given by Grainger and van Heuven was the word *silence*, which is encoded by representations called open-bigrams. These are the combinations of all the letters (with distance no more than 2 intervening letters) displayed in their correct left-to-right relative order. The bigrams for silence are therefore SI, SL, SE, IL, IE, IN, LE, LN, LC, EN, EC, EE, NC, NE, CE. As noted by Schoonbaert and Grainger (2004), in the cases of words with repeated letters (e.g. balance), fewer unique bigram units will be activated and therefore such words should be more difficult to perceive than words with no repetitions. The lack of evidence for differential priming effects in cases of strings with repeated and nonrepeated letters are therefore considered as problematic for the open-bigram model (Davis, 2010; 2012; Grainger, 2008; Schoonbaert & Grainger, 2004).

Previous tachistoscopic letter identification studies have provided evidence for interference effects in cases of rapid processing of repeated letters. In a study conducted by Bjork and Murray (1977), one of two target letters (B or R) was presented in one of the positions in a 4 x 4 matrix either only surrounded by number signs (#) in all other matrix positions, or by number signs and an additional letter. The additional letter always appeared at a different column in the matrix and was either the same letter (B or R), the alternative target letter (R or B), or a nontarget letter (P or K). The target display duration varied between 25 to 50 ms and was adjusted to the performance rate of the participants. The target presentation was preceded and followed by a 4 x 4 matrix mask of dollar signs ($). The backward mask was accompanied by an arrow which pointed at one of the four columns. The task of the participants was to report which of the two possible target letters appeared at the cued column. The results showed that the accuracy was highest when only one letter was displayed and lowest when a target letter was displayed in two different locations. The repeated letter condition was significantly worse than any of the other conditions. These results were unexpected and were interpreted by Bjork and Murray in terms of interference occurring at a perceptual level and limited capacity of feature detectors.

The findings of Bjork and Murray (1977) were referred to as the *repeated-letter inferiority effect* by Egeth and Santee (1981) who further investigated the same phenomenon. In a paradigm similar to the one previously described, two letters were tachistoscopically presented in the middle two adjacent positions in a 3 x 4 matrix. The conditions included repeated target letters in uppercase (AA or EE), mixed-case (Aa or Ee), target letter with the alternative target in uppercase (e.g. AE), mixed-case (Ae), and target letter with nontarget letter in uppercase (AL). The results replicated the repeated-letter inferiority effect and showed that participants' performance was worst in the repeated letter uppercase condition. Most importantly, the second to worse condition in terms of performance was the mixed-case repeated letter condition, suggesting that the inhibitory effect is not only connected to limitations on a perceptual level but also limitations in processing of abstract letter representations.

It is hardly the case, however, that a second instance of a letter could not in any way be beneficial for recognizing the letter's identity. There are reported cases in the literature demonstrating that the simultaneous presentation of two identical target letters facilitate its recognition. In a go/no-go task, participants were significantly faster to respond to the presence of a target letter when two identical target letters were presented than when only one target letter was presented (Grice & Reed, 1992). The facilitation effect was obtained when the two target letters were presented in the same case (AA) as well as when they were presented in mixed-case with no perceptual similarity (A and a). The results suggested that the recognition of the target identity was performed faster in cases when the target is presented twice. This effect has been referred to as the *redundancy gain effect*.

The findings of the tachistoscopic letter identification studies have not been the focus of much discussion in the recent orthographic processing research literature. Effects such as the repeated-letter inferiority effect suggests that processing of repeated letters might involve different mechanisms than processing of different letters. The inhibitory repeated letter effect has been speculated to be caused by positional uncertainty in initial stages of parallel letter processing (Mozer, 1989). One could expect that such effects might occur in the initial stages of word recognition as well, if letters are indeed processed in parallel. Furthermore, there is ample evidence for positional uncertainty in early stages of word recognition (e.g. Kinoshita & Norris, 2009; Lupker, Perea, & Davis, 2008; Peressotti & Grainger, 1999; Schoonbaert & Grainger, 2004; Van Assche & Grainger, 2006; Welvaert, Farioli, & Grainger, 2008). The important question is, therefore, whether repeated letter effects could arise when letters are embedded in strings. The next two chapters of this thesis will focus on investigating effects of letter repetition in reading. They will present more evidence of how the visual system adapted for "hyper-crowding" (Grainger, & Dufau, 2012) deals with repeated letter identities. The findings are obtained with regression (Chapter 6) and factorial (Chapter 7) approaches.

Chapter 6

A Regression Approach to Repeated Letter Effects

Reading alphabetic languages requires the successful identification of letters and their position within the word. In this way, the perceptual system discriminates between lexical units that bear strong form resemblance. It can determine the difference between two words with the same length but differing by a single letter ("orthographic neighbors", such as *farm– form*; Coltheart, Davelaar, Jonasson, & Besner, 1977), have the same letters but not in the same order (*from-form*), or have different length, but lots of common letters (*though* - *through*). One of the goals of orthographic processing research has been to explain how this discrimination is achieved and how bottom up sublexical processes such as encoding of letter identities and their position mediate recognition of the whole word unit. The empirical results have motivated the development and revision of visual word recognition models in which those initial perceptual stages are implemented in their encoding schemes. These schemes determine the models' predictions regarding the word candidates that are considered and, ultimately, the factors affecting lexical selection.

One of the most influential models in visual word recognition, the Interactive-Activation (IA) model (McClelland & Rumelhart, 1981) explains lexical selection by means of spreading activation in a cascaded and interactive manner between representations located in three levels of a hierarchical structure (feature, letter, word). Word nodes that are consistent with the perceptual input get active, while inconsistent ones get inhibited. Once activated, word candidates suppress each other through lateral inhibitory links and compete until the activity of a single word reaches an activation threshold associated with lexical selection. This model has a slot-based scheme in which every letter is assigned to a specific slot (position, channel) and projects its activity only on this channel. The letter *a* in first position will activate words containing the letter *a* in first position and will inhibit others that start with a different letter. It will not activate words in which *a* is in another position. This model could explain how the reading system could discriminate between words with equal length and different letter identities in some of the positions but is not in accordance with evidence from the masked priming literature suggesting that the perceptual system has a considerable degree of positional tolerance.

Contrary to the prediction of the IA model, primes formed by letter transpositions (anwser-ANSWER) produced as strong priming effects as those identical to the targets (Forster, Davis, Schoknecht, & Carter, 1987). In addition, letter strings formed by transposing letters from a base target word have been demonstrated to be orthographically more similar to the target than strings with replaced letters in the corresponding mismatched positions. This finding has been observed with adjacent transpositions, such as *jugde* from the target *judge*, as opposed to the replaced letter control prime *jupte* (Perea & Lupker, 2003), and has been extended to nonadjacent cases (e.g., caniso–CASINO; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2004).

The slot-based scheme was also falsified by studies demonstrating a priming effect with relative position primes in which the absolute order of the letters was disrupted by either letter deletions (e.g., BLCN-BALCON, Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Peressotti & Grainger, 1999), or insertions in the primes (e.g., juastice–JUSTICE; Van Assche & Grainger, 2006; Welvaert, Farioli, & Grainger, 2008). These results suggest that an absolute position specific encoding in the slot-based scheme is inaccurate and motivated the proposal of alternative letter position and identity encoding mechanisms.

Several models with different encoding schemes were later developed. In this chapter, the focus will be on two of them: The relative position parallel open bigram model (Grainger & van Heuven, 2003) and the Spatial Coding Model (Davis, 2010), which are both based on the interactive- activation architecture but have entirely different schemes with which they account for the transposed letters and relative position priming effects. In the parallel open bigram model, the letter level representations from the IA model are replaced by representations of open bigrams. They are in the relative position map level, at which the letter positions are encoded after letters have been initially identified. The position encoding is achieved through activating bigram units containing information of the position of one letter relative to the others, or more specifically, whether a letter is located to the left or to the right of the other letters in the word (up to two intervening letters). The word SILENCE is therefore represented by the open bigrams SI, SL, SE, IL, IE, IN, LE, LN, LC, EN, EC, EE, NC, NE, CE. In analogy to the letter nodes in the IA model, the open bigram nodes are connected to orthographic word representations with excitatory and inhibitory links. Bigrams consistent with the input get activated and feed forward to the word nodes. Words containing active bigrams receive activation, while those lacking consistent bigrams get inhibited. As in the IA model, lexical competition mechanisms are implemented by inhibitory lateral connections between the nodes at the word level. In this encoding scheme, transposed letter and relative position primes will contain most of the targets' constituent representations in the form of open bigrams. These primes will preactivate targets stronger than corresponding control primes that contain fewer consistent bigram units. In this way, the model could successfully simulate both transposed letter and relative position priming effects.

The Spatial Coding Model, unlike the relative position open bigram model (Grainger & van Heuven, 2003) retains the letter representations in its architecture. Unlike the IA model, however, the letter position and identity encoding scheme is not channel specific. In the Spatial Coding Model, a consistent letter of the input could increase the activity of a word node containing that letter, even if it appears in a different position. An important conceptual difference between the Spatial Coding Model and the other two previously described models is that the same (letter) representations encode letter identities in different positions, and so the set of letter representations of *from* and *form* will be identical, unlike IA's channel specific scheme, in which *r* in position 2 is different from *r* in position 3, or the open bigram model which will encode these words with two nonidentical sets of bigram representations (FR, FO, FM, *RO*, RM, OM and FO, FR, FM, *OR*, OM, RM, respectively). In the Spatial Coding Model, the letter positions in word representations are represented by spatial patterns. To incorporate letter position uncertainty, each letter position code of the input stimulus has the shape of a normal distribution, rather than a single value with its spread representing positional uncertainty. The position code of the letter in the stimulus is assigned dynamically after a rapid left to right serial scan. The model also incorporates identity uncertainty which is represented by the height (amplitude) of the distribution and corresponds to the letter node activity at a certain time. The spatial pattern of the input is compared to the spatial pattern of a stored word representation, a procedure called superposition matching. The matching algorithm includes computing the signal-weight difference functions for each letter of the word representation, sums up all the difference functions and finally divides the obtained peak of the superposition function by the length of the word representation. In the case of an identity prime, a perfect match score of 1 is obtained, as all the difference functions are perfectly aligned with a mean of 0 (and peak value of 1 in the simplified case of no identity uncertainty). In the cases of transposed letter primes, not all the difference functions are perfectly aligned to 0, and so in the cases of the positional mismatches a smaller peak value is added to the superposition function, but the total match score is still high. Relatively high match scores will also be calculated for primes with (few) insertions or deletions. Separate mechanisms in the model's architecture are responsible for the penalization in cases of length mismatch between the word representation and the input, and for inhibition from inconsistent stimulus letters.

Despite the commonality of their competitive network architecture and their shared ability to simulate transposed letters and relative position priming effects, the open bigram model (Grainger, van Heuven, 2003) and the Spatial Coding Model (Davis, 2010) have rather dissimilar letter position and identity encoding mechanisms. This could result in qualitatively different predictions of effects in lexical selection. One example of such a case could be the encoding of repeated letter identities in a string and the effects of repeated letters on word recognition.

Although the manner at which letters can be combined to form words is quite rich, often letters appear more than once within a word. This is particularly true for words with more than one syllable, in which the likelihood of observing a repeated letter identity is higher, especially in the cases of vowels or high frequency consonants. Effects of letter repetitions on word recognition have been investigated with behavioral experimental research that has provided mixed and inconclusive results. Schoonbaert and Grainger (2004) used masked primed lexical decision task and did not find any difference in the effects produced by nonword primes formed by deletion of either repeated or unique letters (*balace* vs *balnce* from the target BALANCE). Nor was a repeated letter effect found in their subsequent experiment, in which participants took the same time to reject these same primes when they served as nonword targets. However, the design of their masked-priming experiment also included a between target manipulation. The authors reported overall effect of target type with both words and nonwords containing letter repetition taking significantly longer time to recognize than items without repeated letters.

In another masked-priming lexical decision study, with prime manipulations including insertions, rather than deletions in primes (Van Assche & Grainger, 2006), a difference was not found between three related prime conditions, some of which containing repeated letters. The related primes produced the same priming effect relative to an unrelated control. They were constructed by doubling a letter in the target (jusstice), inserting a letter already present in the target in another nonadjacent position (justisce), and inserting a different letter in the target (juastice). In sum, the masked-priming lexical decision procedure of these studies did not provide evidence of differential processing of repeated and unique letter identities within words.

Results from two other studies, however, suggest that the presence of letter repetition could affect processing difficulty. Gomez, Ratcliff and Perea (2008) reported results from a two-forced choice perceptual identification experiment in which nonword letter strings were recognized significantly less accurately than strings without repeated letters. The authors interpreted these results as an evidence that repeated letters were more difficult to perceive causing preference towards a foil with no repetition. Norris, Kinoshita and van Casteren (2010) argued that an effect of letter repetition was probably not observed in the Schoonbaert and Grainger (2004) masked-primed lexical decision study due to the lack of sensitivity of the task as well as the stimuli selection (longer words, nonadjacent repetitions). Norris et al. demonstrated stronger priming effect in the cases in which a two-replaced-letter primes were constructed by doubling a letter from the target (uueer-UNDER), than using two different letters (ulger-UNDER), with a masked-priming same-different task but not with lexical decision task. They also showed that deletion of an adjacent repeated letter (anex-ANNEX), has a smaller disruption of the form priming effect than deletion of a unique letter (eupt-ERUPT), suggesting differential cost of deleting a repeated versus deleting a unique letter from the target. The authors interpreted these results as evidence of imprecise position encoding at early stages and "leakage" of letter identities to nearby positions, beneficial in cases of adjacent repetitions.

The results of Norris et al. (2010) could have confirmed some methodological issues in investigating repeated letter effects, such as lack of sensitivity of the masked-primed lexical decision task for researching a phenomenon occurring at early perceptual stages and possibly susceptibility to top-down lexical influences. It is not, however, immediately clear how the mechanism of leakage they propose could explain the results of Gomez et al. (2008) suggesting that repeated letter targets are harder to process as well as the overall target type effect reported by Schoonbaert and Grainger (2004) also hinting at inhibitory, rather than facilitatory effect of letter repetition. It is also not clear how such a leakage mechanism would affect nonadjacent repetitions with longer distances between the repeated identities and whether a repeated letter effect will still be present in longer items, in which it is in fact more common for a repetition to occur.

For decades research of visual word recognition has focused on processing of short monosyllabic words as they are simpler and easier to study. As pointed out by Yap and Balota (2009), this has clearly been a limitation in the field as monosyllabic words represent a small percentage of a language vocabulary and processing short items might not necessarily generalize for longer ones. Recently, this limitation has been addressed by constructing large databases (megastudies) providing reaction times of visual word recognition tasks of words with more than one syllable (e.g., Balota et al., 2007; Brysbaert, Stevens, Mandera, & Keuleers, 2016; Ferrand et al., 2010; Keuleers, Lacey, Rastle, & Brysbaert, 2011). The availability of such databases has allowed for the exploration of factors better or only observed with longer words, such as print-to-sound consistency effects in multisyllabic words (Yap & Balota, 2009), improved measures of orthographic similarity (Yarkoni, Balota, & Yap, 2008), the shape of the length effect (New, 2006), effects of the orthographic word structure (Chetail, Balota, Treiman, & Content, 2015).

Also for reasons of simplification, the stimuli in orthographic research experiments were often selected so that they contain no letter repetition, even though, as already discussed, an effect of repeated letters, especially with nonadjacent repetitions, has not been clearly demonstrated. Exploring letter repetition effects is important for the understanding of how the visual system processes identical elements, at a perceptual and abstract level. It is necessary for a more complete understanding of how letter position and letter identity are encoded. As only one of these two dimensions (position and identity) could occur more than once (position cannot be repeated), repeated letters could help disentangling the encoding of these two dimensions, with any differences occurring due to the repetition serving as a marker of processes involved in identity encoding. It could also give more evidence of the relative sublexical contribution of a repeated or unique letter unit to the complex mechanism of lexical access. As words containing repetitions comprise of a great part of a vocabulary, investigating repeated letter effects is also important for the understanding of how these items are processed.

A methodology that could be effective for the investigation of repeated letter effects for a number of reasons is applying a regression approach on megastudies data containing reaction times of visual word recognition tasks in several languages - English, Dutch, and French (Balota et al., 2007; Brysbaert et al., 2016; Ferrand et al., 2010; Keuleers et al., 2011). The English, British, Dutch 2 and French Lexicon projects (ELP, BLP, DLP2, and FLP) contain disyllabic and multisyllabic words in which letter repetitions occur often. The number of repeated letter observations could provide greater power for observing a possible effect than that in previous studies exploring repeated letters using factorial designs. The regression approach could also overcome other behavioural experimentation methodology limitations such as correlation problems (as factors could be covaried out), particularly problematic in visual word recognition, experimental biases in the stimuli selection, list effects, dichotomization of continuous variables (see Balota, Yap, Hutchison, & Cortese, 2012 for a detailed discussion of the advantages of this methodology over factorial designs). It will also allow for a direct cross linguistic comparison of the effect and exploring whether it could be generalized for the processing of different languages or is linked to the idiosyncrasies of some of the languages under consideration.

Added to that, due to the large number of items, with the regression approach the effect could be investigated in more depth. This could be achieved, for example, by exploring repetitions effects within different distances (e.g. adjacent repetitions, nonadjacent repetitions with various number of intervening letters) by adding separate predictors encoding the presence or absence of a repetition within each distance. Additional evidence in this direction could help reconcile inconsistencies in the literature, such as differential effects observed with primes with deleted repeat vs unique letters in adjacent repetitions (Norris et al., 2010), and the absence of that effect in the case of nonadjacent repetitions (Schoonbaert & Grainger, 2004).

Another theoretically motivated question relates to possible dependence of the repetition effect on the consonant-vowel status of the repeated letters. Previous research has provided evidence, suggesting differential role of consonants and vowels in word processing and the importance of the word CV structure at initial stages of lexical access (e.g. Acha & Perea, 2010; Chetail, Balota, Treiman, & Content, 2015; Chetail, Drabs, & Content, 2014; Chetail, Treiman, & Content, 2016; Lupker et al., 2008). Another rationale for investigating the repeated letter effects separately for consonants and vowels is the difference in letter type frequencies. Vowel letters and vowel repetitions are more common (see Table 6.1) and their higher frequency could modulate any letter repetition effect. To investigate possible differences in the processing of repeated consonants and vowels, separate variables could be constructed for each letter type.

Another advantage of using a regression approach on megastudy data for the investigating of repeated letters effects is that the obtained results on the behavioral data, the effects and the unique predictive power of the repeated letter factors, could be compared to precise predictions of computational models regarding this effect. This could be achieved by using the same factors as the ones in the behavioural regression models on dependent variables, such as simulated reaction times of lexical decision task. Evaluating the models' predictions of repeated letter effects could be informative for the understanding of the processes involved in letter position and identity encoding and the selection of the more accurate encoding scheme.

As, already discussed, encoding letter position and identity have been implemented through different encoding schemes in extant models of word recognition, which could lead to different predictions in the cases of repeated letters. The influential IA Model (McClelland & Rumelhart, 1981) could not predict any effect of letter repetition since its slot-based encoding scheme treats two identical letters in different positions as two different letters. Since this scheme has been falsified by evidence in the literature demonstrating effects of transposed letters, superset and subset (types of relative position) primes, the more complicated open-bigram (Grainger, van Heuven, 2003) and spatial coding (Davis, 2010) schemes were later developed. Apart from the apparent differences in their components, these two models also differ in the conception of whether encoding letter position and identity should be local-context dependent or not. The local-context dependent open bigram model will use different set of representations to encode words containing the same letters, but in different positions (such as anagrams). In the cases of letter repetitions, less number of bigrams will be activated and therefore the expectation is that the open bigram model would be likely to predict inhibitory effects of repeated letters (as noted by Schoonbaert & Grainger, 2004).

The Spatial Coding Model (Davis, 2010), on the other hand, has a local-context independent encoding scheme, in which the same letter representations will be activated in cases of anagrams. The Spatial Coding Model has an explicit mechanism that deals with repeated letter cases. It uses bins of clones of letter receptors that interact and cooperate with the final goal of achieving maximum match score between the input and a word representation and not allowing for the same letter unit (repeated or not) to contribute more than once for this calculation. With this mechanism, the Spatial Coding Model effectively treats repeated letters as different ones and is unlikely to predict any effect of letter repetition, unless the effect occurs due to other uncontrolled lexical or sublexical factors. Investigating repeated letter effects and comparing them to the predictions of these models could provide some information of the nature of the effects. The results could also provide answers to the conceptual debate of whether the encoding of letter position and identity should have at least an element of local-context dependency or not. Should the encoding of additional letter *a* depend on whether *a* is already present in the string or not?

The present study explored whether the presence of letter repetitions affect visual word processing difficulty. It aimed to provide more evidence of whether repetition distance and consonant vowel status moderate this effect. The investigation was conducted with the regression approach on visual word recognition tasks data in English, Dutch and French. Simulations of the open bigram model (Grainger & van Heuven, 2003) and the Spatial Coding Model (Davis, 2010) were also included with the purpose of evaluating the models' predictions for the effect and the plausibility of their letter position and identity encoding schemes.

Method

Dependent Variables

The mean correct item latencies across participants of lexical decision task were obtained from the English Lexicon Project (Balota et al., 2007), the British Lexicon Project (Keuleers et al., 2011), the Dutch Lexicon Project 2 (Brysbaert et al., 2016), and the French Lexicon Project (Ferrand et al., 2010). Word naming latencies were acquired from the English Lexicon Project.

Table 6. 1 *Proportions of items containing any letter repetition (at least one repeated letter) and at least one of each of the repetition types in the English Lexicon Project (ELP), British Lexicon Project (BLP), Dutch Lexicon Project 2 (DLP2) and French Lexicon Project (FLP) datasets. The repetition types are presented in terms of the repetition distance (number of intervening letters between the repeated) and consonant-vowel (CV) class of the repeated letter. Words in which the same letter appears more than twice are excluded.*

		Lexicon Project			
Distance	CV	ELP	BLP	DLP2	FLP
0	C	14.5	14.6	12.3	18.9
0	V	3.7	5.1	17.9	0.1
1	C	5.4	3.9	4.4	5.4
1	V	10.2	5.0	14.0	11.3
2	C	8.5	6.9	9.3	8.4
2	V	10.6	8.0	12.3	15.2
3	C	8.0	6.4	6.9	6.6
3	V	7.5	4.8	7.0	8.9
4	C	6.7	5.3	6.9	6.3
4	V	6.6	2.4	6.2	7.1
5	C	4.8	2.9	5.1	4.5
5	V	4.0	0.8	4.5	5.0
6	C	3.0	1.7	3.4	3.1
6	V	2.5	0.2	2.4	2.8
7	C	1.6	0.7	2.2	1.9
7	V	1.3	0.0	1.3	1.4
8	C	0.9	0.3	1.2	1.1
8	V	0.7	0.0	0.5	0.7
9	C	0.5	0.1	0.4	0.5
9	V	0.4	NA	0.1	0.3
10	C	0.2	0.0	0.2	0.2
10	V	0.1	NA	0.1	0.1
11	C	0.1	NA	0.1	0.1
11	V	0	NA	0	0
Any	Any	65.7	54.2	74.1	68.4

Independent Variables

Variables of Interest (Repeated Letters)

The variables of interest were constructed with the purpose of observing the effect of repetition of letter identity on visual word recognition. Two factors were considered while calculating the variables. These were the consonant-vowel status of the repeated letter and the distance between the letter repetition, or how far from each other the two letters with the same identity were. The repetition distance was measured by the number of intervening letters between the repeated ones. There were separate variables for each possible repetition distance. Such division allowed for exploring whether the letter repetition effect was dependent on the distance between letters with same identities. The variables of interest therefore encoded all the possible instances in which a consonant or a vowel letter could be repeated within a certain distance. Each repeated letter variable represented the number of times a consonant or vowel repetition within a specific distance occurs in a word. Here are several examples with English words and their corresponding repeated letters values. The variable *repetition of consonants with distance 0*, summed the number of repeated consonant letters with no intervenor (adjacent repetition), such as *c* in the word *accept* (aCCept) and *d* and *s* in *address* (aDDreSS). For these words the variable had the values 1 and 2, respectively. The variable *consonant repetitions with distance 1* (one intervening letter between the repeated ones) had a value 1 for the word *coconut* (CoConut), as one letter, *c*, is repeated within that distance, and 2 for the word *suspended (*SuSpenDeD), in which both *s* and *d* appear twice. The variable with a *consonant repetition with distance 2* had the values 1 for *hundred* (hunDreD) and 2 for *accountant* (accouNTaNT) and so on. The vowel repetition variables were constructed in the same way. If no repetition was present for a certain condition, the corresponding variable had a value of 0. Words in which one letter appeared more than twice and therefore had two or more possible distances between repetitions of the same letter were discarded from the analyses to avoid additional complexity.

The repeated letter variables were constructed in an identical way for all languages under investigation. A slight exception was French, for which the repeated letter variables were calculated twice with two different algorithms. The diacritic-sensitive took into account diacritic marks and treated letters with and without diacritics as different. With this algorithm, there was no letter repetition in *zèbre*. The diacritic-insensitive algorithm counted letter repetitions only after all diacritic marks were removed from the items. This calculation encoded a repetition of *e* in *zebre* as it was not sensitive to the presence of the diacritic mark. The two separate calculations were performed for two reasons.

First, constructing two separate measures, sensitive and insensitive to the presence of diacritics, could give an opportunity to explore whether diacritics affect the letter and word processing in the cases of repeated letter identities. On one hand, possible influence could be due to the diacritic as an additional visual information that could help discrimination between two otherwise identical visual objects. On the other hand, letters with diacritic marks usually map into different phonemes than the same letters without diacritic marks. Therefore, possible phonological contribution of a letter repetition effect due to phoneme duplication could be attenuated in the cases in which one of the letters is diacritically marked and is pronounced in a different manner.

The second reason was to provide an appropriate baseline for the evaluation of visual word recognition models with no implementation of diacritic marks in their encoding schemes. Comparing the effect of letter repetition in behavioral data and in models' simulations therefore required diacritic insensitive repeated letter measures. Apart from employing two separate algorithms that treated diacritics differently, the repeated letters variables were constructed in the same way as for the analyses of the other lexicon projects.

Control variables

Due to the fact that the investigation was crosslinguistic and the three languages (English, Dutch, French) had their own idiosyncrasies, the list of covariates was not identical across the different lexicons. However, care was taken so that important control factors were included in the regression models of each of the languages.

English Lexicon Project. The control variables obtained from the English Lexicon Project (Balota et al., 2007) were: logarithmically transformed subtitle contextual diversity and word frequency measures; word length (number of letters); orthographic neighborhood size (number of orthographic neighbors, Coltheart N; Coltheart et al., 1977); phonological neighborhood size (the number of words differing by a single phoneme); Levenshtein orthographic distance (OLD20, the average orthographic Levenshtein distance of the 20 nearest neighbors, Yarkoni et al., 2008); Levenshtein phonological distance (PLD20); number of morphemes; as well as two different measures of bigram frequency: mean bigram frequency and bigram frequency by position. Apart from avoiding confounds in the behavioral regression results, bigram frequencies were important controls as the predictions of one of the word recognition model under evaluation could be sensitive to these measures (the relative position open bigram model; Grainger, & van Heuven, 2003). The quadratic term of word length was also included as a predictor (New, 2006; Yap & Balota, 2009).

In addition to the control factors provided in the English Lexicon Project (Balota et al., 2007), several additional phonological variables were constructed and added to the regression models. They were added to ensure better control over phonological factors in word identification. For that purpose, word pronunciations were acquired from CELEX (Baayen, Piepenbrock, & van Rijn, 1993). Words that were not found in the CELEX database were excluded from the analysis. The additional variables were: first phoneme, primary lexical stress, number of phonemes, number of syllables, and several phonological consistency measures. The first phoneme variable was entered as a categorical variable whose levels were each of the possible phonemes that could appear as an initial sound in English. The primary lexical stress position variable was dummy coded and reflected the stressed syllable in a word, the first stressed syllable serving as a baseline. The consistency measures reflected the consistency of mapping of print to sound and included feedforward onset, feedforward rime, feedback onset and feedback rime consistency of the first syllable as well as four composite measures of the same type which represented the mean consistency across all the syllables in a word (see Yap & Balota, 2009, for a detailed discussion of consistency measures). As the construction of the consistency measurements depended on the syllabification of the words, special care was taken so that orthographic and phonological syllabifications matched before performing the calculations. In the cases of inconsistent syllabification between the phonological and orthographic forms, the orthographic syllable was adjusted to the phonological one. The ratio between the orthographic Levenstein distance (OLD20) and the phonological Levenshtein distance (PLD20) was also included as a separate measure of phonological consistency (Yap & Balota, 2009). Heterophonic homograph entries such as *bow* that had multiple pronunciations for the same orthographic form and therefore multiple values of the phonological variables (phonological consistencies, phonological neighborhood, stress pattern) were not included in the analyses (N = 370).

British Lexicon Project. The control variables obtained from the British Lexicon Project were: two different measures for orthographic neighborhood size (Coltheart N and OLD20), number of letters (word length), as well as the number of syllables in a word. The quadratic term of word length was also included as a predictor (New, 2006; Yap & Balota, 2009). The logarithmically transformed word frequency measures in Zipf scale and the contextual diversity measures were obtained from SUBTLEX-UK and were also added as control variables in the regression analyses (van Heuven, Mandera, Keuleers, & Brysbaert, 2014).

As in the English Lexicon Project (Balota et al., 2007) analyses, the additional phonological variables, calculated based on the word pronunciation in CELEX (Baayen et al., 1993) were also included as control predictors. These were first phoneme, primary lexical stress, number of phonemes, all first syllable and composite phonological consistency measures. In addition, the phonological neighborhood size and the average phonological Levenshtein distance of the 20 nearest neighbors (PLD20) were calculated using the *vwr* package (Keuleers, 2015) as implemented in R version 3.4.1 (R Core Team, 2017). The ratio between OLD20 and PLD20 was included as an additional phonological consistency measure (Yap & Balota, 2009). Heterophonic homographs were not included in the analyses (N = 298).

In addition, mean type-based bigram frequency was calculated by counting the number of times a bigram appears in all English words from the CELEX database (Baayen et al., 1993), regardless of bigram position and word length (see Westbury & Buchanan, 2002 for the description of a similar measure). For example, the bigram frequency of ac was increased after encountering both *back* and *act*. The frequencies of all bigrams in a word were then summed and divided by the number of word letters minus one. The *vwr* package in R (Keuleers, 2015) was used for acquiring the list of words. The mean positional bigram frequency was calculated in a similar way, the only difference being that the bigram counts were performed for the specific bigram position, rather than for all positions. This measure was bigram position, but not word length specific, i.e. all words that contained the bigram in the specific position contributed to its count. The bigram *ac* in position 1 was counted in both *act* and *action*, but not in *back*, where *ac* in position 2 was counted instead.

To control for possible morphological effects, two morphological variables were included in the analyses. The first variable was constructed by counting the number of morphemes after immediate segmentation of the lemma. The second variable represented the number of elements after the inflectional transformation of the wordform. The morphological database from CELEX (Baayen et al., 1993) was used for the construction of these variables.

Dutch Lexicon Project 2. The control variables obtained from the Dutch Lexicon Project 2 were word length, number of syllables, SUBTLEX2 word frequency (added as a control after a logarithmic transformation), number of phonemes, orthographic Levenstein distance (OLD20), the phonological Levenshtein distance provided in the lexicon (PLD30)[8], Coltheart N. As this lexicon also provided ratings of concreteness and age of acquisition, these were also added as control factors.

In addition, bigram frequency measures were calculated in an identical way as for the analyses of the British Lexicon Project. Mean bigram frequency and positional bigram frequency were therefore included in the model. The number of elements after immediate segmentation of the lemma was added as a morphological factor. This calculation was performed on the morphological analyses provided by CELEX (Baayen et al., 1993).

French Lexicon Project. The control variables provided in the French Lexicon Project (Ferrand et al., 2010) and included in the regression model were two measures of word frequency (cfreqmovies and cfreqbooks). The logarithmically transformed sum of both frequencies and their quadratic term were added as suggested by Ferrand et al. (2010) as a frequency measure accounting for largest amount of variance. Other important controls provided by the lexicon and included in the model were number of letters (word length) and number of syllables. In addition to these variables, several other important lexical characteristics were obtained from the *Lexique 3* database (www.lexique.org; New, Brysbaert, Veronis, & Pallier, 2007; New, Pallier, Brysbaert, & Ferrand, 2004). The pronunciation of the words was used to extract the information of the first phoneme, which was entered as a categorical variable. The orthographical Levenstein distance (OLD20) and the phonological Levenstein distance (PLD20) were entered as measures of neighborhood densities. The number of morphemes of the word item was also added as a predictor. In the cases in which several possible values were matched to the same orthographic form, a preference was given to the biggest value (larger number of morphemes). In addition, nonpositional and positional mean type bigram frequencies were calculated for each of the items. The calculations were based on the *Lexique 3* word list with items without spaces and dashes. The list was generated from the *vwr* package in R (Keuleers, 2015).

Results

[8] The Dutch Lexicon 2 project provided phonological neighborhood distance measure that was equal to the average phonological Levenshtein distance of the 30 nearest neighbors, unlike the measure in the English Lexicon project, in which the number of neighbors was 20.

Lexical Decision Task

A hierarchical regression analyses was performed on the lexical decision latencies of the selected items from each of the lexicons. The first step included all described control variables. The total amount of variance explained in each of the regression models was $R^2 = 54.45\%$ for the English Lexicon Project (ELP), $R^2 = 43.97\%$ for the British Lexicon Project (BLP), $R^2 = 43.34\%$ for the Dutch Lexicon Project 2 (DLP2), and $R^2 = 42.31\%$ for the French Lexicon Project (FLP). In the next step, the repeated letter variables were added to the models. Their inclusion significantly improved all models: English, $F(26, 28920) = 10.35$, $p < .001$; British, $F(20, 24874) = 7.101$, $p < .001$; Dutch, $F(28, 18023) = 12.21$, $p < .001$, and French, $F(28, 31534) = 12.47$, $p < .001$. These variables accounted respectively for an additional $\Delta R^2 = 0.42\%$, $\Delta R^2 = 0.32\%$, $\Delta R^2 = 1.06\%$, and $\Delta R^2 = 0.63\%$ unique variance.

Adjacent repetitions

The coefficients of the repeated letter variables can be seen in Figure 6.1. When the repeated letters were adjacent, there was a 6 ms significant facilitation effect for vowel repetitions and a small (3 ms) nonsignificant facilitation effect for consonant repetitions in the ELP regression. In the BLP regressions, the 4 ms inhibitory effect was significant for consonants, while the 3 ms effect was nonsignificant ($p = .142$) and in the opposite direction for adjacent vowel repetitions. In the DLP 2 regression model, the results for the adjacent repetitions showed dissociation between consonants and vowels, with consonants having a significant 5 ms inhibitory effect, while vowels produced significant 7 ms facilitation effect. In the FLP regressions, the 11 ms effect of adjacent consonant repetitions was inhibitory and significant. The effect of adjacent vowels was different, depending on whether diacritic marks were disregarded or not, with the variables, constructed with the diacritics sensitive algorithm having an inhibitory nonsignificant 9 ms effect, while the same variable produced significant 26 ms facilitation when diacritics were not taken into account. Overall, the results suggested a small facilitation effect of vowel repetitions, except for the diacritics-sensitive vowel variable in the French Lexicon project, while the effect of the adjacent consonants trended towards small inhibition, except for in the ELP model, in which it was not significant.

Nonadjacent repetitions (1-3 intervening letters)

When the repetitions were within a 1-to-3-intervening-letters distance, all consonants and vowels variables in all lexicons indicated a significant inhibitory effect. In ELP this effect was in the range 11 ms to 13 ms when the distance was within 2 intervening letters and dropped to 4 ms and 8 ms for the 3 intervening letters variables, vowel and consonant repetitions, respectively. In BLP, the effect size was 6 ms, 9 ms, and 7 ms for the vowel repetitions and 11 ms, 10 ms and 3 ms for consonant repetitions. The effect was slightly smaller in size, but quite consistent in DLP2. It ranged between 3 ms and 9 ms with a similar pattern for vowels and consonants. In FLP, the effect of repeated letters within the 1 to 3 letters distance was in the range from 10 ms to 14 ms for vowels and 8 ms to 10 ms for consonants.

Nonadjacent repetitions (more than 3 intervening letters)

When the repetitions were within a longer than 3 intervening letters distance, the pattern of results was not as consistent and clear as the one in the previous distance interval. However, as in the previous distance interval, the pattern was inhibitory. There were some differences within the lexicons as well as between the consonants and vowel repetitions. In ELP, 7 of the repeated letter variables within that distance indicated significant inhibitory effect. In this lexicon the vowel repetitions within 9 and 10 letters distance peaked and indicated big effects with sizes 30 ms and 68 ms, respectively. A similar peak was also observed in the BLP results, in which the repeated letters vowel variable with distance 6 had a 5 ms effect size. In this database, none of the consonant variables within that distance interval showed a significant effect. In DLP2, there were significant inhibitory effects of the 4 letters distance for both letter types, as well as for the 5 and 7 letters distance vowels repetition. However, the effect shifted its direction and was significant for vowel repetition within a 9-letters distance. In FLP, the only significant variables that encoded repetition within that distance interval were the consonant repetition variables with 5 and 6 intervening letters between the repetitions.

Lexical Decision (up to ten-letters-long words)

Regression models were also fitted on subsets of the words from all lexicons, that were up to ten letters long. This was done with the purpose of providing a comparison between the behavioral data on these subsets and simulation results of computational models that fit processing of shorter words better. The simulations were not performed on longer words to avoid these implementational limitations. The diacritics-insensitive variables were used for the French Lexicon Project analyses, as diacritic marks were not implemented in the models under examination. The coefficients of the repeated letter variables on these subsets can be seen in Figure 6.2. Overall, the patterns did not deviate from those observed with the slightly bigger datasets. The adjacent vowel repetitions trended towards small facilitation, while the adjacent consonant repetitions had either null or small inhibitory effect. The results at the 1-3 intervening letters distance were consistently significant and inhibitory. The pattern at longer distances was broadly inhibitory, but not all variables were significant. Some noticeable differences between the results of the smaller and larger datasets, however, were the lack of a significant inconsistent facilitation effect of a vowel repetition at the longer repetition distances in DLP2, as well as the larger number of observed significant inhibitory effects for vowels in FLP in longer distances (5, 6, and 7 intervening letters).

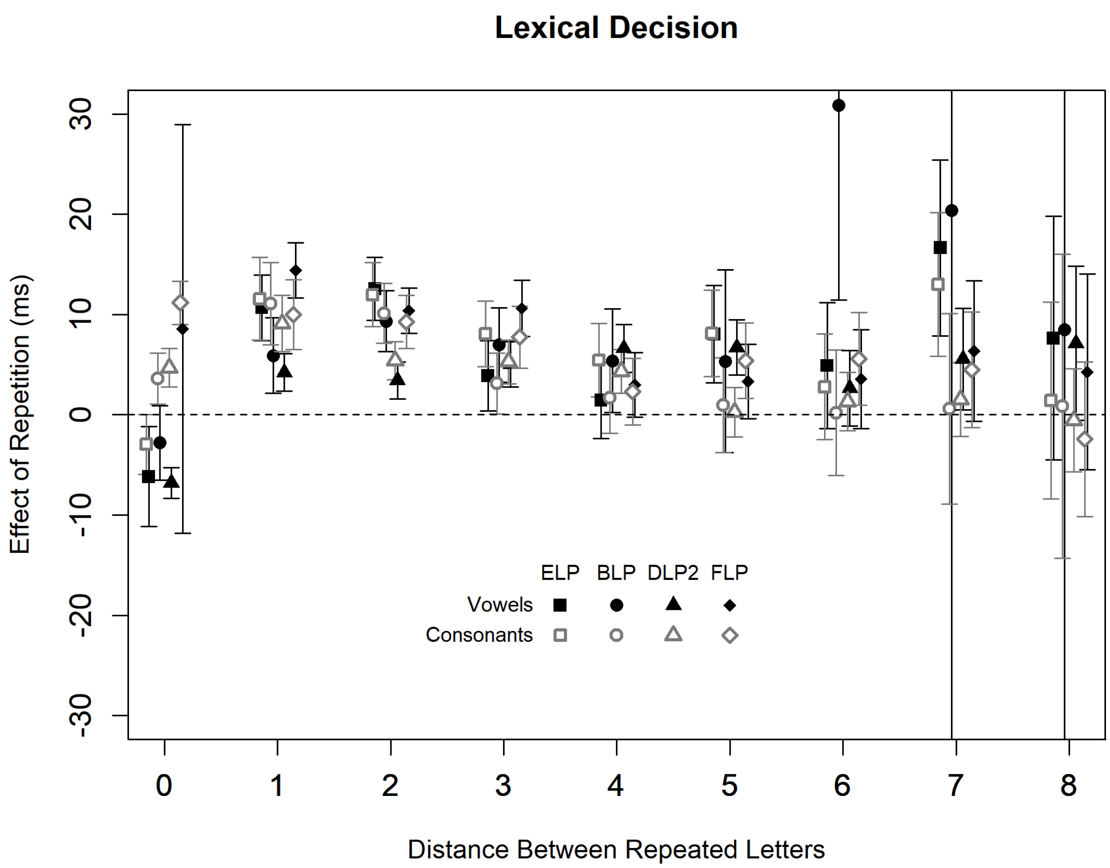

Figure 6. 1 Repeated letter effects in English Lexicon Project (ELP), British Lexicon Project (BLP), Dutch Lexicon Project 2 (DLP2) and French Lexicon Project (FLP; with diacritics). Positive values indicate inhibition, negative values indicate facilitation. The distance is measured with the number of intervening letters between the repeated ones. Error bars represent 95% confidence intervals.

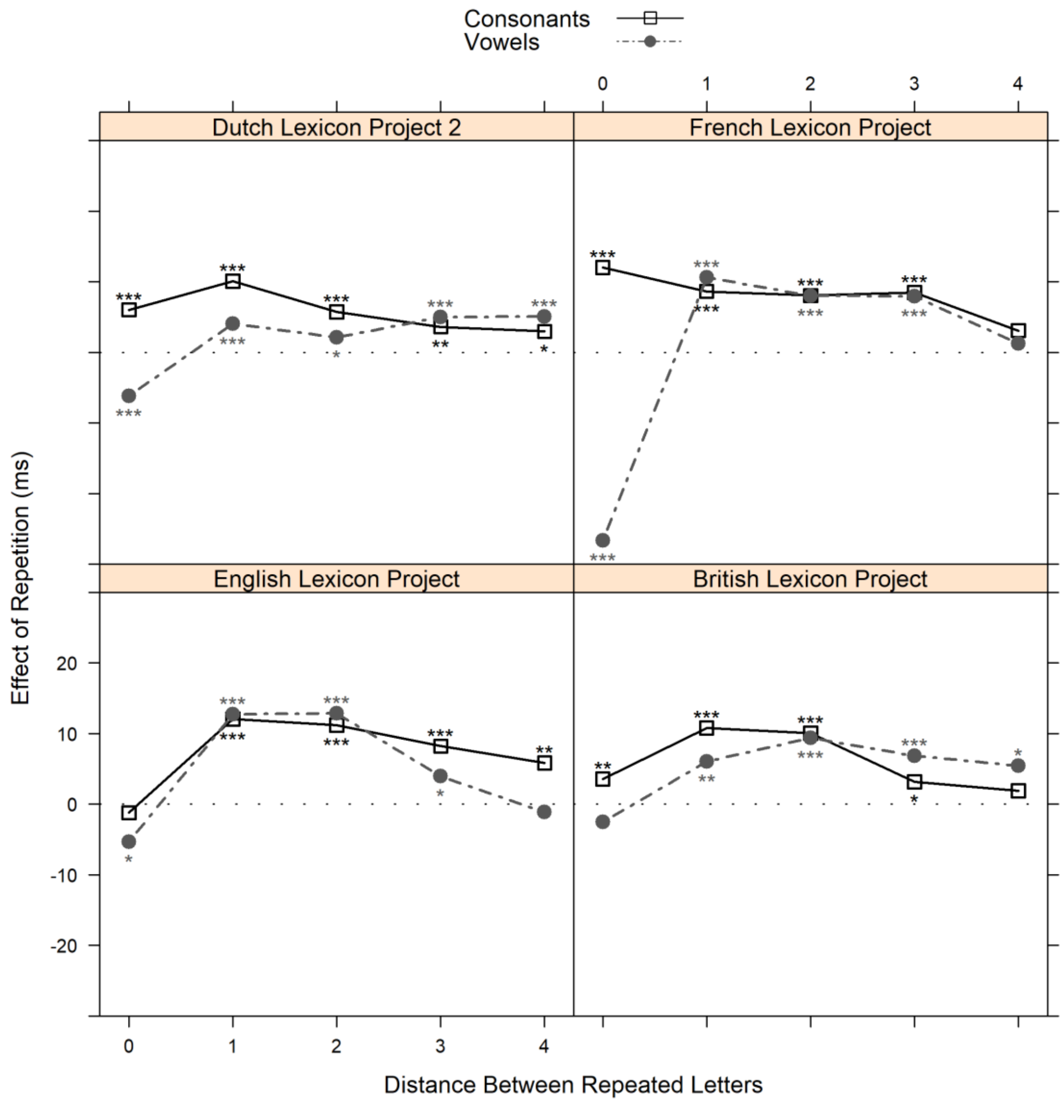

Figure 6. 2 Repeated letter effects in subsets of the lexicon projects with words no longer than ten letters. Positive values indicate inhibition, negative values indicate facilitation. *** $p < .001$; ** $p < .01$; * $p < .05$

Lexical Decision Task Simulations

Spatial Coding Model

Lexical decision task simulations were run with the Spatial Coding Model (SCM; Davis, 2010) on the data sets of words up to ten letters long from ELP, BLP, DLP2 and FLP using the SCM simulator[9]. Prior to each simulation, the model's vocabulary was set to the word list of the corresponding lexicon. The produced lexical decision reaction times of the correctly recognized words were then entered in regression models as the dependent variable. The control predictor variables were identical to the ones in the corresponding behavioral data regression models and were held constant across models' simulations. These variables explained R^2 = 36.21%, R^2 = 75.68%, R^2 = 66.76%, R^2 = 53.83% of the variance in the model's reaction times for ELP, BLP, DLP2 and FLP, respectively. In the next step, the repeated letter variables were added to the models. All models were significantly improved: English, $F(18, 25982) = 1.633$, $p = .044$; British, $F(18, 24839) = 8.602$, $p < .001$; Dutch 2, $F(18, 18389) = 9.684$, $p < .001$, and French, $F(18, 26781) = 37.88$, $p < .001$. These variables accounted respectively for an additional ΔR^2 = 0.07%, ΔR^2 = 0.15%, ΔR^2 = 0.31%, and ΔR^2 = 1.15% unique variance.

The effects of the repeated letter variables predicted by SCM for the four datasets could be seen in *Figures 6.3*. The model's predictions did not agree with the patterns observed in the empirical data. The consistent inhibitory pattern in the distance of 1-to-3 intervening letters was not present in the SCM simulation results. The model predicted very small significant facilitation effects of less than a cycle[10] in ELP for the adjacent consonant repetition, the consonant and vowel repetitions with distance 3 and the consonant repetition with distance 4. In BLP, the model again predicted lots of small facilitation effects for the repeated letter variables, but there were two larger inhibitory effects of the consonant and vowel variables in distance 8 (2 and 10 cycles respectively). In DLP2, the consistent inhibitory pattern evident in the corresponding regression was not observed in the SCM predictions. However, there were significant inhibitory effects in three of the vowel variables with the large distances between the repetition, 5 (1 cycle), 6 (2 cycles), and 7 (1 cycle). In FLP, SCM predicted strongest inhibitory effect for adjacent vowel repetitions (3 cycles), and an inhibitory effect for consonant repetitions with distance 8 (1 cycle) and small facilitation effects for the adjacent consonant repetition and most of the vowel repetitions, therefore also not matching the behavioral pattern of results.

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[9] Downloaded from http://www.pc.rhul.ac.uk/staff/c.davis/SpatialCodingModel/

[10] Coefficients of SCM RT in simple linear regression models with behavioral lexical decision task RTs for ELP, BLP, DLP2, and FLP as dependent variables: 2.75, 4.207, 2.823, 4.039.

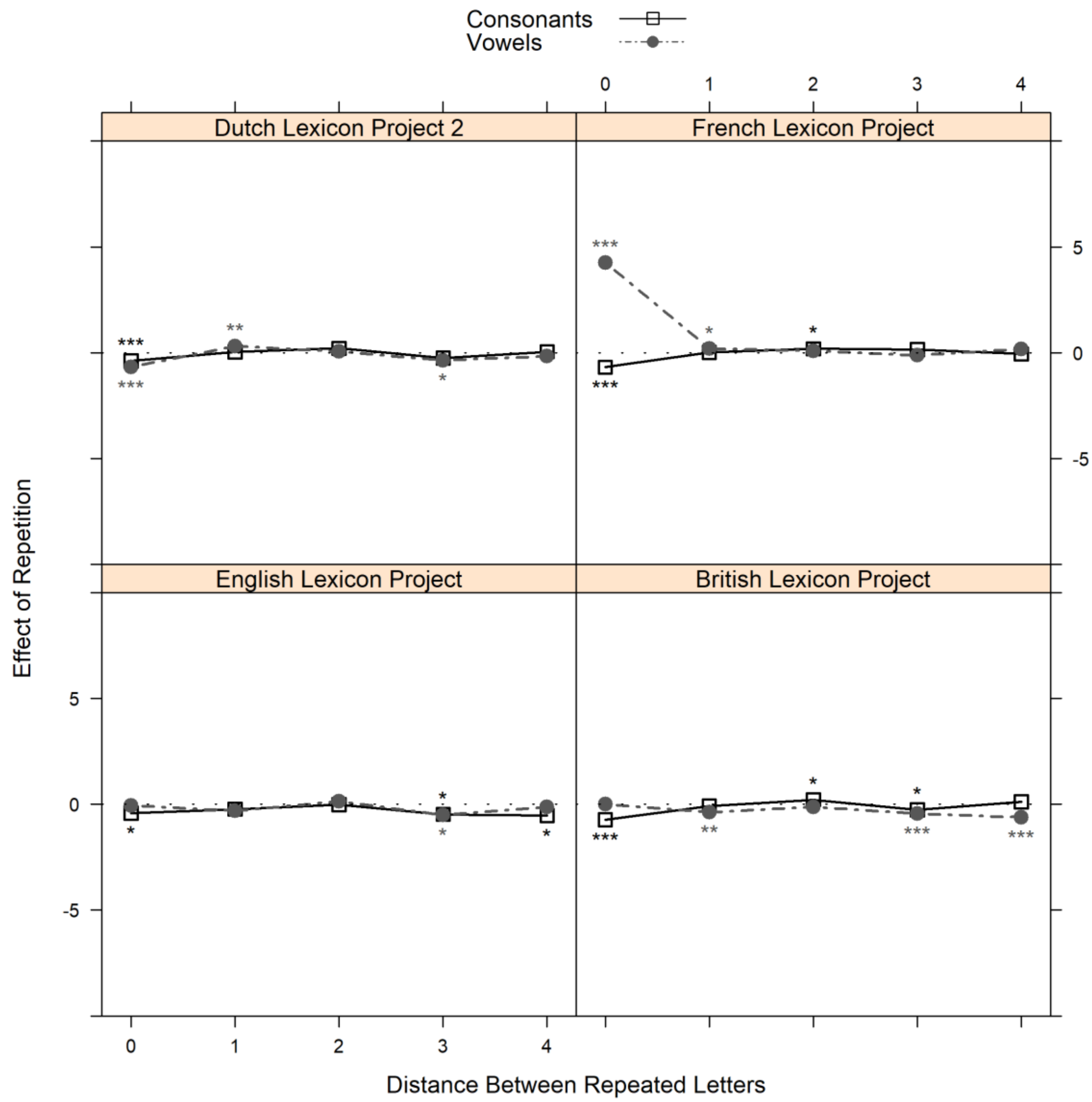

Figure 6. 3 Spatial Coding Model's predictions of repeated letter effects. Positive values indicate inhibition, negative values indicate facilitation. *** $p < .001$; ** $p < .01$; * $p < .05$

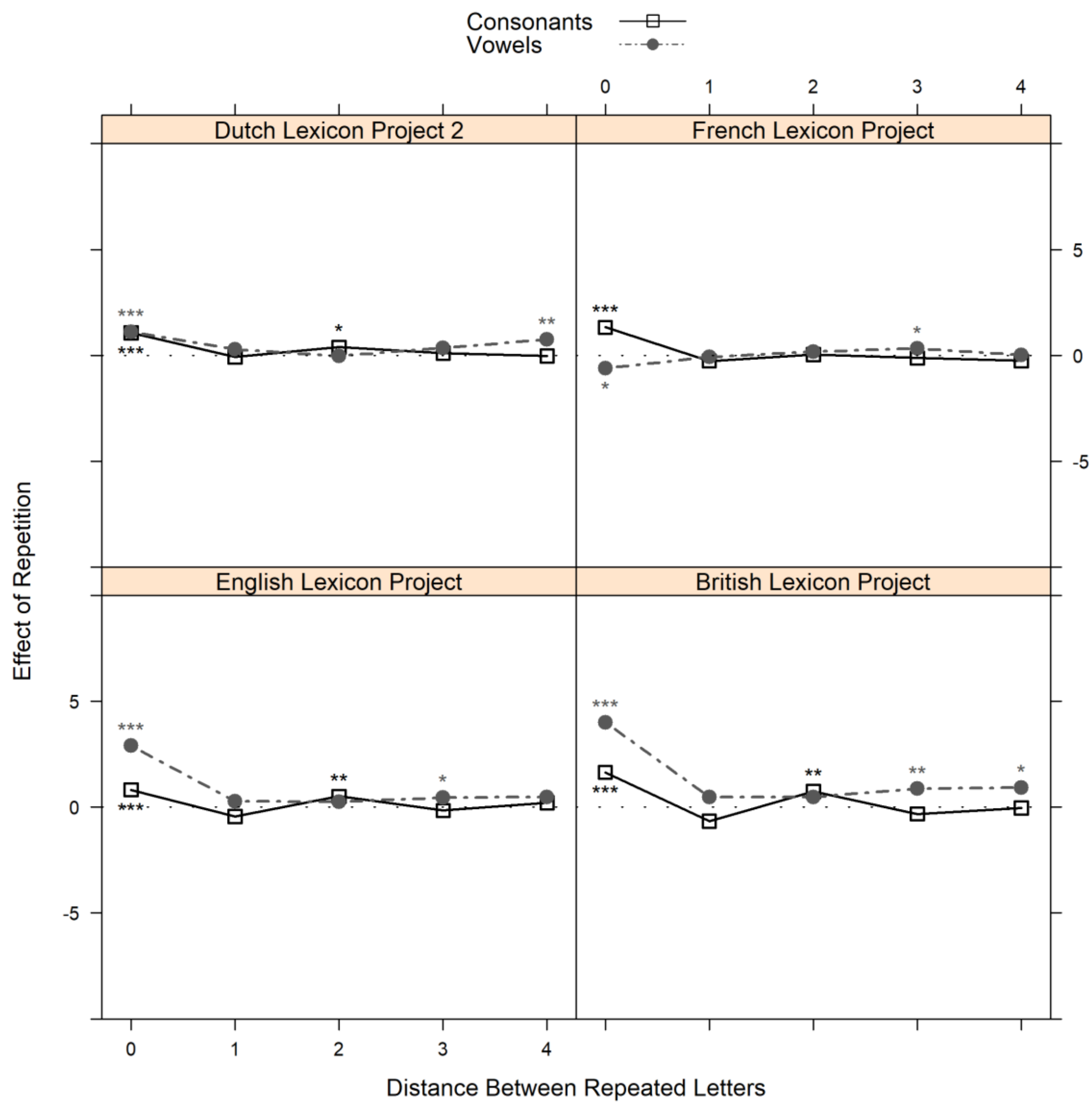

Figure 6. 4 Relative Position Open Bigram Model's predictions of repeated letter effects. Positive values indicate inhibition, negative values indicate facilitation. *** $p < .001$; ** $p < .01$; * $p < .05$

Relative Position Open Bigram Model

Lexical decision task simulations were also run with the Relative Position open bigram Model (RPM; Grainger, & van Heuven, 2003) on the same reference data sets as the ones used for the SCM simulations. The RPM simulations were run with the *EasyNet* software (http://adelmanlab.org/easyNet/). The model's vocabulary was set to the corresponding lexicon word list prior to each simulation. Only the correctly recognized words were included in the analyses (see *Figures 6.4.1.-6.4.4.* for number of observations in each dataset and patterns of repeated letter effects). The control predictors explained R^2 = 21.46%, R^2 = 23.33%, R^2 = 22.15%, R^2 = 15.19% of the variance of the model's reaction times for ELP, BLP, DLP2 and FLP, respectively. Adding the repeated letter predictors improved all four models: English, $F(18, 23020) = 7.309$, $p < .001$; British, $F(17, 21804) = 13.94$, $p < .001$; Dutch 2, $F(18, 17437) = 5.169$, $p < .001$, and French, $F(18, 21268) = 11.63$, $p < .001$. These variables accounted respectively for an additional ΔR^2 = 0.45%, ΔR^2 = 0.82%, ΔR^2 = 0.41%, and ΔR^2 = 0.83% unique variance.

As could be seen in Figure 6.4., RPM tended to predict inhibitory, rather than facilitatory effects of repeated letters. However, in most of the datasets, the effects were larger[11] for the adjacent repetitions and were not consistent in the 1-3-letters distance interval, therefore also failing to capture the empirical data pattern.

Word Naming Task

A linear regression model was also fitted with the latencies from the word naming task, obtained from the English Lexicon Project. The same control variables were entered in the model as the ones in the lexical decision model. These variables explained R^2 = 54.14% of the variance. The model was significantly improved after adding the repeated letters predictors, $F(26, 28924) = 12.68$, $p < .001$. They explained additional ΔR^2 = 0.5167% unique variance. The effects of repeated letters could be seen in Figure 6.5. Overall, the pattern was the same as the one in the lexical decision data. In the word naming results, however, both adjacent repetitions had a significant facilitation effect and were a bit larger in size than those in the lexical decision results (8 ms for vowel repetitions and 6 ms for consonant repetitions). This facilitation effect was followed by consistent inhibitory effects in the interval of 1-to-3 intervening letters for both letter types. In the more than three letters distance interval, most of the variables, especially the vowel repetitions were significant, and, as in the lexical decision data, there was a peak of the inhibitory effect in the long-distance vowel repetitions. The variables with distances 8, 9, and 10 had 12 ms, 17 ms, and 38 ms effects.

[11] Coefficients of RPM RT in simple linear regression models with behavioral lexical decision task RTs for ELP, BLP, DLP2, and FLP as dependent variables:-1.967, -0.4515, -0.587, -1.621

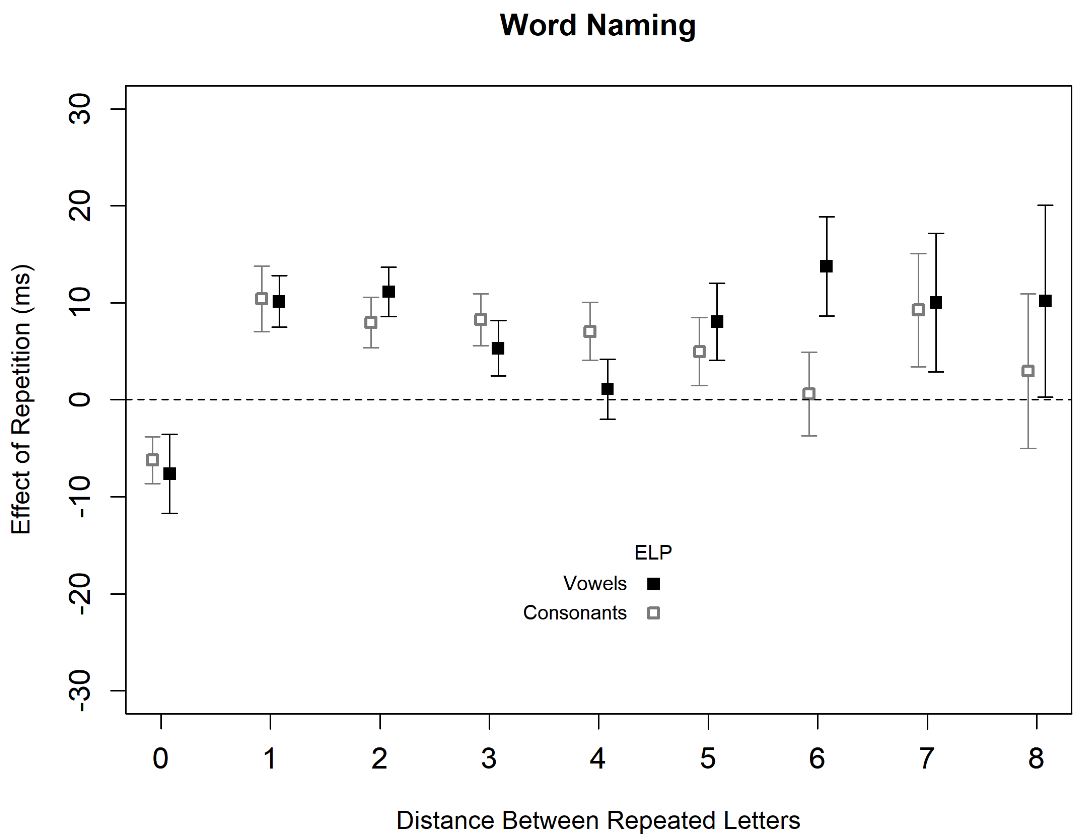

Figure 6. 5 Repeated letter effects in word naming in English Lexicon Project. Positive values indicate inhibition, negative values indicate facilitation. The distance is measured with the number of intervening letters between the repeated ones. Error bars represent 95% confidence intervals.

Discussion

The presence of letter repetitions in words significantly predicted reaction times of lexical decision and word naming tasks and accounted for additional unique variance after controlling of important lexical and sublexical variables. The results of the regression analyses suggested that the presence of nonadjacent letter repetition delays visual word processing speed. The inhibitory repeated letter effect was robust in the cases in which the repeated letters were intervened by up three letters. The effect was less consistent but still present with increasing distance between the repetitions. The effect was observed in all three languages under consideration: English, Dutch, and French. This replication implies that the inhibition of letter repetition might be linked to a general mechanism in visual word recognition rather than to idiosyncrasies of a single language. The obtained results are in accordance with the reported target type effect in Schoonbaert and Grainger's (2004) study, in which targets containing nonadjacent repetitions took longer to process. However, they disagree with the masked priming data, reported by these authors and by Van Assche and Grainger (2006), which provided no evidence for differential processing between repeated and unique letter identities. The results are also broadly consistent with Gomez et al.'s (2008) perceptual identification data that showed lower accuracies for stimuli containing repetition in comparison to stimuli with no repetition. A difference between their results and the results presented here is that Gomez et al. reported inhibitory repeated letter effects in both adjacent and nonadjacent repetitions, while the inhibitory pattern in the present study is more consistent in the cases of nonadjacent repetitions.

In the cases of adjacent repetitions, the effect had alternating patterns, suggesting that adjacent repetitions might be a special case of letter repetitions. The results also implied possible dissociation between consonants and vowels and double letter processing in different languages. In English, the inhibitory effect disappeared and even trended towards facilitation, especially in the cases of vowel repetitions. In Dutch, the vowel-consonant dissociation was clearly observed, with consonants producing a small but significant inhibitory effect, while vowels having a small but significant facilitatory effect. In French, the adjacent consonants preserved their inhibitory pattern. It should be noted that adjacent vowel repetitions are extremely rare in French, while in Dutch they are quite common. The differential effects might therefore result from the adjacent double letters idiosyncrasies of the language.

The different patterns of adjacent repetition might be due to counteractive processes that are not associated with cases of nonadjacent repetition and possible benefits of the letters being in contiguous positions. Such interpretation is consistent with the idea that adjacent repetition (letter doubling) should be coded as an additional dimension, that is separate from letter identity and letter position. This idea was influenced by results of language production and was also supported by evidence from visual word recognition research. It has been demonstrated that participants are more likely to misperceive the number of letters in a word and report a word with repetition (WEED instead of WED) if it was presented with a distractor word with another double letter (WOOD) than with a distractor word with no repetition (WORD; Fischer-Baum, 2017). Another reason of the diminished inhibitory effect in the cases of adjacent repetitions might be linked to the proposed letter identity "leakage" to nearby positions (Gomez et al., 2008; Norris et al., 2010) that could possibly be less detrimental in the cases of same adjacent identities than in the cases of nonadjacent ones.

The finding of inhibitory effects of letter repetitions suggests that there is a mechanism related to the rapid processing of identical sublexical elements (such as letters) that has not been previously described in the visual word recognition literature. In accordance with the speculation of Schoonbaert & Grainger (2004), the open bigram model (Grainger & van Heuven, 2003) indeed predicted inhibitory effects in cases of repeated letters as less bigram units will be activated than in the case of no repeated letters. However, this encoding scheme could not capture the effect in the empirical results. The specific prediction of this model on word lists of four lexicon projects was not matched to the observed pattern as it overestimated the inhibitory adjacent-repetition effect and underestimated the nonadjacent one, therefore depicting the opposite inhibitory pattern than the one in the lexicon projects. It might be worth exploring what the predictions of the model would be if the adjacent repetition is implemented in the model's encoding scheme as a separate special case (of bigram representation) and how such an implementation could affect the model's predictions of the repeated letter effect.

It was, perhaps, less surprising that the spatial coding scheme (Davis, 2010) also did not contribute to a successful simulation of the repeated letter effects, as the scheme contains explicit mechanism that prevents repeated letter identities from playing a different role than nonrepeated ones. The Spatial Coding Model did not predict the observed inhibitory pattern and in cases even predicted effects in the opposite direction. The results obtained in this study therefore present a challenge for both models and possibly signal the necessity of implementation of a mechanism explaining how processing of repeated letters is different from processing of different ones.

Such a mechanism might indeed be linked to smaller number of activated abstract representations in the cases of repetitions compared to cases with no repetitions, in analogy to the proposal of Schoonbaert and Grainger (2004). Another reason for the inhibitory repetition effect might be limitations of the perceptual system in either very early low-level stages or later more abstract levels in the form of incapability of dissociating between two identical (letter) units. These processing limitations might lead to inability to keep track of the number of similar letter identities (and misperceiving one of them). Such incapability might result from functional specialization and modularity of the processing components (letter receptors) associated with particular letter identity. In such a scenario, processing of two identical elements might not be achieved in the rapid parallel manner, in which it has been previously demonstrated that letters are perceived (Adelman, Marquis, & Sabatos-DeVito, 2010), as the same component might be involved in encoding two letters at once, therefore resulting in some processing delay. Another possibility is that the positional encoding rather than the identity encoding is delayed in cases of repeated letters. With identical signals coming from separate locations, making it more difficult for the visual system to allocate two identical letters to their corresponding positions than two different letters.

In conclusion, the results of the present study demonstrated a robust inhibitory effect which was replicated in all three languages under consideration. The effect was stable in the cases of up to three intervening letters, it was broadly consistent in larger distances and decreased in the cases of adjacent repetitions. The observed inhibitory pattern of repeated letter effects in the regression analyses was not predicted by two leading computational models and it is not yet reflected in any mechanism in the visual word recognition literature. These results have important implications for development of theories of visual word recognition and, more specifically, for understanding letter position and identity encoding and sublexical orthographic processes mediating lexical access. The obtained effects should motivate additional research in that direction, as well as additional theoretical and computational modelling effort with the purpose of the better understanding of the processes involved in the repeated letters effects. I continue exploring these effects in the next chapter of this thesis.

Chapter 7

A Factorial Approach to Repeated Letter Effects

The present study is motivated by the results of the regression analyses reported in the previous chapter and continues investigating the effects of repeated letters on visual word recognition. Unlike the previous study, which employed a regression approach on megastudy data, the present study used a factorial design approach for the investigation of the same phenomenon. As this approach gives the experimenter the ability to control and actively manipulate certain conditions, it might prove to be more appropriate for investigating causal relationships associated with the repeated letters effect as well as exploring its underlying mechanisms. As previous experimental studies addressing the effect have provided inconclusive results, the present study had an initial goal to establish a repeated letters effect with a factorial approach and provide possible explanations for the previous inconsistent results in the literature. The aim of the present study was also to provide additional evidence for the processes involved in the repeated letter effects. Such evidence could have important implications for developing theories of letter processing and encoding of letter position and identity. For these purposes, the investigation begins with a thorough review of previous studies exploring repeated letter effects with factorial designs as well as possible explanations for their inconsistent results. These are followed by a presentation of five novel experiments addressing specific research questions and a discussion of the results in terms of contributions, limitations and future research directions.

A well-known and often cited study in the orthographic processing literature was conducted by Schoonbaert and Grainger (2004) who investigated effects of repeated letters with a masked-form-primed lexical decision task (Forster, Davis, Schoknecht, & Carter, 1987). In this task, participants indicate whether a letter string presented on a computer string forms a genuine word or not by pressing one of two corresponding keys. Participants are typically unaware of the presence of the prime briefly presented after a mask (######) and prior to the target. Nevertheless, they are often faster when the prime is related in form to the target (e.g. bontrast-CONTRAST) in comparison to when it is not (shiuder-CONTRAST). The difference between the two conditions, the priming effect, is usually interpreted as the degree to which the orthographic codes between the related prime and the target overlap. In line with the findings that primes formed by deletion of letters from the target (relative position subset or deletion primes, e.g. e.g., BLCN-BALCON) produce form priming effects (e.g. Peressotti & Grainger, 1999), contrary to the predictions of the position specific encoding scheme (McClelland & Rumelhart, 1981), Schoonbaert and Grainger used a deletion prime manipulation to investigate repeated letter effects. They tested whether the orthographic codes of two related deletion primes will be equally similar to the target, i.e. will produce the same priming effect, when the deleted letter was repeated in the target and when it was unique. By doing so, they effectively addressed the problem of whether a letter unit contributes equally to the recognition of the whole word in cases of a single and multiple occurrences of the letter unit. The authors reported two lexical decision experiments with repeated letters. In Experiment 1, they used 7-letter-long French words, half of which contained a non-adjacent letter repetition, with initial and final letters kept unique. The other half of the stimuli did not contain any repetition and were matched by the repeated words by CV-structure, word frequency and number of orthographic neighbors (Coltheart's N; words of equal length that differ by only one letter in the same position; Coltheart, Davelaar, Jonasson, & Besner, 1977). The design contained three different primes. Two of them were constructed by deleting either a unique or a repeated letter from the target and the third prime type was an unrelated wordlike 6-letter prime. In the control no-repetition condition, the letter in the same position was deleted as the corresponding repeated letter condition. The authors reported a main effect of target type (although in the latency results the effect was significant only in the by-subjects analysis) with participants being significantly slower and less accurate when the target contained a repetition in comparison to when it did not. However, both types of related primes produced the same priming effect. The repeated letter condition was numerically smaller but not significantly different from the unique letter one (repeated: 565 ms, unique: 572 ms, unrelated 607 ms). The authors did not control for the CV status of the deleted letter which was much more often a vowel, than a consonant. They addressed this problem in a post-hoc analysis that showed no interaction between CV status and type of prime (repeat vs. unique). The authors concluded that the CV-status of the removed letter did not affect the priming effect. The distance between the repeated letters, was not considered as a factor and was not mentioned in the design. Similar results of a main effect of target type were also reported for the nonword trials, suggesting that targets with repetition were harder to process.

In their second experiment, Schoonbaert and Grainger (2004) used another technique to explore whether the status of the deleted target letter (repeated vs. unique) affects the resemblance of the deletion primes to the target. They employed an unprimed lexical decision task and compared the speed and accuracy in rejecting the deletion prime nonwords in the repeated and the unique conditions. The authors used the primes from their first experiment as nonword targets. The results showed no difference between the two conditions and again did not provide any evidence of differential processing between repeated and unique letters. However, as previously mentioned, most of the deleted letters in the repeated condition were vowels, so their deletion resulted in orthographically illegal crowded consonant clusters which might have played a facilitation role for rejecting those items as words. Taken together, Schoonbaert and Grainger (2004) concluded that the results provided mixed evidence for the effect of letter repetition in the process of word identification. The masked priming paradigm did not suggest any differential processing between repeated and unique letters to the process of lexical access. Nor was such evidence provided with the unprimed lexical decision task. The main effect of target type, however, was at odds with the other results. The authors did not eliminate the possibility that the null result might be due to lack of sensitivity of the masked-priming lexical decision task and the manipulation they have used.

In another masked-primed lexical decision study, van Assche and Grainger (2006) explored the effects of repetition and adjacency using a type of relative position prime manipulation, in which letters were inserted, rather than deleted from a target (superset primes). They used 7-letter-long French words (e.g. justice) and constructed 3 different related conditions which they compared to an unrelated 8-letter-long condition (benpalqo) and an identity prime (justice). The related conditions were constructed by repeating either the third or the fifth letter of the target (jusstice or justice); inserting in sixth or third position a letter already present in the target (justisce or juistice); and inserting a different letter in those positions (juastice or justimce). The results showed that the three related prime conditions were not significantly different between each other, they produced the same priming effect relative to the unrelated control and were also not significantly different from the identity prime. In a subsequent experiment, the authors used the same stimuli to compare the same priming conditions, except for inserting two, rather than one letter in each of the conditions (jussstice or justiiice; justissce or juiistice; jurqstice or justiaoce), which they compared to a nine-letter unrelated condition (bauelmoqi) and an identity prime (justice). The results had the same pattern as the ones in their first experiment. This study, therefore, provided no evidence of differential processing between repeated and unique letter identities. In fact, these results did not show any evidence that the priming effect could be decreased in any way by redundant letters, regardless of whether they are repeated or not. Such evidence was, however, later provided by Welvaert, Farioli, and Grainger, (2008) who demonstrated a cost of approximately 11 ms per letter insertion. In a form priming megastudy conducted by Adelman et al. (2014), a prime in which two repeated letters were inserted (deshhign) in a target (design) produced larger priming effect (6 ms difference) than a prime with insertions of two different letters (desaxign) suggesting that one redundant doubled identity is less disruptive to the target recognition than two redundant letter identities. This result is inconsistent with the lack of difference in the corresponding comparison in the study of van Assche and Grainger (2006).

Norris, Kinoshita, and van Casteren, (2010) used a different methodology for exploring effects of adjacent letter repetitions, the same different task combined with masked priming. In this task, a lowercase letter string serves as a temporal reference presented for about 1 s simultaneously and above a mask of symbols (#######). This event is succeeded by the presentation of a prime that appears at the place of the mask (in lowercase), followed by the target (in uppercase). The task of the participants is to indicate whether the reference and the target contained the same letters in the same order or not, disregarding their case difference. The trials of interest are usually the ones in which the reference and the target are the same. In those trials, robust masked form priming effects could occur for both word and nonword targets (Kinoshita & Norris, 2009), unlike in the lexical decision task in which the priming effects are usually restricted to word targets. The different trials usually serve as fillers and priming effects in those are usually not observed (e.g. Kinoshita & Norris, 2009; Norris & Kinoshita, 2008; Norris et al., 2010) except in some cases in which an inhibitory priming effect could be obtained when the related prime is related to the reference (a zero-contingency scenario, e.g. field-field-HOUSE), rather than to the target (a predictive-contingency scenario, e.g. field-house-HOUSE; Perea, Moret-Tatay, & Carreiras, 2011). The masked-primed same-different task is posited to be insensitive to lexical factors and the priming effect in this task is suggested to reflect orthographical processes only (Kinoshita & Norris, 2009; Norris & Kinoshita, 2008; Norris et al., 2010). The latter argument, however, was recently challenged by evidence in the literature suggesting a partial phonological contribution (Lupker, Nakayama, & Perea, 2015; Lupker, Nakayama, & Yoshihara, 2018).

Norris et al. (2010) argued that the same-different task might be a more appropriate tool for investigating small sublexical effects such as effects of letter repetitions. They addressed the letter repetition effect in the context of investigating processes underlying letter position and identity encoding. In accordance with evidence from the literature, suggesting perceptual noise and position uncertainty in early stages of word recognition (e.g. Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003; 2004; Peressotti & Grainger, 1999; Van Assche & Grainger, 2006; Welvaert et al., 2008), implemented in models such as the overlap model (Gomez, Ratcliff, & Perea, 2008), they proposed a mechanism of "leakage" of a letter identity to nearby positions as a result of this uncertainty. They hypothesized that such a mechanism would predict a larger priming effect for a replaced-letter prime in which two of the target's letters are replaced by doubling letters already present in the target (uueer - UNDER) than for a replaced-letter prime constructed by replacing two letters with other letters, not present in the target (ulger- UNDER). Such a difference was not observed in these two conditions in a masked-primed lexical decision task[12] but was demonstrated with a masked-primed same-different task with the same number of participants. The authors argued that the observed repeated letter priming advantage was not necessarily at odds with the results of Schoonbaert and Grainger (2004) that showed no difference between repeated letter and unique letter conditions. Norris et al. argued that the inconsistency of the results could be attributed to the difference in the sensitivity of the methodologies of the two studies. They suggested that the null result in the unprimed lexical decision task in Experiment 2 of Schoonbaert and Grainger could be due to that task being inappropriate for exploring the effect. They provided two explanations of the obtained null results. They suggested that effects that are observed due to positional or identity uncertainty, such as the repeated letter effect, would be smaller and could disappear when the targets are clearly observed (hence no uncertainty), as is in the case of an unprimed lexical decision task. Another explanation they provided suggested possible counteractive effects. Norris et al. argued that nonwords constructed by deleting a repeated letter (balnce) could indeed by orthographically more similar to the base word (balance) than the unique-letter-deletion nonwords (balace), therefore accessing the word more quickly and delaying the no response. However, repeated letters might be harder to detect which could influence the results during spelling check processes, that might be involved in such a task. Norris et al. posited that such an argument is consistent with the reported main effect of target type. The fact that repeated letters might be more difficult to detect than different ones is indeed consistent with the target type effect reported by Schoonbaert and Grainger but is not clear how this explanation could at the same time address the lack of difference between the repeated and unique letter conditions in the masked priming results in the same experiment. Norris et al. explained the discrepancies between the results of their replaced letter results and the masked-primed experiment in Schoonbaert and Grainger study by lack of sensitivity of the manipulation of the latter authors due to the several reasons. These were: manipulating one, rather than two letters; using non-

[12] The reported mean response times in the repeated-replaced condition were 7 ms shorter than those in the nonrepeated-replaced conditions with a sample size of 25 participants, 100 targets and 6 priming conditions. The repeated-replaced condition was also not significantly different from a transposed-letter condition (udner), suggesting that the experiment was possibly underpowered.

adjacent letters in which the leakage might have a smaller effect; and using lexical decision task, that is more sensitive to lexical factors that could hide small orthographic effects.

To support their claims, Norris et al. (2010) conducted a pair of experiments, which they referred to as being a "conceptual replication" of Schoonbaert and Grainger's (2004), Experiment 1. They used the masked priming paradigm combined with the same-different task in the first experiment and with lexical decision task in the second. They compared the priming effects between identity prime, a prime with one deleted letter and one replaced letter. Crucially, the design also included between target manipulation. Half of the target words contained adjacent repetition (annex), while the other half contained no repetition (erupt). The results showed that in both tasks, the difference between identity and a deleted-letter primes were only significant in the targets with no repetition (eupt-erupt) and not in the repeated letter condition (anex-annex). It was also demonstrated that the difference between the deleted-letter prime and the replaced-letter one in the repeated letter condition (anex-alnex) was only significantly different with the same-different task and not with the lexical decision task, in which the 12 ms difference did not reach significance. These results supported their claim that the same-different task might be more sensitive for detecting smaller orthographic effects. Norris et al. (2010) concluded that the results in their study were in accordance with the hypothesis of identity leakage due to the initial ambiguity of letter position and identity at initial perceptual stages. In this mechanism, the evidence for the presence of an identity of a single position is spread over nearby positions, therefore giving some advantage to primes such as *uueer* over *ulger* for the target *under*, as well as to *anex* for annex over *eupt* for *erupt*.

To test the overlap model that incorporates letter position and identity uncertainty, Gomez, Ratcliff and Perea (2008) used the perceptual identification task and compared the difficulty of processing of strings with repeated letters to strings without repetition. They presented 5-letter-long nonwords for 60 ms after which participants were given a choice between two alternatives. The results showed that accuracy of participants was extremely low when the target contained letter repetition. The authors reported mean accuracy of .684 for adjacent repetitions and .681 for nonadjacent repetitions. When the incorrect response and not the target contained repetitions, the mean accuracy was .807 and .779 respectively. When both the target and the foil contained repeated letters, the accuracy was .786 and .720 for adjacent and nonadjacent repetitions, respectively. The authors speculated that participants had a bias toward choosing a string without repetition and suggested that the repeated letter effect might be due to repeated letters being difficult to detect at early perceptual stages.

Taken together, previous studies have shown no evidence for differential processing between different and repeated nonadjacent letters with the masked-form priming paradigm (Schoonbaert & Grainger, 2004; Welvaert et al., 2008). In the cases of adjacent repetitions, dissociations between processing of repeated and unique letter identities was suggested by the masked form priming megastudy of Adelman et al. 2014, who demonstrated that central insertions of two identical letters in the prime was less detrimental to target recognition than insertion of two different letters. This suggestion was further supported by Norris et al. (2010) who demonstrated larger priming effects when doubling two target letters (uueer-UNDER) than replacing the same mismatched letters with two letters not present in the target (ulger). In addition, in another experiment they showed that deleting one of the two adjacent repeated letters had a smaller processing cost than deleting a unique letter from the target. The adjacent repeated letter evidence provided by Norris et al. was more pronounced when the masked-priming paradigm was combined with the same-different task than with the lexical decision task. To summarize, the masked-priming paradigm has demonstrated repeated letter effects only with adjacent repetitions, suggesting that these might be easier to detect with this methodology. In addition, the evidence also raises methodological concerns regarding the sensitivity of the masked-primed lexical decision task to effects operating on a letter level, such as the repeated letter effects and an advantage of the masked-primed same-different task for detecting such processes.

Apart from the results of inhibitory repeated letter effects presented in Chapter 6, some evidence for repeated nonadjacent letter effects was also provided by Schoonbaert and Grainger (2004) who reported a main effect of target type. Irrespective of the primes, trials with words and nonwords containing repeated letters had longer response times and lower accuracy than targets with no repetitions. Gomez et al. (2008) also reported much lower accuracy on targets with repeated letters (both adjacent and nonadjacent) than on targets with no repetitions with the two-forced-choice perceptual identification task, suggesting that this methodology could be more sensitive for detecting repeated letter effects than masked-priming, particularly when combined with a lexical decision task. However, as already discussed, a repeated letters effect in cases of nonadjacent repetitions, as suggested by the regression approach study in Chapter 6, have not yet been demonstrated in the masked-priming literature. In addition, although there is evidence for an effect of adjacent repetition, there is no demonstration with a factorial design approach that adjacent and nonadjacent repetitions involve different processing mechanisms. The answers to these questions and the further exploration of the effect is essential for understanding how the visual system treats multiple occurrences of identical letters.

To address these questions and to attempt to support the results in Chapter 6, five different experiments were conducted. The first experiment used the masked priming lexical decision task. Unlike any other studies using this methodology to explore repeated letter effects, however, a transposed letter priming manipulation was employed. The motivation behind this choice was the fact that any additional processes associated with missed identities (as in deletion primes) or redundant identities (insertion primes) will not be artificially introduced. Therefore, any letter repetition effect should arise only from processes associated with the positional mismatch of the repetition. The priming effect produced by a transposed-letter prime that disrupts the distance between the repeated letters will be compared to priming effects produced by transpositions of unique identities. Such a comparison will allow for exploring processes that might be idiosyncratic to repeated letters. It would also provide some evidence of how similar strings with an adjacent repetition to strings with no adjacent repetition are to each other. To the best of our knowledge, masked-priming transposed letter results of repeated letters have not yet been reported. Such a manipulation will therefore be informative for the mechanisms involved in letter position and identity encoding and processing of multiple occurrences of the same letter unit.

The factorial design investigation of repeated letter effects will continue with two experiments using the two-forced-choice perceptual identification task that is considered to be appropriate for capturing perceptual effects occurring in early stages of word recognition. Experiment 2 will focus on testing how the visual system keeps track of the number of occurrences of letter identities, while Experiment 3 will follow up from the transposition manipulation similar to Experiment 1 to test positional encoding in cases of repeated and unique letter identities. The final two experiments will employ the same-different task to provide methodological comparison between masked priming and perceptual identification task as well as to test whether the established results could be replicated in different paradigms.

Experiment 1: Lexical Decision Task with Transposed Letter Primes

This experiment used a masked primed lexical decision task. It investigated whether repeated adjacent letters in English played the same role in word identification as two letters with different identity. It tested whether splitting an adjacent repetition apart by transposing one of the repeated letters with a nonadjacent letter would produce the same priming effect as the one in a similar nonadjacent transposition in words with no adjacent repeated letters. Previous research with the masked-primed lexical decision task has demonstrated that nonword primes formed by transposing two nonadjacent consonants in a word produce a robust priming effect compared to a two-replaced-letters control (caniso-CASINO; caviro-CASINO; Perea & Lupker, 2004). This effect was first demonstrated in Spanish and was later replicated in English (Lupker et al., 2008). To test whether identical adjacent letters affected word processing, we compared the priming effect formed by transposition of either repeated consonant letters (*opsope*-*oppose*) or different consonant letters (*codemy*-*comedy*). If processing of adjacent repetition is associated with a mechanism that differs from that of processing two different letters, that should be observed in differential priming effect between the two conditions. Norris et al. (2010) proposed a mechanism of identity leakage to nearby positions at early stages of word identification and suggested that in cases of adjacent repetitions this process would be less detrimental as each of the two letters would provide some evidence towards the presence of the other letter. In cases of nonadjacent repetitions, however, this leakage will have a smaller effect as it will have to span across one or more intervening letters. In line with such a proposal, transposed-letter primes affecting the adjacency of a repetition should produce smaller priming effect than transposed-letter primes affecting letters with different identity as some initial advantage of the adjacent repetition will be lost. If, on the other hand, there are no specific processes associated with adjacent repeated letters, the transposed-letter priming effect in the two conditions should be the same.

Method

Participants

One-hundred-and-two native English speakers participated in the experiment in exchange for small payment or course credit. Four of the participants were excluded from the analyses due to low accuracy of their responses (less than 75% on all trials).

Stimuli and Design

A total of 160 words were chosen for the word trials. Half of the words were taken from Lupker et al., (2008), Experiment 1 (Mean Subtlex UK log frequency = 3.41 (SD = 0.56); log frequency Zipf = 4.10 (SD = 0.56); Mean length = 7.25 (SD = 0.86). The other half were selected so that the words contained one adjacent repetition of consonant letters and were matched on word frequency and length with the words that contained no such repetition (Mean Subtlex UK log frequency = 3.32 (SD = 0.58); log frequency Zipf = 4.01 (SD = 0.58); Mean length = 7.25 (SD = 0.86). In addition, 160 words were selected for the construction of nonwords for the nonword trials (Mean Subtlex UK log frequency = 2.38 (SD = 0.99); log frequency Zipf = 3.08 (SD = 0.99). They were matched in length with the word targets, Mean length = 7.25 (SD = 0.86). The nonwords were formed by replacing one or two of the consonant letters from the original word with other consonants. In half of the cases the replacement formed an adjacent consonant repetition. Two different prime types were formed: a transposed prime type, in which two internal nonadjacent consonants separated by one vowel were transposed (e.g. academy-adacemy; accurate – acrucate); and a replaced prime type, in which the affected letters in the transposed condition were replaced by other consonants (e.g. academy – abanemy; accurate – acmusate). All participants saw stimuli from all four conditions: two prime types (transposed, replaced) and two prime targets (with and without adjacent repetition). However, each of the target was seen in only one of the two possible prime type conditions. Two counterbalancing lists were created for that purpose.

Procedure

Trials were presented in a new randomized order for each participant, intermixing all four conditions. Each trial began with a fixation cross, presented for 300 ms, followed by a 200 ms blank screen after which a forward mask (########) appeared for 500 ms. The mask was followed by a presentation in lowercase of the prime for 50 ms. The target was then presented in uppercase and stayed on the computer screen until response. The primes and the targets were all presented in Courier New font, sizes 12.5 and 20 respectively. The purpose of the case and size manipulations were to minimize visual overlap between the stimuli. The stimuli were presented in black on a white background. The task was lexical decision. Participants were instructed to indicate their decision regarding the lexicality of the target string (real word or not a real word) as quickly and as accurately as possible by pressing one of two corresponding keys (left and right shift on a computer keyboard). Feedback was given after each trial. The DMDX software (Forster & Forster, 2003) was used for stimuli presentation and data collection.

Results

Response Time

Prior to the response time analysis of the word trials, trials with response time less than 150 ms or greater than 1500 ms (0.51%) and incorrect trials (6.77%) were removed. Mean response times and accuracy by condition are reported in Table 7.1. A linear mixed-effects model was fitted with prime type, word type and their interaction as fixed factors. The by-subject intercepts and slopes for prime type, target type and their interaction and the by-item intercepts and slopes for prime type were added as random factors (full model). The model was fitted with the *lme4* package in R (Bates, Maechler, Bolker, & Walker, 2015). Type II Wald chi-square tests were performed on the fitted model to establish the significance of the fixed main effects as well as their interaction. The effect of prime type was significant $\chi^2(1) = 13.718$, $p < .001$. Trials with transposed letter primes were responded to significantly faster than trials with replaced letter primes. However, the interaction between prime type and target type was not significant $\chi^2(1) = 2.367$, $p = .124$.

Table 7. 1 *Mean Response Times (ms) in Experiment 1 for Word Targets and Error Rates (in Percentages, in parentheses) as a Function of Prime Type and Target Type*

Prime	Nonrepeated target	Repeated target
Transposed	608 (5.2)	611 (7.6)
Replaced	621 (5.9)	617 (9.0)
Priming	13 (0.7)	6 (1.4)

Accuracy

A generalized mixed effects model with binomial distribution was fitted for the word accuracy analyses with the same structure as the one in the latency analysis (full model). The results revealed a significant main effect of target type, $\chi^2(1) = 6.495$, $p = .011$. Participants made significantly more errors on the target words that contained adjacent consonant repetition than on targets with no adjacent repetition. No other results were significant.

Discussion

The results of Experiment 1 did not provide evidence with the masked priming paradigm of differential processing between two repeated adjacent letters and two different adjacent letters. The critical manipulations in the experiment involved splitting the two identical consonant letters apart by transposing one of them with another nonadjacent consonant, thus enlarging the distance between the repeated letters. The transposed-letters priming effect produced by the set of words containing adjacent repetition was not significantly different from the transposed-letters priming effect produced by the set of words with no adjacent repetition, as evident by the lack of significant interaction between target type and prime type. However, the pattern of the results suggested a smaller priming effect for the adjacent repetition targets than for the targets with no adjacent repetition, which is in line with the view that adjacent repeated letters are processed in different way than two different adjacent letters. It should be noted that the size of the transposed-letters priming effect was quite small in both target type conditions. For the adjacent repetition targets it was only 6 ms and for targets with no adjacent repetition it was 13 ms. In comparison, in the cases of nonadjacent repetition targets set, Lupker et al. (2008) reported a 24 ms priming effect with the same stimuli. In that study, participants were also slower (31 ms slower in the TL condition) and more accurate than those in the present study, suggesting different performance strategies between the participants in the two studies with participants in the current one prioritizing speed over accuracy.

Experiment 2: Perceptual Identification with Insertions and Deletions

In this experiment, the two-forced-choice perceptual identification task was used for the investigation of repeated letter effects. A previous study using the same task for exploring this effect was the study of Gomez et al. (2008). What sets the two studies apart is the critical manipulation used in the two studies, evident in the relationship between the target and the foil (the wrong choice). In the present study, the target and the foil were never the same length. The foil was formed by either deleting or inserting a letter. In their Experiment 4, Gomez et al. compared strings with the same length that included replacements and transpositions. They had three main conditions in which the repeated letters were either in the target, or in the foil or in both. The repeated targets in their conditions also appeared within different differences. The present study, on the other hand, focuses on a non-adjacent repetition in which the repeated letters are always separated by one letter. This choice was motivated by the stable inhibitory pattern for repeated letters within that distance demonstrated in Chapter 6, as well as by the necessity for more evidence due to the gap in the orthographic processing research literature. The purpose of the experiment was to test whether the number of nonadjacent repeated letters could be determined in early perceptual stages. If the system is not able to detect or keep track of the number of the identities, such processing limitations could explain the inhibitory effect reported in the study of Chapter 6.

Another important aim of this experiment was to provide evidence regarding the cause of the low accuracy results for the repeated letter targets of Experiment 4 in Gomez et al. (2008). One possible explanation for their result could be a bias toward choosing targets with no repetition due to some unnaturalness of targets with repeated letters. Such an explanation does not imply any effects due to the presence of repeated letters per se. Another explanation, however, could be that the presence of repeated letters raises the level of processing difficulty of those targets. To test the reason of the results reported by Gomez et al. the comparison was made between trial type (repeat vs unique), rather than target type, as in the case of Gomez et al. As the repeated letters were not only in the target, but also in the foil, any effect of repetition could not be attributed to bias of choosing a string with no letter repetition.

Unlike the stimuli in Experiment 1 of the present chapter, nonword stimuli were used in Experiment 2 for the intended manipulation. Another difference between the present experiment and that of Gomez et al. was the length of the stimuli. Five-letter-long stimuli were used in Gomez et al. while the stimuli in this experiment were seven and eight-letters long. The greater length was chosen for two reasons. First, repetitions are more likely to be observed in longer words. Therefore, the processes involved in possible observed effects would be more likely to generalize for processing of longer items with repeated letters. Second, longer lengths allow for variation in the positions in which the repetitions occur, thus making the items less predictable and more variable.

Method

Participants

Sixty-four undergraduate students from the University of Warwick took part in the experiment for in exchange for course credit. They were tested either individually or in a group of two.

Stimuli and Design

The materials consisted of 352[13] eight-letter nonwords, constructed so that they were pronounceable and did not deviate substantially from the orthotactics and phonotactics of English. Each of them contained a repetition of a letter. The repeated letters occurred equal times (88) in positions 2 and 4; 3 and 5; 4 and 6; 5 and 7. Half of the repeated letters in each position condition were consonants and the other half were vowels. The initial and final letters were never repeated. For each of the items, 7 additional derivatives were constructed and so each family of items had 8 different members in it. The second version of the items were constructed by replacing the repeated letters with other repeated letters from the same corresponding consonant-vowel class (e.g. DRARTIEN-DLALTIEN). The third version of the items were derived by replacing the first occurrence of the repeated letter from the first item version with the repeated letter from the second item version (DRARTIEN-DLARTIEN). The fourth member was constructed in a similar way as the third one, the only difference being that the second occurrence of the repeated letter of the first version was the one that was replaced by the repeated letter of the second type (DRARTIEN-DRALTIEN). Thus, the first four versions of the items contained two different eight-letter nonwords with repeated letters (repeated condition) and two different nonwords with no repeated letters (unique condition). All four versions were used to keep the design symmetrical as well as to counterbalance possible statistical regularities effects such as letter and bigram frequencies.

The next four versions of the items represented one-letter-deletion derivatives of the eight-letter nonwords. They were constructed by deleting one of the letters in the critical positions where a repetition occurred in the repeated condition. The fifth version of the items were derived by deleting the first occurrence of the repeated letter of the first type (DRARTIEN-DARTIEN). The sixth item was derived by deleting the second occurrence of the first type (DRARTIEN-DRATIEN). The seventh and the eighth versions were constructed in the same way as the previous two versions, but the first and the second occurrences of the second repeated letter type were deleted (DLALTIEN - DALTIEN; DLALTIEN-DLATIEN). The initial 352 items were constructed so that their deletion derivatives remained pronounceable.

Each of the eight versions of an item family served as a target in a perceptual identification two-alternative forced-choice task, in which participants had to choose the correct response from a

[13] Twelve of the items were excluded from the analysis due to a programming error that led to three rather than two occurrences of a repeated letter in some of the items' versions

target and a foil. Each of those versions also served as a foil. There were two possible foils for each target. When the target was one of the four eight-letter targets, the two possible foils were the corresponding seven-letter versions with omission of one of the two letters in critical positions. For example, the two possible foils for DRARTIEN were DARTIEN and DRATIEN. When the target was one of the seven-letter item versions, the two possible foils were the corresponding repeated or unique eight-letter versions. Thus, when the length of the target was seven letters, the foils had an additional inserted letter. This was the letter in the same position that was omitted to form the seven-letter target. Thus, the two possible foils for DRATIEN were DRARTIEN and DRALTIEN.

In each trial, the target and the foil were never the same length. The critical comparison was the one between repeated or unique letter condition. When the targets were eight-letter long, the critical manipulation was done in the target, which either contained repeated letters or not. When the targets were seven-letters long, the repeated letters were either present or not in the foil. This design afforded testing of how participants would respond to both insertions and deletions of letters that were either already present or not in the target. The purpose of this contrast was to test the ability of the participants to detect the number of letters that shared the same identity in a brief presentation of pronounceable letter strings.

Each participant saw only one of the eight versions of the items with one of the two possible foils. In addition, the position of the correct response and their corresponding left and right buttons was carefully counterbalanced so that the correct responses were equal times on the left and on the right for each of the contrasting conditions. These manipulations led to sixteen different counterbalancing lists.[14]

Procedure

[14] In half of the counterbalancing lists the seven-letter long targets, constructed by deleting the second occurrence of the repeated letter were always matched with a repeated letter foil. The correct response was always on the right. The targets in which the first occurrence of a repeated letter was deleted were always matched with a unique letter foil. The correct response was always on the left. The opposite was done for the other half of the counterbalancing lists. For trials with eight letter long targets, in each of the counterbalancing lists there was an equal number of foils created by deleting the first and the second occurrence of repetition and matched with a repeated letter target and an equal number matched by a unique letter target. For each of those conditions the correct response always appeared equal times on the left and on the right.

The experiment was conducted on a 17” CRT Sony Trinitron CPD-G220 monitor. The DMDX software (Forster & Forster, 2003) was used for the presentation of the stimuli and for data collection. The refresh rate was set to 10ms. All stimuli were presented in black on a white background. Each trial began with a 10-symbols-long mask (##########), presented in the center of the screen for 900 ms in a Courier New font, size 23. The mask was followed by the target nonword, presented for 110 ms in upper Courier New font, size 20. After the presentation of the target, the screen remained blank for 10 ms after which the mask appeared again in the place of the target simultaneously with two choices which were displayed below the mask. The choices were in Courier New font, size 23 and were presented to the left and to the right of the middle of the screen. Participants had to perform a two-alternative forced-choice task. One of the alternatives was the target itself and represented the correct choice and the wrong alternative was one of the two possible foils of that target. Participants were asked to indicate which of the two alternatives was displayed on the screen by pressing either the left shift key for the alternative on the left or the right shift key for the alternative on the right. They were instructed to be as accurate as possible and had up to 2000 ms to respond. Accuracy feedback was given after each trial. In addition, participants’ current percentages of correct responses were displayed after the completion of every 44 trials. Participants were encouraged to constantly try to improve their performance as much as possible and were given a break in the middle of the experiment.

Results

Insertions in foils

The accuracy results per condition can be seen in Figure 7.1. A generalized linear mixed effects model with binomial distribution was fitted for the accuracy analyses with inserted letter condition (repeated/unique) as a fixed effect and by-subjects and by-items intercepts and slopes for condition as random effects. The effect of letter condition was significant, $\chi^2(1) = 15.399$, $p < .001$. Participants produced significantly more errors when the inserted letter in the foil was already present in the target than when it was not.

Deletions in foils

A generalized linear mixed effects model with binomial distribution was fitted for the accuracy analyses with inserted letter condition (repeated/unique) as a fixed effect and by-subjects and by-items intercepts and slopes for condition as random effects. As in the insertions analyses, the effect of letter condition was significant, $\chi^2(1) = 19.922$, $p < .001$. Participants produced significantly more errors when the target contained a letter repetition than when it did not.

Insertions and deletions in foils

A generalized linear mixed effects model with binomial distribution was fitted for the accuracy analyses of all the trials in the experiment. The model contained trial condition (repeated/unique), target length (seven/eight) and their interaction as fixed effects and by-subjects and by-items intercepts and slopes for trial condition, target length and their interaction as random effects (the full model). The results revealed significant main effect of trial condition, $\chi^2(1) = 28.141$, $p < .001$, and significant main effect of target length $\chi^2(1) = 16.036$, $p < .001$. The interaction between the two factors was not significant, $\chi^2(1) = 1.901$, $p = .168$. Participants were significantly less accurate when the trial contained letter repetition and when the targets were eight-letters long than when the trials had no repetition and the targets were seven-letters long.

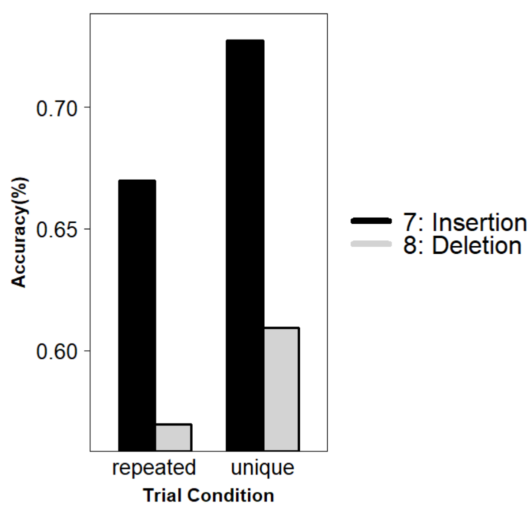

Figure 7. 1 Percentage accuracy per trial condition (repeated vs. unique) for seven-letter-long targets with letter insertion in foils and for eight-letter-long targets with letter deletion in foils.

Discussion

The results in Experiment 2 showed that participants were significantly less accurate whenever they had to report whether they saw one or two letters with the same identity. They performed significantly worse when an additional inserted letter in the foil was already present in the target, therefore producing a letter repetition, then when the inserted letter was different from any letters in the target. In the trials, in which the foil was missing a letter from the target, the accuracy was significantly lower when the missing letter was a repeated one, than when it was a unique one. These results suggest that letter numerosity might be difficult to process at early stages of orthographic processing and rule out an explanation involving a bias toward choosing a string with no repeated letters.   The results also indicated lower accuracy results for the eight-letter-long targets than for the seven-letter-long targets, suggesting that the longer targets were harder to perceive.

Experiment 3: Perceptual Identification with Transposed Letters

This experiment aimed to further explore processes involved in perception of nonadjacent repeated letter strings. The focus in Experiment 3 was on testing whether the positional encoding of a letter is local-context-dependent, more specifically whether the position of a letter identity can be affected or not by the presence of another letter with the same identity. For this purpose, the foils in the present two-forced-choice perceptual identification task were formed by an adjacent letter transposition.

Method

Participants

Fifty-six native English speakers were tested. They either received course credit or were paid £3 for their participation. They were tested either individually or in a group of two.

Stimuli and Design

352 eight-letter-long pronounceable nonwords were constructed. They were divided into four equal numbers, so that 88 of them contained the same letter in second position and in the fourth position, 88 had the same letter in the third and fifth positions, 88 had the same letter in the fourth and sixth positions and the other 88 had the same letter in the fifth and the seventh position. The initial and the final letters were never repeated. The repeated letters were always divided by one intervening letter. In each quarter half of the repeated letters were consonants

and the other half were vowels. For each of the 352 items, an alternative with no letter repetition of letters was constructed by replacing one of the repeated letters with another letter from the same consonant-vowel class. Half of the items had replaced the first occurrence of the repeated letter and the other half had replaced the second occurrence of the repeated letter. In order to test participants' ability to detect letter position when the same letter is present more than once in a letter string, for each of the 352 nonwords and its non-repetition alternative a transposed nonword version was created. The initial and final letters were not transposed as these could have differed too much in perceptibility in comparison to inner letters. For the group probing positions 2 and 4 the fourth and the fifth letter changed their places (DRARTIEN-DRATRIEN; DLARTIEN-DLATRIEN). For the 3-5 group, the fifth and the sixth letter were transposed (JUBOBIAL-JUBOIBAL; JUVOBIAL-JUVOIBAL). In the 4-6 group the third and the fourth letters swapped their places (UBARTRIL-UBRATRIL; UBARTNIL-UBRATNIL) and in the 5-7 group the fourth and the fifth letters changed their positions (POSEMAMY-POSMEAMY; POSEMACY-POSMEACY). The choice of the transposed positions was made as to preserve the pronounceability and orthotactic legality of the nonwords. These transpositions led to shifting the position of the first occurrence of the repeated letters in half of the stimuli and the second occurrence in the other half. The first two and the final two letters were kept constant.

The independent variables were *repetition* and *distance*, each with two levels: the target either contained a repetition or not and this repetition was intervened by either one or two other letters. (In this design DLARTIEN served as a control for DRARTIEN and DLATRIEN was the control of DRATRIEN). Participants performed a two-forced choice perceptual identification task in which the transposed version of the target served as the incorrect choice. Each participant saw only one of the four possible derivatives. The position at which the correct answer appeared was carefully counterbalanced so that half of them appeared on the left and the other half on the right for each condition. In addition, the same target appeared on the left at one list and on the other in another. The total number of counterbalancing lists were thus eight.

Procedure

The experiment was conducted on a CRT Sony Trinitron CPD-G220 monitor. DMDX software (Forster & Forster, 2003) was used for the presentation of the stimuli. The refresh rate was set to 10ms. The beginning of each trial started with a 10-symbols-long mask (##########), presented on a CRT monitor on the center of the screen for 900 ms in a Courier New font, size 23, followed by the target nonword presented for 130ms in upper Courier New font, size 20.

After the target, the screen remained blank for 10ms after which the mask was presented again in the place of the target simultaneously with two choices which appeared near the bottom of the screen. The choices were in Courier New, size 23 and appeared to the left and to the right of the middle of the screen. All letters were presented in black on a white background. Participants had to perform a two-forced-choice task. One of the alternatives was the target itself and represented the correct choice and the other alternative was always the target's transposed derivative. Participants were asked to indicate which of the two alternatives they saw by pressing either left shift for the alternative on the left or right shift for the alternative on the right. They were instructed to be as accurate as possible and had up to 2000 ms to respond. Feedback was given after each trial and in addition, participants' percentage of correct responses was displayed after every 44 completed trials. Participants were encouraged to try to improve their performance as much as possible and were given a break after the completion of half of the trials.

Results and Discussion

Mean accuracy by condition is displayed in Table 7.2. A generalized linear mixed effects model with binomial distribution was fitted for the accuracy analyses with letter condition (repeated/unique), distance (one letter/two letters) and their interaction as a fixed effects and by-subjects and by-items intercepts as random effects. The main effect of distance was significant, $\chi^2(1) = 6.92$, $p = .009$. The items, that were constructed by the transposition of the original ones were harder to identify than the originals. The effect of letter condition was not significant, $\chi^2(1) = 1.976$, $p = .16$, neither was the interaction between the two factors, $\chi^2 < 1$. These results did not provide any evidence of worse performance due to the repetitions of letters. There was even a trend towards the opposite direction.

Table 7. 2 *Mean Accuracy (%) by Condition in Experiment 3*

	Condition	
Distance	Repeated	Unique
1	66.8	65.6
2	64.9	64.2

Experiment 4: Same-Different Task with Deletion Primes

The last two experiments described in this chapter used the same-different task, combined with the masked priming paradigm. They followed up from Experiment 2 and aimed to investigate perceptual similarities of deletion and insertion primes in the context of repeated letter effects. Experiment 4 explored the priming effect of deletion primes on targets with and without repeated letters. The results of Experiment 2 demonstrated that participants were less accurate in a two-forced-choice perceptual identification task when the foil missed one of two repeated letters than when it missed a unique letter. These results suggested that the two choices were perceived as more similar in the repeated letter condition than in the unique letter condition. The purpose of Experiment 4 was to test whether higher orthographic similarity between a deletion prime and target with repeated letters than between a deletion prime and target with no repeated letters could be established with a masked-priming paradigm. The same-different task was used, as it has been demonstrated that with this task robust priming effects could be obtained with nonword targets and that it is sensitive to small orthographic manipulations (Kinoshita & Norris, 2009; Norris et al., 2010). The effect of identity primes on the two target types was also tested to make sure that any deletion priming differences could not be attributed to one of the target types being more prone to priming in general.

Method

Participants

Sixty-six native English speakers took part in the experiment for a small payment. The last two were replacements for those with low accuracy scores (correct on less than 70% of the trials), leaving data from 64 for analysis.

Materials and Design

The same stimuli as the ones in Experiment 2 were used[15]. The task was to determine whether two letter strings, a reference and a target, were same or different, so there were two trial types that occurred equal times: same and different. To minimize the counterbalancing list conditions, from each item family only one of the two eight letter long versions containing repetition and

[15] The items that erroneously contained three occurrences of the same letter from the set were modified so that a letter appeared no more than twice in an item.

only one not containing repetition were selected as targets for both the same and different trials. They also served as references in the same trials. The design included 4 different prime types, constructed by crossing the factors *relatedness* (related/unrelated) and *length* (7 letters/ 8 letters). In the same trials, the 8-letters-long related prime was identical to the target and the reference. The 7-letter related prime was the same as the identity with omission of a single letter. The omitted letter was the different one between the repeated letter family version (DRARTIEN) and the nonrepeated letter one (DLARTIEN), so the relationship between the 7-letter related prime (DARTIEN) and the two target types was the same: The prime contained seven out of eight letters of the target. The unrelated primes were constructed by pairing each family with another family so that both families shared no more than three common letters. Where it was not possible to pair families so that control primes shared two or fewer letters with their target, one letter was changed in the prime to meet this constraint. After those manipulations, the unrelated primes contained no more than two common letters with the targets. The seven letter unrelated primes were constructed by deleting one common letter from the eight letter unrelated primes. Where there was a choice, the letter whose omission preserved pronounceability was chosen. The seven-letter-long unrelated primes had no more than one common letter with the target.

The previously unselected eight-letters long versions of an item family served as references for the different trials. There were two different reference types. The reference either contained a repetition for which the second repeated letter version from a family was selected (DLALTIEN) or not, for which the second unique letter version from the family was selected (DRALTIEN). The two different reference types occurred equal times in the different trials for each target type, so the outcome could not be determined only be the presence or absence of a repetition in the reference. For half of the items the repeated letter reference was selected and for the other half the unique letter reference was selected.

A zero-contingency scenario was adopted for the different trials. In this scenario, the correct response cannot be predicted by the relationship between the reference and the prime, as in both trial type conditions, the prime is related to the reference. In the different trials, the identity primes were the same as the reference, the 7-letter related prime was more related to the reference than to the target (APOPLECY- APOLECY- ARORLECY) and the two unrelated prime conditions were the same as the unrelated primes in the same trials and were neither related to the reference nor to the target.

Thus, the design of the experiment contained four factors: 2 x target types (repeated letters, unique letters), x 2 prime relatedness (related, unrelated) x 2 prime length (7 letters, 8 letters) x 2 trial type (same, different). Each participant saw only one version of an item in only one of the possible conditions but was presented with all the different conditions in the design.

Procedure

Participants were tested individually in a quiet room. The DMDX software (Forster & Forster, 2003) was used for stimulus presentation and data collection. Stimuli were presented on a CRT monitor with a 10 ms refresh rate. Each trial began with a presentation of a 10-symbols (#) long mask in the center of the screen and the reference above it. These were presented for 1 s after which the reference disappeared and the prime replaced the mask. The prime was displayed for 60 ms and it was followed by the target. The target stayed on the screen until response with a 2 s timeout. The reference and the target were presented in lowercase and the target was presented in uppercase. All stimuli appeared black on a white background. Courier New font was used, sizes 12.5 for the reference and the prime and 20 for the target. Participants were instructed to respond as quickly and as accurately as possible whether the pair of nonwords they saw on the screen were the same or different by pressing one of two corresponding buttons (left shift for different, right shift for same). They were instructed to disregard the difference in the case. The presence of the primes was not mentioned.

Results

Same Trials

Response Time. Prior to the response time analyses, trials with incorrect responses (8.7%) and response times faster than 150 ms and slower than 1500 ms were removed (1.3% of the correct trials). Mean response times and error rates by condition are displayed in Table 7.3. A linear mixed-effects model was fitted with target type (unique/repeated), prime relatedness (unrelated /related), prime length (7 letters/ 8 letters) and their interaction as fixed effects and by-subjects and by-items intercepts as random factors. The effect of prime relatedness was significant, $\chi^2(1) = 35.153$, $p < .001$. The effect of target type was not significant $\chi^2(1) = 1.859$, $p = .173$. The effect of prime length and all the interactions were not significant, $\chi^2 <1$. These results suggested that participants were not significantly delayed in the repeated letters target condition.

Interestingly, they were equally primed by the identity 8 letter primes and by a deletion 7 letter primes and the priming effect did not differ across target type conditions.

Accuracy. For the accuracy analyses, a generalized linear mixed effects model with binomial distribution was fitted with the same structure as the model for the response time analyses. The results revealed a main effect of prime relatedness, $\chi^2(1) = 4.89$, $p = .027$. Participants produced significantly more errors when the primes were unrelated than when the primes were related. No other results were significant, all $\chi^2 < 1$.

Table 7. 3 *Mean Reaction Times (ms) and Error Rates (%) by Condition in Same Trials*

	Target Type			
	Unique		Repeated	
Prime Type	7 letters	8 letters	7 letters	8 letters
Unrelated	763(9.9)	760(9.3)	767(8.8)	764(8.9)
Related	735(8.0)	739(8.3)	742(8.2)	743(7.9)
Priming	28(1.9)	21(1)	25(0.6)	21(1)

Different Trials

Response Time. Prior to the response time analyses, trials with incorrect responses (20.2%) and response times faster than 150 ms and slower than 1500 ms were removed (1.7% of the correct trials). Mean response times and error rates by condition with one letter-different reference (no repeated letters) and two-letter different reference (with a repeated letter) are displayed in Table 7.4 and Table 7.5, respectively. A linear mixed-effects model was fitted with target type (unique/repeated), prime relatedness (unrelated /related) and prime length (7 letters/ 8 letters), reference type (repeated/ unique) and their interaction as fixed effects and by-subjects and by-items intercepts as random factors. The results revealed a significant main effect of target type, $\chi^2(1) = 510.344$, $p < .001$; reference type, $\chi^2(1) = 486.747$, $p < .001$; and significant interaction between target type and reference type, $\chi^2(1) = 17.869$, $p < .001$. Participants were significantly slower when responding to a unique target type than to a target type with a repetition. They were also significantly slower when the reference was two letter-different from the target than it was only one letter different and they were extremely delayed when the target and the reference contained no repeated letters. In this condition, the target was effectively a transposed version of the reference (olebuvan-OBELUVAN). The effect of prime length approached significance, $\chi^2(1) = 3.011$, $p < .082$. When the model was fitted on a subset of the different trials in which the reference was two-letter different from the target and contained a repetition, the results revealed a significant interaction between prime relatedness and prime length, $\chi^2(1) = 3.929$, $p = .047$. The interaction was driven by the inhibitory trend observed by the related primes when they were identical to the reference.

Accuracy. For the accuracy analyses, a generalized linear mixed effects model with binomial distribution was fitted with target type, reference type and their interaction as fixed effects and by-subjects and by-item intercepts as random effects. The prime relatedness and length were excluded from the model as it failed to converge even after dropping the random slopes. The results revealed a main effect of target type, $\chi^2(1) = 304.85$, $p < .001$, a main effect of reference type, $\chi^2(1) = 211.58$, $p < .001$, and a significant interaction between the two factors, $\chi^2(1) = 57.11$, $p < .001$.

Table 7. 4 *Mean Reaction Times (ms) and Error Rates (%) by Condition in Different Trials with No Letter Repetition in the Reference*

	Target Type			
	Unique		Repeated	
Prime Type	7 letters	8 letters	7 letters	8 letters
Unrelated	878(34)	883(33)	809(22)	802(23)
Related	870(36)	876(35)	815(22)	807(23)
Priming	8(-2)	7(-2)	6(0)	5(0)

Table 7. 5 *Mean Reaction Times (ms) and Error Rates (%) by Condition in Different Trials with Letter Repetition in the Reference*

	Target Type			
	Unique		Repeated	
Prime Type	7 letters	8 letters	7 letters	8 letters
Unrelated	782(17)	761(20)	694(6)	676(6)
Related	784(19)	772(22)	682(5)	691(5)
Priming	-2(-2)	-9(-2)	12(1)	-15(1)

Discussion

In summary, the most important results in Experiment 4 were that the deletion primes produced the same priming effect to both types of targets: with and without repeated letters. Furthermore, there was no effect of target type in the response time analysis in the same trials, suggesting that both types of targets took the same time to process, therefore showing no effect of repeated letters. No difference was observed in the identity priming effects as well, suggesting that the two target types were equally prone to priming. Overall, Experiment 4 did not provide any evidence of the expected repeated letter effects.

Experiment 5: Same-Different Task with Insertions in Primes

Experiment 5 explored whether the orthographic similarity between insertion primes and targets could be affected by the status of the inserted letter (repeated vs unique). This experiment differs from previous studies with similar manipulation by the task (same-different rather than lexical decision) and the lexicality of the targets (nonwords rather than words). The aim of this experiment was to test whether the insertion prime with repeated letters would produce stronger priming effect than insertion primes with no repeated letters. This expectation was generated by the results of Experiment 2, suggesting that foils with an inserted letter already present in the target were more similar to targets than foils with an inserted letter that was not present in the target. The repetitions of letters in the insertion primes were nonadjacent with one intervening letter between the two repeated ones.

Method

Participants

Seventy-five native English speakers took part in the experiment for a small payment. The last three participants were replacements for those with low accuracy scores (correct on less than 75% of the trials), leaving data from 72 for analysis.

Materials and Design

The same set of items as those in Experiment 4 were used. However, this time the seven-letter items served as targets and references and were primed by the eight-letter items. The references and the primes were identical for the same and different trial types. There were three different prime types: A related prime, containing an insertion of a letter already present in the target (drartien-DARTIEN); a related prime, containing an insertion of letter not already present in the target (dlartien- DARTIEN); an unrelated prime (sichovue- DARTIEN). For the different trials, the alternative seven-letter version was chosen from the family set. It differed by the same trial target and the reference by only one letter (dartien-sichovue-DALTIEN).

Procedure

The procedure was identical to the one in Experiment 4.

Results

Same Trials

Response Time. Prior to the response time analyses, trials with response times faster than 150 ms and slower than 1500 ms (0.47%) and incorrect responses (7.43%) were removed. Mean response times and error rates by condition are displayed in Table 4. A linear mixed-effects model was fitted with a prime type (unrelated/ related repeat/ related unique) as a fixed effect and by-subjects and by-items intercepts and slopes for prime type as random factors (the full model). The effect of prime type was significant, $\chi^2(2) = 83.402$, $p < .001$. A post-hoc pairwise comparison between the three conditions revealed that the difference between the repeated letter related prime conditions and the unrelated prime condition was significant, $\chi^2(1) = 80.001$, $p < .001$, as was the difference between the unique letter prime and the unrelated prime, $\chi^2(1) = 47.829$, $p < .001$. The difference between the two related primes was also significant, $\chi^2(1) = 7.52$, $p = .006$, with participants responding significantly faster in the related repeat condition than in the related unique condition.

Table 7. 6 *Mean Reaction Times (ms) and Error Rates (%) by Condition for Same and Different Trials in Experiment 5*

	Trial	
	Same	Different
Prime Type		
Unrelated	656(9.0)	676(9.9)
Related repeat	618(7.1)	682(12.8)
Related unique	627(6.6)	679(11.7)
Priming repeat	38(1.9)	-6(-2.9)
Priming unique	29(2.4)	-3(-1.8)

Accuracy. For the accuracy analyses, a generalized linear mixed effects model with binomial distribution was fitted with prime type as a fixed effect and by-subjects and by-items intercepts and slopes for prime type as random effects (the full model). The effect of prime type was significant, $\chi^2(2) = 9.621$, $p = .008$. Post-hoc tests revealed that the difference between the repeated letter related prime and the unrelated prime was significantly different, $\chi^2(1) = 7.847$, $p = .005$, as was the difference between the related unique prime and the unrelated prime, $\chi^2(1) = 6.292$, $p = .012$, but not the difference between the two related prime type conditions ($\chi^2 <1$). People produced significantly fewer errors in the two related prime conditions than in the unrelated prime condition.

Different Trials

Response Time. Prior to the response time analyses, trials with response times faster than 150 ms and slower than 1500 ms (0.70%) and incorrect responses (11.21%) were removed. A linear mixed-effects model was fitted with prime type (unrelated/ related repeat/ related unique) as a fixed effect and by-subjects and by-items intercepts and by-items slopes for prime type as random factors (the by-subjects slope for prime type was dropped due to converge failure). The effect of prime type was not significant, $\chi^2(2) = 2.259$, $p = .323$.

Accuracy

For the accuracy analyses, a generalized linear mixed effects model with binomial distribution was fitted with prime type as a fixed effect and by-subjects and by-items intercepts and slopes for prime type as random effects (full model). The effect of prime type was significant, $\chi^2(2) = 12.896$, $p = .002$. Post-hoc pairwise contrasts revealed significant difference between the repeated letter related prime and the unrelated prime, $\chi^2(1) = 12.879$, $p < .001$, and between the unique related and unrelated prime, $\chi^2(1) = 4.213$, $p = .04$. The difference between the two related conditions did not reach significance, $\chi^2(1) = 2.819$, $p = .093$. People produced significantly more errors in the related prime conditions, than in the unrelated prime conditions.

Discussion

In summary, the most important finding in Experiment 5 was the stronger priming effect produced in the repeated letter condition than in the unique letter condition. To the best of our knowledge, this is the first reported case of nonadjacent repeated letter effects obtained with the masked priming paradigm.

General Discussion

The results from the present study provided mixed support for the hypothesis that the mechanisms underlying processing of repeated letters in a letter string are not the same as those of different letters. Evidence in support of this claim was obtained in the cases in which the strings with repeated letters were presented for a brief duration (Experiment 2, deletion in foils, Experiment 5, insertion in primes) or when the task involved a rapid decision of whether a briefly presented string contained one or two letters with the same identity (Experiment 2, insertions in foils). The results of these two experiments suggested that the processing system was more capable of discriminating between two strings that differed by one deleted or inserted letter if the letter was unique than if it was repeated. When a letter repetition was present, the strings were perceived as more similar to each other than the strings with no repetition. This finding was evident in the low accuracy scores in the repeated letter trials of the perceptual identification task in Experiment 2. It was also supported by the results of Experiment 5 with the stronger priming effect obtained in the repeated letter condition than the unique letter condition. This masked-primed finding suggests that the repeated letter effect was not caused by conscious strategies or biases. Furthermore, as the same-different task was used, as well as a prime presentation of 50 ms, it could be implied that the observed priming effect had a predominantly, if not solely, orthographic nature. To the best of my knowledge, there has not been a previous report of nonadjacent repeated letter effects with masked insertion primes. The apparent inconsistency between the two studies could possibly or at least partially be explained by the methodological differences between the studies. Experiment 5 used a same-different task and nonword targets while Van Assche and Grainger (2006) used a lexical decision task with word targets. It is possible that lexical factors that were eliminated in the present experiment, masked possible effects in the lexical decision study. Such an explanation is consistent with the argument of Norris et al. (2010) that the same-different task might be more sensitive to small bottom-up orthographic effects.

Although the tasks and the manipulations were different, it might seem that the findings in Experiment 5 also disagree with the results of Schoonbaert and Grainger (2004), who did not find any effect of the status of the deleted letter (repeated vs. unique) in deletion primes. However, these results, seem to be in line with the results of Experiment 4 from the present study. Although the manipulations in the Schoonbaert and Grainger's study and Experiment 4 were not entirely identical, they were conceptually similar as in both studies the primes lacked a letter from the target. The results from Experiment 4 here showed that the same deletion prime facilitates equally well the recognition of two targets, differing only by whether the missing letter in the prime was repeated in the target or not. Schoonbaert and Grainger used a within-target manipulation and found no difference between a prime with deleted repeated letter and a prime with deleted unique letter. The results from both Experiment 4 and the study of Schoonbaert and Grainger did not provide evidence of differential priming between the two conditions. However, unlike the study of Schoonbaert and Grainger, no significant target type effect was observed in Experiment 4. Targets, containing repetition did not take significantly longer to process. Unlike their study and Experiment 5, however, in Experiment 4 the strings with the repeated letters were presented unambiguously and for a long duration twice: as a reference and as a target. In the identity prime condition, the repeated letter string presentations were even three, including the masked prime as well. It is possible that the numerous presentations and their unambiguity have led to increased top down effects and decreased bottom-up effects that operate on a stage of initial perceptual uncertainty. Unlike the perceptual identification task and the lexical decision task, in the same-different task participants have a strong expectation of the target that is about to follow. Their attention has been modified by the presentation of the reference. The target's predictability is quite high, and the positions and identities of all letters have already been cued. It is therefore possible that an attention guided mechanism of serial search and spelling verification processes might have masked the effect. In layman's terms, it could be said that participants knew what to look for and where. It is therefore not straightforward to compare target type effects between these methodologies.

No evidence for repeated letter effects was provided by Experiments 1 and 3. The research question of these two experiments, however, was different from the one in the other experiments. Rather than exploring relationship involving insertion and deletion and testing how the system processes one and two occurrences of the same identity, the focus on these two experiments was on testing whether possible repeated letter effects results from increased difficulty of letter position encoding in these cases. Such an idea is consistent with the proposed identity leakage mechanism, described in Norris et al. (2010). In both experiments, it was the distance between the repeated letters rather than their number that was manipulated. Unlike the other experiments, the repeated letters were either present or absent in both strings in each condition (prime and target, Experiment 1), target and foil (Experiment 3). Experiment 1 did not show different transposed-letter priming effects for repeated letters. Similarly, Experiment 3 suggested that adjacent transpositions were equally perceptually confusing both when repeated letters were involved and when they were not. These results, therefore, did not provide evidence in support of the idea that repeated letter identities could affect the letter position encoding more than different letter identities through the leakage mechanism described in Norris et al. Furthermore, the results question the possibility that such a mechanism could by itself explain the repeated letter effects observed in Experiment 2 and Experiment 5.

One possible explanation for these findings could be that the perceptual system has a processing limitation for registering the presence of multiple occurrences of the same letter at early stages of processing. The system could perceive the two identical letters but cannot perceive that they are two, that the same letter representation is present at two different locations. Such an assumption is consistent with the repetition blindness phenomenon and the problem of registering two different tokens of the same type. Kanwisher (1987) found that participants were unable to report the second occurrence of a word from a word list in a rapid serial visual presentation (RSVP), when words were presented for a 117 ms followed by a mask and when the two occurrences were intervened by a small number of items. Since the effect was larger with a smaller number of intervenors, Kanwisher argued that the effect was not due to people forgetting the items. She also discarded the possibility that the tokens were not perceived. In Experiment 3 of her study, she demonstrated that when the word lists were truncated after the second occurrence of the repeated word, or its corresponding nonrepeated conrol word, and participants had to report the final item in lists of various length, their accuracy was higher when the final word was repeated than when it was not. Kanwisher posited that the repetition blindness phenomenon is not related to inability of recognizing the type of the occurrences, but rather to "individuating" the items as two tokens of the same type.

Two apparent differences between Kanwisher's study (1987) and the present are: the serial versus the parallel presentation of the repeated items; their scale (words vs. letters). However, the problem of perceiving several occurrences (tokens) of the same letter (type) has also been explored with a parallel presentation of letter strings containing repetitions. Mozer (1989) showed that participants were less accurate when they had to report the number of letters in a briefly presented display when a string of letters was formed by repeating the same letter (DDDD) than when it was formed by different letters (NRVT). He referred to this effect as "homogeneity effect" and argued that it is dependent on the common form of the items. He extended his findings and demonstrated that a repeated letter effect can also operate on the level of abstract letter identities. When the task required recognition of the letter identities, rather than just counting the visual objects, the number of two nonadjacent repeated letter targets presented in different case was still harder to perceive than the number of two distinct letters. Participants were less accurate when they reported the total number of As and Es in a display of two CVC strings when the display contained repeated letters (BEC mes) than when the target letters were not repeated (ner TAL). Mozer proposed a model of parallel processing of information from different visual fields. The repeated letter (homogeneity) effect is caused by spatial uncertainty and imprecision in retrieving the exact location information of the two repeated objects. As the system differentiates between the two instances of a single object by the difference in their location, in stages that have insufficient spatial information it is unable to process their number. Mozer argued that the repetition blindness phenomenon described by Kanwisher resembles the homogeneity effect in his study. The difference in the mechanisms of the two effects, according to him, were that the insufficient processing time in the rapid serial visual presentation led to inability for the events to be tagged to a temporal serial position in a sequence, while the homogeneity effect in parallel processing were caused by inefficient spatial tagging. In both cases, the information of the number of identical objects therefore could not be retrieved. Mozer also suggested that serial attentional scanning could decrease spatial uncertainty and weaken the homogeneity effect.

Taken together, the evidence provided by the results of the present study and previous studies describing similar effects suggests that the repeated letter effects observed in Experiment 2 and Experiment 5 could possibly be attributed to the inability of the visual system to register the multiple occurrences (tokens) of the same letter type under conditions of rapid visual presentation. As letters are processed in parallel (Adelman, Marquis, & Sabatos-DeVito, 2010) and positional letter information has been demonstrated to be noisy in early stages of visual word recognition (e.g., Lupker et al., 2008; Peressotti & Grainger, 1999; Schoonbaert & Grainger, 2004; Van Assche & Grainger, 2006; Welvaert et al., 2008), it is possible that the repeated letters cannot be linked to their position, the only information by which they differ, and therefore cannot be discriminated as separate tokens of the same type. Future research of the repeated letter effect with a focus on the processing of the individual repeated letters, multiple occurrences of the same letter, positional and perceptual grouping effects could further help the understanding of the underlying mechanisms of processing letter repetitions. The future research possibilities will be further discussed in the final chapter of the thesis.

Chapter 8

Conclusion

This thesis explored two different aspects in orthographic processing in word recognition. The first part of the thesis reflected on processes typically associated with the lexical level while the second part focused on prelexical stages and letter level processing. The exploration of the lexical effects began with revision of the lexical competition hypothesis that suggests that the process of word recognition is mediated by competitive mechanisms among the considered word candidates. The studies in Chapter 3 and Chapter 4 employed the masked-priming technique commonly used in exploring similarities between the orthographic code between two letter strings. The argument that the observed priming effect is not a function of simply the form similarities between the prime-target pair but also the similarities of the pair to other word representations in the mental lexicon (e.g., Davis, 2003; Grainger & Jacobs, 1993; Lupker & Davis, 2009) was carefully explored.

The study in Chapter 3 (Trifonova & Adelman, 2018) tested the argument of Lupker and Davis (2009) that modifying the original masked-priming methodology by presenting the target before the prime would filter out the prime-target resemblance to other competitors, thus enabling a clear evaluation of the similarity between the two strings. With sandwich priming, according to Lupker and Davis, primes moderately similar to the target will produce facilitation effects as counteractive competition mechanisms will be reduced by the target preprime presentation. Evidence was presented that ruled out this account of the sandwich priming boost. In Experiment 2 of the study, the priming effect in a sandwich priming condition with a competitor word preprime remained in the same direction and was comparable to the facilitation effect in the target-prime-target sandwich condition. This finding was not predicted by Davis's competitive network model (Davis, 2010) which suggested that an inhibitory priming effect should be observed once a high-frequency shared-neighbor word is presented before the prime in the masked-priming methodology. In a competitive network account, such word preprimes should introduce a strong competition and therefore delay the target recognition due to their high word frequency and shared orthographic neighborhood with both the prime and the target. In such shared-neighborhood scenario, the competitor's activity is supported by the whole prime-target pair.

Arguably, even stronger evidence against the sandwich priming account of Lupker and Davis (2009) was provided by the results of Experiment 3 in which the competitor preprime boosted the priming effect of a transposed-all prime in a way comparable to the sandwich priming boost in the target preprime condition. A significant facilitation effect was observed in the competitor preprime condition, which was not present in the conventional masked-priming condition. These results suggest that decreased lexical competition is not the underlying mechanism of the sandwich priming technique. Findings obtained with this technique should therefore be reevaluated and discussed in terms of processes other than reduction of lexical competition. The results reported in Chapter 3 have important methodological as well as theoretical implications for research of orthographic processing and possibly for developing theories for more general cognitive processes in the visual domain. Such findings imply that the visual system is capable of extracting consistent information and is facilitated in the process of recognition when two similar strings are rapidly presented before the target. Further investigation of the flexibility of the visual system regarding the degree of deviation from consistency in the visual events (preprime-prime-target) might be warranted. Other interesting direction for future research might be comparison of the sandwich priming effect in different preprime lexicality conditions that could provide further support of a prelexical locus of the sandwich priming boost.

Chapter 4 continued the exploration of the lexical competitor effects and the mechanisms underlying information processing in the sandwich priming technique. Unlike the study in Chapter 3, however, the design in the experiments described in Chapter 4 replaced the position of the competitor neighbor word which was always presented as a prime and was directly followed by the target. The effect of the competitor prime was compared in three conditions: conventional priming, sandwich priming and a modified sandwich priming in which the preprime was an unrelated word. Although there was a trend towards a sandwich boost in the sandwich priming condition, the results did not indicate differential priming between the three preprime conditions. The most striking result was, however, the lack of inhibitory effect produced by a neighbor word prime to the target. This effect was not observed in two experiments thus questioning the robustness of the effect in general.

To the best of my knowledge, there have not been reported inhibitory effects of related word preprimes or primes in comparison to an unrelated condition in a sandwich priming paradigm. The motivation behind designing the sandwich priming paradigm was the inefficiency of primes moderately related to targets in producing significant facilitation effect. That this inefficiency was due to counteractive lexical competition processes was an untested assumption of Lupker and Davis (2009). Assuming that such inhibitory processes do take place and could be observed in a procedure with two masked events before the target presentation, one possible explanation for the lack of inhibitory effects in the studies of Chapter 3 and Chapter 4 might be the insufficient prime duration (50 ms) for lexical competition processes to take place and a robust inhibitory effect to be obtained. An even more stringent test for the mechanisms underlying sandwich priming and the lexical competition hypothesis in general might be investigating priming effects in different preprime-prime duration ratios. As already noted, direct lexicality comparisons could also be informative.

The second part of the thesis focused on bottom-up aspects in lexical selection and letter processing in word recognition. The study in Chapter 6 used the regression approach on big data and researched the underexplored area of letter repetitions in word identification. Care was taken to include important control variables in the regression models in order to isolate the unique effect of the variables under investigation. The results showed that the variables encoding the presence of letter repetitions in words accounted for additional unique variance in the reaction times of lexical decision and word naming tasks after important controls were included in the models. There was an inhibitory effect of letter repetition that was most robustly observed when the repeated letters occurred in close proximity but not in immediate adjacency to each other. These results were replicated with two different English databases (the English and British Lexicon Projects; Balota et al., 2007; Keuleers, Lacey, Rastle, & Brysbaert, 2012), as well as with Dutch and French databases (Brysbaert, Stevens, Mandera, & Keuleers, 2016; Ferrand et al., 2010). These inhibitory patterns were not captured by two models of visual word recognition both based on the Interactive Activation model (McClelland & Rumelhart, 1981), but encoding letter position and identity in a conceptually different way. The local-context specific open-bigram model of Grainger and van Heuven (2003) correctly predicted an inhibitory effect but overestimated this effect in the adjacent repeated conditions and underestimated it in the nonadjacent repeated conditions. The context-independent Spatial Coding Model (Davis, 2010) did not predict the inhibitory pattern observed in the empirical results.

The problem of repeated letter effects was further explored in Chapter 7 with a factorial approach. The goal of this study was to replicate the findings in Chapter 6 that suggested differential processing of repeated letter and unique letter identities in word identification. The study also aimed to resolve previous empirical inconsistencies and providing more evidence regarding the underlying mechanisms of the repeated letter effects. The study comprised of five different experiments employing different experimental paradigms. Repeated letter effects were observed in two of the experiments with different paradigms. They were evident in the lower accuracy results in the repeated condition in a two-forced-choice perceptual identification task. In this task, a repeated or unique letter was either inserted in or deleted from the foil. The results suggested that it was easier for the participants to notice that there was a missing or an extraneous letter when the letter was unique than when it was repeated. A repeated letter effect was also observed in masked-priming same different task in which an insertion prime produced a stronger priming effect when the inserted letter was already in the target (and thus formed a nonadjacent repetition) than when the inserted letter was not present in the target (the unique condition). These results extended previous findings of lower accuracy in perception of strings containing letter repetitions than strings without letter repetitions (Gomez et al. 2008) with insertions and deletions manipulation and different target-foil length. They contradicted previously reported null results with masked priming with nonadjacent repetition in insertion primes (Van Assche & Grainger, 2006) and extended masked priming results suggesting differential processing of repeated adjacent letters to different letters (Norris et al. 2010). One could argue that these findings were not in accordance with the null results reported with deletion primes by Schoonbaert and Grainger (2004). However, in a conceptually similar manipulation, differential priming effects were also not observed when the repeated letter condition did not reflect repetition in the prime (Experiment 4). Repeated letter effects were also not observed when the manipulations included transposition of the repeated letters (Experiment 1 and 3).

Taken together, the evidence provided in Chapter 6 and Chapter 7 hints at an explanation reflecting limitations of the processing system in perceiving multiple letter tokens of the same type at early stages of processing. Such an explanation is in accordance with findings of tachistoscopic letter identification studies (Bjork & Murray, 1977; Egeth & Santee, 1981) demonstrating interference in cases of processing two identical letters in a visual array, the study of Mozer (1989) demonstrating lower accuracy in evaluation of numerosity of letters in cases of repetitions, and resembles the explanation of cognitive phenomena observed in rapid serial visual presentation (Kanwisher, 1987). Open questions include performance of the perceptual system in conditions with more than two occurrences of letter tokens in strings as well as effects of adjacency (perceptual grouping), distance between the repetitions, as well as letter positions. Such an explanation for the observed inhibitory repeated letter effects in Chapter 6 and the repeated letter effects in Chapter 7 might motivate incorporating token count mechanisms in models of visual word recognition. A similar proposal was recently made by

Houghton (2018). Such mechanisms should be associated with some degree of delay in the perception of multiple occurrences of the same type.

The explanation of the repeated letter effects observed in the studies of this thesis, such as lack of perception that there were more than one instances of the same letter in initial stages of word recognition, is inconsistent with the understanding of priming effects in terms of similarities between the prime-target pair, or similarities between the prime-target pair as well as similarities between the pair and other lexical units. Therefore, this explanation is not in accordance with standard interactive activation accounts of priming effects. In these accounts, the priming effect is predicted by a match score that measures the degree of the orthographic consistency (similarity) between the prime and the target. The present argument suggests that the stronger priming effect observed in the repeated letter insertion conditions in Chapter 7 was not necessarily due to the stronger orthographic consistency and higher match score between the prime-target pair in the repeated letter condition than in the unique letter condition. An alternative explanation of the effect in terms of processing limitations is also possible. This result might as well be observed due to misperception of the inconsistent information (rather than perception of the consistent information) in the prime. Such misperception would result in less inhibition and therefore larger effect of facilitation in the repeated letter condition than in the unique letter condition in which the inconsistent information was easier to be perceived.

As already discussed, the IA model is “a powerful theoretical framework” for the visual word recognition field. Its legacy is evident in the ample research motivated by the model’s assumptions and predictions. It can also be seen in the core architecture of some of the most prominent models of visual word recognition. Some of the model’s assumptions, however, have proven to be oversimplifications that are not consistent with real empirical data. An example of such an oversimplification is the IA model’s position specific encoding scheme, which disagrees with evidence suggesting considerable degree of positional intolerance of the perceptual system at early recognition stages. The findings presented in this thesis suggest that the IA based localist hierarchical models might be oversimplifying perceptual process in word identification by implementing them through means of gradual increase of the activity of corresponding representations. These models do not assume any processing limitations and do not include implementations of mechanisms in which the information regarding processing representations could be misperceived or lost. For example, it is assumed that all letter identity information in the input should be taken into consideration and are eventually perfectly encoded. When information is weak it is nevertheless accurate. This assumption might deviate from the actual processing mechanisms of the visual system which might be limited in early perceptual stages. Such limitations might be observed, for example, in cases of rapid processing of similar or even identical information. It might be the case that at such stages some of the information could not be extracted or measured quantitatively and is lost or synthesized. Such an account is consistent with the sandwich priming boost described in Chapter 3 in which three similar visual events lead to faster performance than different visual events even in conditions in which the competitive account predicted significant delays in the similar condition. Evidence consistent with the suggested imprecision of the visual system in quantitative evaluation of the visual information was provided by the studies exploring repeated letter effects. The results of the studies in this thesis are therefore suggestive that accounts of visual word recognition need to consider mechanisms of misperception and processing limitations of the visual system.

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Appendix

A Stimuli in Experiment 1 Chapter 3

1-LD	2-LD	3-LD	4-LD	5-LD	7-LD	Target	Competitor
			Word Trials				
axticle	axbicle	axbvcle	axbvwle	axbvwhe	nxbvwhm	ARTICLE	ARTISTE
csbinet	cslinet	cslwnet	cslwvet	cslwvxt	rslwvxk	CABINET	CABARET
cvreful	cvmeful	cvmsful	cvmsdul	cvmsdxl	wvmsdxk	CAREFUL	CARAMEL
czntral	czwtral	czwkral	czwkmal	czwkmsl	vzwkmsb	CENTRAL	CONTROL
cdapter	cdnpter	cdnqter	cdnqfer	cdnqfmr	wdnqfmz	CHAPTER	CHARTER
cbimate	cbwmate	cbwvate	cbwvste	cbwvsfe	nbwvsfn	CLIMATE	COINAGE
cvstume	cvxtume	cvxkume	cvxknme	cvxknze	wvxknzw	COSTUME	CONSUME
cvunter	cvxnter	cvxmter	cvxmker	cvxmkzr	svxmkzs	COUNTER	CLUSTER
cnurage	cnwrage	cnwvage	cnwvmge	cnwvmqe	xnwvmqs	COURAGE	COINAGE
dslight	dsfight	dsfxght	dsfxyht	dsfxybt	ksfxybk	DELIGHT	DEFIANT
dvstroy	dvctroy	dvckroy	dvckmoy	dvckmxy	fvckmxp	DESTROY	DESTINY
dmsplay	dmvplay	dmvglay	dmvgfay	dmvgfxy	hmvgfxj	DISPLAY	DISOBEY
fzctory	fzwtory	fzwdory	fzwdsry	fzwdsny	lzwdsnj	FACTORY	FANTASY
fwculty	fwxulty	fwxslty	fwxshty	fwxshky	bwxshkp	FACULTY	FALSITY
fmshion	fmvhion	fmvkion	fmvkcon	fmvkcxn	bmvkcxw	FASHION	FACTION
fwreign	fwzeign	fwzvign	fwzvmgn	fwzvmqn	dwzvmqc	FOREIGN	FOREMAN
fxrgive	fxsgive	fxspive	fxspmve	fxspmce	txspmcw	FORGIVE	FORGAVE
fnrmula	fnvmula	fnvwula	fnvwzla	fnvwzda	knvwzds	FORMULA	FERRULE
fsrtune	fsmtune	fsmdune	fsmdcne	fsmdcwe	hsmdcwv	FORTUNE	FORGONE
fxneral	fxveral	fxvzral	fxvzsal	fxvzscl	kxvzsct	FUNERAL	FEDERAL
hzliday	hztiday	hztrday	hztrkay	hztrkny	bztrknp	HOLIDAY	HALFWAY
hzstile	hzntile	hznkile	hznkvle	hznkvbe	dznkvbw	HOSTILE	HOSTAGE
hvsband	hvxband	hvxkand	hvxkwnd	hvxkwmd	lvxkwml	HUSBAND	HOLLAND
icprove	icjrove	icjwove	icjwxve	icjwxze	scjwxzs	IMPROVE	IMPLORE
imclude	imzlude	imztude	imztsde	imztshe	wmztshw	INCLUDE	INCLINE
jvurney	jvxrney	jvxzney	jvxzmey	jvxzmsy	pvxzmsg	JOURNEY	JOINERY
jnstice	jnrtice	jnrdice	jnrdvce	jnrdvxe	gnrdvxw	JUSTICE	JASMINE
kvngdom	kvrgdom	kvrpdom	kvrphom	kvrphxm	tvrphxw	KINGDOM	GINGHAM
krtchen	krdchen	krdxhen	krdxlen	krdxlsn	frdxlsw	KITCHEN	KINSMEN
mvchine	mvshine	mvsdine	mvsdxne	mvsdxre	wvsdxrw	MACHINE	MACHETE
mwdical	mwtical	mwtvcal	mwtvxal	mwtvxnl	rwtvxnf	MEDICAL	MAGICAL
mxsical	mxvical	mxvncal	mxvnzal	mxvnzwl	rxvnzwk	MUSICAL	MARITAL
nxtwork	nxhwork	nxhzork	nxhzsrk	nxhzsvk	mxhzsvf	NETWORK	NEWBORN
pvyment	pvqment	pvqrent	pvqrwnt	pvqrwzt	gvqrwzf	PAYMENT	PATIENT
pvcture	pvnture	pvnkure	pvnkwre	pvnkwze	qvnkwzs	PICTURE	PASTURE
phastic	phwstic	phwntic	phwndic	phwndvc	yhwndvr	PLASTIC	PHALLIC

pxverty	pxwerty	pxwzrty	pxwznty	pxwznhy	qxwznhg	POVERTY	PUBERTY
pwoduce	pwxduce	pwxluce	pwxlsce	pwxlsve	jwxlsvn	PRODUCE	PROCURE
pxoduct	pxvduct	pxvkuct	pxvkwct	pxvkwzt	qxvkwzl	PRODUCT	PREDICT
pvoject	pvnject	pvnqect	pvnqsct	pvnqsmt	gvnqsmf	PROJECT	PROTECT
pxomise	pxwmise	pxwvise	pxwvcse	pxwvcze	jxwvczn	PROMISE	PREMISE
pvotein	pvmtein	pvmfein	pvmfsin	pvmfszn	qvmfszc	PROTEIN	PROTEAN
psovide	psnvide	psnmide	psnmzde	psnmzte	ysnmztx	PROVIDE	PRESIDE
qvality	qvslity	qvsfity	qvsfmty	qvsfmky	gvsfmkj	QUALITY	QUALIFY
rcspond	rcwpond	rcwjond	rcwjznd	rcwjzxd	vcwjzxh	RESPOND	RESOUND
rxutine	rxwtine	rxwdine	rxwdzne	rxwdzse	vxwdzsm	ROUTINE	RAGTIME
scrvant	scmvant	scmzant	scmzwnt	scmzwct	xcmzwcd	SERVANT	SERPENT
sxldier	sxtdier	sxtkier	sxtkver	sxtkvwr	nxtkvwc	SOLDIER	SILLIER
sdomach	sdzmach	sdzrach	sdzrwch	sdzrwnh	vdzrwnk	STOMACH	SPINACH
Shorage	shwrage	shwcage	shwcvge	shwcvye	xhwcvyn	STORAGE	SALVAGE
swrface	swmface	swmhace	swmhxce	swmhxze	nwmhxzn	SURFACE	SUFFICE
tciumph	tcvumph	tcvsmph	tcvswph	tcvswyh	bcvswyl	TRIUMPH	TALLISH
tzouble	tzvuble	tzvxble	tzvxfle	tzvxfhe	dzvxfhs	TROUBLE	TREMBLE
tjpical	tjqical	tjqvcal	tjqvral	tjqvrsl	hjqvrsd	TYPICAL	TOPICAL
uviform	uvwform	uvwhorm	uvwhxrm	uvwhxsm	cvwhxsz	UNIFORM	UNICORN
ujright	ujcight	ujcvght	ujcvyht	ujcvyft	xjcvyfk	UPRIGHT	UPTIGHT
vsriety	vsziety	vszmety	vszmwty	vszmwky	nszmwkg	VARIETY	VARSITY
vzrsion	vzcsion	vzcmion	vzcmwon	vzcmwzn	xzcmwzx	VERSION	VENISON
vwctory	vwstory	vwskory	vwskxry	vwskxny	mwskxnj	VICTORY	VICEROY
wvrship	wvnship	wvnchip	wvnclip	wvnclzp	xvnclzq	WORSHIP	WARSHIP
			Nonword Trials				
twobide	twmbide	twmhide	twmhzde	twmhzfe	lwmhzfx	TROBIDE	TRYBIDE
vsdilar	vshilar	vshzlar	vshztar	vshztmr	nshztmx	VIDILAR	VIDIJAR
lstchen	lsdchen	lsdwhen	lsdwfen	lsdwfxn	ksdwfxr	LETCHEN	LETXHEN
dzpimal	dzyimal	dzynmal	dzynxal	dzynxsl	hzynxsf	DAPIMAL	DJPIMAL
svralge	svnalge	svnzlge	svnzhge	svnzhje	wvnzhjm	SCRALGE	SCRAKGE
dwrplex	dwmplex	dwmjlex	dwmjbex	dwmjbcx	fwmjbcn	DORPLEX	DOKPLEX
dsfture	dskture	dskbure	dskbwre	dskbwne	hskbwnz	DIFTURE	DIFTULE
wzrbace	wzvbace	wzvhace	wzvhnce	wzvhnme	xzvhnmx	WURBACE	WURBAME
onelage	onclage	oncfage	oncfwge	oncfwje	mncfwjz	OVELAGE	OVELAGC
psurcil	pszrcil	pszmcil	pszmwil	pszmwvl	gszmwvd	POURCIL	POURGIL
bslerce	bsderce	bsdwrce	bsdwxce	bsdwxne	hsdwxnv	BILERCE	BILEWCE
sbuvent	sbrvent	sbrxent	sbrxznt	sbrxzmt	wbrxzmk	SLUVENT	SLUKENT
fwrbose	fwmbose	fwmhose	fwmhcse	fwmhcve	lwmhcvx	FURBOSE	FUQBOSE
bvferce	bvkerce	bvkxrce	bvkxzce	bvkxzne	dvkxzns	BEFERCE	BEFEWCE
kslefit	ksbefit	ksbxfit	ksbxhit	ksbxhrt	dsbxhrd	KELEFIT	KELEXIT
asprain	asyrain	asyzain	asyzwin	asyzwmn	csyzwmc	AXPRAIN	AXPCAIN
txpular	txjular	txjmlar	txjmhar	txjmhwr	fxjmhws	TEPULAR	TQPULAR
sboromy	sbxromy	sbxvomy	sbxvnmy	sbxvncy	wbxvncp	STOROMY	STOPOMY

dxanity	dxvnity	dxvsity	dxvswty	dxvswhy	fxvswhg	DEANITY	DEANFTY
frlance	frtance	frtvnce	frtvsce	frtvswe	drtvswx	FOLANCE	FOLGNCE
bxdital	bxfital	bxfstal	bxfshal	bxfshzl	kxfshzk	BEDITAL	BEDIFAL
swnfact	swzfact	swzhact	swzhmct	swzhmvt	xwzhmvb	SONFACT	SJNFACT
mzverop	mzwerop	mzwsrop	mzwscop	mzwscxp	nzwscxy	MEVEROP	MEVEROK
dsrfelt	dszfelt	dszkelt	dszkclt	dszkcbt	hszkcbh	DERFELT	DERFEVT
avagour	avcgour	avcqour	avcqzur	avcqzxr	svcqzxw	AMAGOUR	ABAGOUR
bslefom	bshefom	bshvfom	bshvtom	bshvtwm	dshvtwc	BOLEFOM	DOLEFOM
cmlpete	cmfpete	cmfqete	cmfqste	cmfqshe	wmfqshx	CALPETE	CAHPETE
cfonity	cfrnity	cfrwity	cfrwsty	cfrwsky	xfrwskp	CHONITY	CVONITY
cvdselt	cvkselt	cvkzelt	cvkzrlt	cvkzrht	wvkzrhb	CODSELT	CWDSELT
etkeror	etderor	etdwror	etdwxor	etdwxmr	stdwxmv	ELKEROR	EFKEROR
fmlpion	fmdpion	fmdqion	fmdqvon	fmdqvrn	hmdqvrw	FILPION	FILPIHN
hvlbony	hvfbony	hvftony	hvftrny	hvftrzy	dvftrzj	HALBONY	HALBVNY
iwbelse	iwtelse	iwtzlse	iwtzdse	iwtzdxe	cwtzdxn	IMBELSE	IMBETSE
lmdance	lmfance	lmfwnce	lmfwrce	lmfwrxe	hmfwrxs	LIDANCE	LTDANCE
mvfster	mvdster	mvdcter	mvdcker	mvdckzr	wvdckzn	MAFSTER	MLFSTER
nxrvral	nxzvral	nxzmral	nxzmsal	nxzmscl	wxzmscf	NERVRAL	NERVRQL
pxdefic	pxkefic	pxkwfic	pxkwlic	pxkwlrc	jxkwlrs	PADEFIC	PYDEFIC
pzvulty	pzculty	pzcxlty	pzcxbty	pzcxbfy	jzcxbfj	PEVULTY	PEVUDTY
pselacy	pswlacy	pswfacy	pswfzcy	pswfzvy	gswfzvj	PRELACY	PFELACY
rcdival	rchival	rchwval	rchwnal	rchwnsl	xchwnsb	REDIVAL	REDIVWL
syorvet	sywrvet	sywzvet	sywzcet	sywzcnt	xywzcnh	SPORVET	SPORVGT
snvitor	sncitor	sncxtor	sncxdor	sncxdmr	wncxdmz	SEVITOR	SEVWTOR
tcamial	tcwmial	tcwsial	tcwszal	tcwszvl	kcwszvb	TRAMIAL	TRABIAL
wkasber	wkmsber	wkmvber	wkmvter	wkmvtnr	ckmvtnc	WHASBER	WHASBQR
egilade	egmlade	egmfade	egmfwde	egmfwte	xgmfwtn	EPILADE	EPIGADE
syueane	syweane	sywrane	sywrmne	sywrmve	xywrmvz	SQUEANE	SQBEANE
tnshure	tnxhure	tnxbure	tnxbmre	tnxbmce	fnxbmcw	TOSHURE	TOSDURE
oxlbard	oxkbard	oxkhard	oxkhwrd	oxkhwvd	nxkhwvt	OULBARD	OULBXRD
tlagger	tlmgger	tlmqger	tlmqjer	tlmqjwr	klmqjwv	THAGGER	THASGER
sralven	srxlven	srxtven	srxtzen	srxtzcn	mrxtzcm	SWALVEN	SWAQVEN
mnbical	mnfical	mnfscal	mnfsval	mnfsvxl	wnfsvxt	MABICAL	MABICFL
gvemmar	gvsmmar	gvswmar	gvswcar	gvswcxr	qvswcxn	GREMMAR	GNEMMAR
qxandel	qxcndel	qxcvdel	qxcvkel	qxcvkzl	yxcvkzb	QUANDEL	QUAFDEL
mwrfory	mwcfory	mwctory	mwctzry	mwctzsy	xwctzsq	MERFORY	MERFORD
ovatelf	ovctelf	ovchelf	ovchxlf	ovchxdf	mvchxdb	ONATELF	OGATELF
cwngarm	cwxgarm	cwxparm	cwxpsrm	cwxpszm	vwxpszv	CONGARM	COQGARM
crndial	crvdial	crvhial	crvhsal	crvhszl	xrvhszb	CONDIAL	CONDIXL
grbadic	grladic	grlvdic	grlvkic	grlvkwc	prlvkwn	GEBADIC	GEBADIW
cxnvent	cxsvent	cxswent	cxswznt	cxswzmt	rxswzmk	CANVENT	CGNVENT
dvflare	dvhlare	dvhtare	dvhtnre	dvhtnwe	kvhtnwc	DEFLARE	DMFLARE

(Appendixes continue)

B Stimuli in Experiment 2 Chapter 3

Related prime competitor	Unrelated prime competitor	Related prime identity	Unrelated prime identity	Related prime no	Unrelated prime no	Target	Competitor
			Word Trials				
aqound	vfxwyi	apound	clqezw	azound	wlyvxe	ABOUND	AROUND
aczing	wrpqlj	acqing	xsmuob	acring	qjovwr	ACHING	ACTING
arjful	ponqdh	arwful	ipbowg	ariful	cjzkgw	ARTFUL	ARMFUL
lanish	woledz	danish	rkmedo	uanish	jpmowr	BANISH	VANISH
bfards	tyhzql	bgards	jzylmc	bhards	lkizwy	BEARDS	BOARDS
ieckon	gtyliv	deckon	sjdthy	weckon	tispaw	BECKON	RECKON
bkeach	kzdmgn	bveach	kiufos	bfeach	vjgmwq	BLEACH	BREACH
bridfe	uxcnow	bridae	cmqzyj	bridfe	asoxkv	BRIDLE	BRIDGE
aruise	zymhvx	aruise	xhzjlp	jruise	dojqvk	BRUISE	CRUISE
iandle	urzkgb	jandle	ptjvyk	qandle	ywtmzf	CANDLE	HANDLE
iasket	uoqdgp	zasket	vowlhr	xasket	duhrwx	CASKET	BASKET
chagts	iljzbv	chavts	mybfdl	chadts	efgqwj	CHANTS	CHARTS
chiues	lugqbk	chines	rpdfnk	chiwes	fodaxw	CHIVES	CHIMES
plawed	nrmgsj	blawed	yxzijq	slawed	yoikzq	CLAWED	FLAWED
cxowns	dhtmxe	ceowns	fyxizm	ceowns	dfgixj	CLOWNS	CROWNS
coajed	rbfqlu	coaved	zujnwr	coaqed	fjgsnz	COAXED	COATED
qoward	unvipj	goward	gufsjy	eoward	sgqpuv	COWARD	TOWARD
xringe	bmtpju	bringe	lbxzov	bringe	aqjpmx	CRINGE	FRINGE
devths	lnibxr	dekths	fbjorv	devths	ybmfjn	DEPTHS	DEATHS
ezotic	bjpdyw	eyotic	lwjqup	eaotic	uqgwln	EROTIC	EXOTIC
flgshy	txujqz	flushy	rtogiv	flmshy	dtcpbn	FLASHY	FLESHY
gvants	lukzef	gxants	bkjdox	gyants	mcojlz	GIANTS	GRANTS
glopes	irnwtm	gloxes	pnywmq	glotes	xkcunj	GLOBES	GLOVES
grapts	ljdimz	grapks	xwcmfq	grapns	kwvufj	GRAPHS	GRAPES
vockey	qugrdl	nockey	lvnfud	qockey	pltgzm	JOCKEY	HOCKEY
eoints	gckzrb	koints	mfdyrk	loints	eqdhuy	JOINTS	POINTS
kemons	cuwzqp	gemons	rapbzx	uemons	pkxzvc	LEMONS	DEMONS
sizard	nktuoq	oizard	nfbejq	gizard	yfuobe	LIZARD	WIZARD
malure	zwfpil	mazure	gvzpkj	mabure	gqjcfl	MANURE	MATURE
lighty	jpofdx	aighty	qjzxcp	vighty	pkajbw	MIGHTY	EIGHTY
nivels	ugqimt	npvels	bzdyrg	nrvels	dqymir	NAVELS	NOVELS
noxice	ghdjak	noaice	fdaqhy	nowice	gpmalx	NOVICE	NOTICE
paiced	buyjfx	paised	wcvhft	paiwed	oxsfwh	PAIRED	PAINED
pbrish	jzyxbv	pmrish	junokv	pcrish	xjluoq	PERISH	PARISH
placsd	bxsjtu	plackd	ouyqth	placud	qmufyw	PLACID	PLACED

plazue	tszrfi	plamue	rcksby	platue	vtbywo	PLAQUE	PLAGUE
pzrtly	gzicuj	pkrtly	wgnecu	pgrtly	cqhjuz	PORTLY	PARTLY
rounce	ydlzgw	gounce	xhwryv	dounce	khrsgi	POUNCE	BOUNCE
sreach	vmiodl	yreach	sfowvn	vreach	lgjzwd	PREACH	BREACH
quotps	kgilrf	quotfs	dylfcr	quotrs	dliymr	QUOTAS	QUOTES
vesign	wzyout	qesign	lmtcaw	fesign	ywpzlo	RESIGN	DESIGN
sjmple	cdfgbh	swmple	krwdoq	scmple	hrxfjb	SAMPLE	SIMPLE
janity	mjgpdq	canity	mczwep	ganity	rojkup	SANITY	VANITY
sxrawl	zgnbhi	smrawl	megdiy	sjrawl	bgdmjk	SCRAWL	SPRAWL
shrinc	czdyvp	shriny	wfzayd	shrinq	pczavy	SHRINE	SHRINK
sgiver	jcfaqb	sniver	ywpqug	suiver	qzwbmd	SLIVER	SHIVER
spiwal	cyuvzw	spihal	edtmzq	spifal	zvwyjh	SPINAL	SPIRAL
spaint	wyqgab	speint	bjzwac	spaint	huckda	SPLINT	SPRINT
squear	zpgjdb	squeab	yjvpgr	squeaw	nbrxgc	SQUEAL	SQUEAK
squikt	mhlzgk	squilt	czfjew	squimt	jwmhva	SQUINT	SQUIRT
smarch	jidbxl	snarch	oyqbkx	sbarch	jwdzuo	STARCH	SEARCH
steafy	vzhoix	steahy	vpcgwl	steaoy	hofblg	STEAMY	STEADY
uneaid	jbtwmy	unwaid	kvzqrm	unoaid	wrjvol	UNSAID	UNPAID
urable	tdikyr	uyable	djzmpf	uvable	qyxjik	USABLE	UNABLE
gaults	edcwhj	iaults	kqocdg	paults	rdyiok	VAULTS	FAULTS
bortex	qfdpnu	fortex	izdhaw	lortex	akzfdp	VORTEX	CORTEX
wrevch	oxyqdi	wreqch	ujibfs	wreich	qaljyi	WRETCH	WRENCH
pouths	pxqcwk	rouths	ngvxbw	gouths	rwpbzl	YOUTHS	MOUTHS
savern	ihygpq	bavern	ubqfpl	savern	zlsjky	CAVERN	TAVERN
revtal	sjkmqp	reztal	ygqowz	rejtal	qpsivu	RECTAL	RENTAL
soream	qwoylv	soream	jhliup	sjream	zxudlh	SCREAM	STREAM
xorbid	thjzvn	jorbid	qskhcw	porbid	gpzvcx	FORBID	MORBID
merbal	ikqmou	werbal	ignfod	uerbal	ofwczg	HERBAL	VERBAL
aermit	sojbgd	fermit	vjgzxw	zermit	nfxoqa	HERMIT	PERMIT
vowled	ypafix	vowled	pcrjgq	cowled	mujvxr	HOWLED	BOWLED
qegion	sjzhpb	tegion	vcqshz	tegion	svzcbx	LEGION	REGION
suxked	tphjvz	sugked	prownv	suqked	bamqvz	SULKED	SUCKED
chails	bujwty	chaims	wvxoyp	chaibs	kvgtbd	CHAINS	CHAIRS
pistou	kuhdxj	pistou	xwjgch	pistox	zwqmju	PISTON	PISTOL
stafle	ydhcoi	stawle	hqgrfu	stajle	dwnmch	STAPLE	STABLE
trisle	dykhgo	triule	xhbvcn	trizle	kwhdab	TRIPLE	TRIFLE
raniom	qhwgex	rangom	lfiuxz	ranwom	tybqiz	RANSOM	RANDOM
deqour	gaxnlm	deiour	lxsnfq	dekour	yxcbpw	DETOUR	DEVOUR
gailor	egpwkj	failor	ebhypk	cailor	vuhekg	TAILOR	SAILOR
mildeu	uvabnt	mildeb	unyqkz	milden	scgjop	MILDEW	MILDER
outlar	ikrxvf	outlad	gepcsq	outlaf	rxcnsz	OUTLAW	OUTLAY
qreath	ouyxml	ireath	uldcog	kreath	jfivnx	WREATH	BREATH

convep	mldkpr	convek	jbadzg	convei	kfgald	CONVEX	CONVEY
Nonword Trials							
avouse	wjvfic	alouse	xikyqc	abouse	ctkwhy	ANOUSE	AROUSE
enuing	lqjrzw	enming	vpqslk	enting	txkfyr	ENCING	ENDING
aktral	gkjhwc	aftral	npzyqd	aitral	fjnwpo	ARTRAL	ASTRAL
canide	hdxjtw	caniye	ydlukg	caniqe	vmguly	CANISE	CANINE
pealms	tqnzgu	uealms	fivwyg	uealms	cpxqfh	BEALMS	REALMS
cuckoi	bpxyam	cuckor	vfthag	cuckoi	hprxtw	CUCKON	CUCKOO
bzeaks	umniyo	bqeaks	nmjztq	boeaks	ygwtqo	BLEAKS	BREAKS
fwible	dzcasq	fcible	jwchtu	fvible	swhtnj	FLIBLE	FOIBLE
sluike	mnwopd	sluioe	pthmok	sluiwe	bqpgvf	SLUISE	SLUICE
garble	yhzsun	varble	fxkdyj	harble	wyogdj	CARBLE	MARBLE
caghet	fuxwgs	caohet	dorfbn	cadhet	wrxqno	CAMHET	CACHET
jhatch	xnlrgs	ehatch	ypzwib	ghatch	gmsuvn	CHATCH	THATCH
chrsts	opkyrl	chosts	qjowud	chfsts	nuwvrj	CHISTS	CHESTS
cldtch	vnezxd	clvtch	ibmqjr	clvtch	jxgsvr	CLATCH	CLUTCH
clohds	wyjveq	clovds	vbnejw	clonds	yhtfik	CLOLDS	CLOUDS
koathe	zyvrgp	voathe	idxwjg	goathe	ufyzvj	COATHE	LOATHE
cqrate	kzysiv	cmrate	gbsdzm	cmrate	qwgidy	CORATE	CURATE
zrithe	dobfpv	drithe	jgyxob	brithe	ksjmpl	CRITHE	WRITHE
mength	akxfrc	pength	bmayox	iength	iuobrw	DENGTH	LENGTH
etxnic	xplgra	etwnic	xsofga	etjnic	davqsr	ETUNIC	ETHNIC
suandy	oefmtc	sfandy	bzxljt	slandy	tjzoev	SPANDY	SHANDY
wivlds	kgymox	wiqlds	jrcqmn	wiglds	ogkmbh	WIALDS	WIELDS
zrobes	nyxdlg	zrobes	uyikgf	xrobes	nzajqk	WROBES	PROBES
gracns	wtpeom	graons	lvxpbh	grakns	yzjfpt	GRAUNS	GRAINS
fickey	oaslud	oickey	arwobs	jickey	jwgsuq	VICKEY	MICKEY
wonths	qvrxdf	qonths	xdqicp	donths	xyikcl	JONTHS	MONTHS
iepots	fhcugq	qepots	hyawkg	cepots	bxgauh	LEPOTS	DEPOTS
cazard	ymsgln	iazard	tyuomk	nazard	mbiygj	FAZARD	HAZARD
manogs	ldbfzh	manofs	dcqhwz	manohs	huyvxg	MANOPS	MANORS
corthy	jslqbc	corthy	ueqpln	vorthy	zdbgqn	MORTHY	WORTHY
wanals	ygkrzd	xanals	oqpbuw	zanals	vudqkz	NANALS	CANALS
xevile	ykmfzd	kevile	qtsgfp	aevile	xztbpc	NEVILE	REVILE
garmth	sfnqdk	oarmth	blnxou	uarmth	jukqfb	PARMTH	WARMTH
mrdish	gjtbru	madish	ckjzgl	mrdish	nxzljy	MEDISH	MODISH
spaynd	cwjfbz	spayld	unltfh	spayfd	bfwqxz	SPAYID	SPAYED
plaoce	zujgwf	plaoce	ntdjqf	playce	mwzsnx	PLARCE	PLAICE
mosqly	xcqpfz	mosdly	fbqjwn	mosuly	awuphb	MOSKLY	MOSTLY
fourts	enbdmj	jourts	eanqwh	jourts	nkvigh	POURTS	COURTS
erouch	evnwxg	irouch	siezya	wrouch	nqfmzt	PROUCH	CROUCH
ihotos	mwfxca	xhotos	xqfiwg	ihotos	vyzfbk	THOTOS	PHOTOS

resake	mqzudx	resane	ytoqgu	resave	vjzfdk	RESAPE	RESALE
rathle	fogibk	ratkle	fydhkw	ratule	dbsucv	RATPLE	RATTLE
muziny	awcrvp	mujiny	cqvxzl	muxiny	jvapzx	MUNINY	MUTINY
scrals	fydtvo	scrahs	qugxey	scrags	dfihtm	SCRACS	SCRAPS
shriyt	olunaj	shriot	qegbux	shribt	cvagbx	SHRIST	SHRIFT
suider	ljhxyb	snider	aqgvck	syider	xblnzt	SWIDER	SPIDER
spilit	juovqf	spidit	wexqfm	spibit	qhxzwv	SPINIT	SPIRIT
splids	waqexk	spliks	qehcwg	spliws	dmrjxy	SPLIBS	SPLITS
squejl	whvtdk	squejl	yxcpbn	squehl	jxmgrc	SQUEEL	SQUEAL
squice	zancyx	squihe	xtwdyp	squiwe	flwghb	SQUIVE	SQUIRE
staroe	uiqkwn	starpe	dfwyuo	starxe	oyncfx	STARGE	STARVE
steexy	djvxru	steefy	orwvxh	steewy	fmrwdh	STEEKY	STEELY
unhipe	jcdmqh	unzipe	qjgwal	unmipe	xywkav	UNSIPE	UNRIPE
oyacle	npdhju	okacle	zkmqnd	oxacle	hybgms	OTACLE	ORACLE
iawked	tsprox	xawked	bsjqmo	lawked	zxurqp	VAWKED	HAWKED
sertex	yqnpvc	hertex	npdcsl	kertex	cndfgv	JERTEX	AERTEX
irends	auhyjl	hrends	glqihx	jrends	afhmju	WRENDS	TRENDS
lnched	pjluxt	vnched	mfatwx	gnched	rjzxgo	YNCHED	INCHED
cadegs	gpjlqi	cadeus	qglwnf	cadeis	zjugkw	CADEMS	CADETS
recuil	qbatpn	recuil	nvfgbm	recmil	zjtgnq	RECSIL	RECOIL
threao	bqxylg	threal	ojxzfp	threan	wkixuj	THREAM	THREAD
curgid	hkybnl	yurgid	pzneyc	purgid	pweyjz	FURGID	TURGID
yungal	mcvprb	iungal	trswec	pungal	ejbdkr	HUNGAL	FUNGAL
dubmit	ajpczy	aubmit	vnxqcg	kubmit	flnqcd	HUBMIT	SUBMIT
forpse	mugfnz	qorpse	bljnkd	worpse	fkydqu	HORPSE	CORPSE
iemean	rycvou	uemean	fiktgu	oemean	vugjbr	LEMEAN	DEMEAN
suroed	yzmnba	surjed	lnbkwv	surxed	mwbvtl	SURPED	SURGED
chaqps	ijuztl	chazps	igrbdv	chaxps	ovnqjl	CHAWPS	CHAMPS
custod	wevrxq	custoa	zljxph	custoy	hazyjg	CUSTON	CUSTOM
czadle	kuwynj	cnadle	wpnbyo	cjadle	wusxjz	CHADLE	CRADLE
primlx	gskcwz	primlz	tsznco	primlj	zktcab	PRIMLE	PRIMLY
eannoy	jchves	wannoy	uwdgxs	dannoy	cqfjug	RANNOY	TANNOY
rwgour	yxcdfn	rsgour	pfcbls	rlgour	daxjhp	REGOUR	RIGOUR
facjor	pbuwgm	facnor	gnzimh	facdor	nxqkwb	FACLOR	FACTOR
midgeb	zbnlvk	midgeo	zxpbno	midgek	ybrxnz	MIDGEW	MIDGET
outkay	mhgbei	outjay	hfsiqv	outvay	cxezgr	OUTNAY	OUTLAY
soeath	cqfbil	sceath	wknoig	sbeath	ubdoqy	SMEATH	SHEATH
confed	savigy	confez	aipxvq	confev	sgauit	CONFEW	CONFER

(Appendixes continue)

C Stimuli in Experiment 3 Chapter 3

T-all prime	Unrelated prime competitor	Unrelated prime identity	Unrelated prime no	Target	Competitor
			Word Trials		
bauodn	hqtpic	iwjety	ifymqg	ABOUND	AROUND
caihgn	xfyqju	yjxbls	wjefby	ACHING	ACTING
raftlu	vosdeg	xsjbed	oecikp	ARTFUL	ARMFUL
abinhs	depuqg	yeuotf	ckpxlf	BANISH	VANISH
ebrasd	mnxlcz	ytuclw	vicqpj	BEARDS	BOARDS
ebkcno	ltmivp	luxzqd	ytmazx	BECKON	RECKON
lbaehc	ktjmzn	ujvxyf	oizxwq	BLEACH	BREACH
rbdiel	kjfumw	fcupam	jtposq	BRIDLE	BRIDGE
rbiues	wfopdq	mznahq	xknhgz	BRUISE	CRUISE
acdnel	wvogqm	pyfvmi	ktsiqy	CANDLE	HANDLE
ackste	jgvyro	wivrqg	igxlhd	CASKET	BASKET
hcnast	xlzjpm	gjwvml	jbpxom	CHANTS	CHARTS
hcvise	wakpuy	rpfkag	kabqxt	CHIVES	CHIMES
lcwade	kohnms	yzjpxh	bzvkmn	CLAWED	FLAWED
lcwosn	mhbjyv	ikqzeu	fphayd	CLOWNS	CROWNS
ocxade	knbsuf	qifuzy	rnfibh	COAXED	COATED
ocawdr	begivl	gsluxm	leufhn	COWARD	TOWARD
rcnieg	mkytwd	mwphqb	olyaph	CRINGE	FRINGE
edtpsh	ywfbjq	gqfrix	bnqyrf	DEPTHS	DEATHS
retoci	wvjmsg	wypsgu	nbfdlq	EROTIC	EXOTIC
lfsayh	nrxkci	pvunmi	rbzxnq	FLASHY	FLESHY
ignast	wcypmb	wdobzc	ckyuwo	GIANTS	GRANTS
lgbose	twufxj	jztdxr	kqrwxu	GLOBES	GLOVES
rgpash	zcxqdj	bmkvxj	ovkbcd	GRAPHS	GRAPES
ojkcye	mnpfqd	uxdfts	nsltdu	JOCKEY	HOCKEY
ojnist	qyebvx	yhxklz	mcehbr	JOINTS	POINTS
elomsn	rfybpz	zxcpgw	gvbypt	LEMONS	DEMONS
ilazdr	yboxne	buoxqc	jxobsm	LIZARD	WIZARD
amuner	bpvyli	qlcvxk	xdbqoi	MANURE	MATURE
imhgyt	pndxbq	arnxvp	flnwox	MIGHTY	EIGHTY
anevsl	xpzkdr	rtwkjd	fwigdq	NAVELS	NOVELS
onivec	lxsmby	zhqgwu	sdukhg	NOVICE	NOTICE
apride	ocglsb	cztklg	mkqovl	PAIRED	PAINED
epirhs	fbtjwl	wbmzut	dutwlv	PERISH	PARISH
lpcadi	rkhnvs	onwxzf	vfuxog	PLACID	PLACED

lpqaeu	yotmwn	xnwhyk	iowmdf	PLAQUE	PLAGUE
optryl	cishkf	ukbhzj	mwnskg	PORTLY	PARTLY
opnuec	qxmkhs	rsgiqt	jktqif	POUNCE	BOUNCE
rpaehc	dzlyow	iwugdv	dnskzj	PREACH	BREACH
uqtosa	rvnyxp	jnfhvb	wzrpby	QUOTAS	QUOTES
erisng	pbqzlw	akuxzh	cvmblf	RESIGN	DESIGN
aspmel	fhrjbk	hoqgdx	ugvyqj	SAMPLE	SIMPLE
asinyt	mzwblu	mkdfjp	kgrmcz	SANITY	VANITY
csarlw	eyzmnt	kfgdtq	mbeqxf	SCRAWL	SPRAWL
hsiren	lwqgay	fouqlt	adoxcp	SHRINE	SHRINK
lsvire	poatcn	ypgctd	zdactx	SLIVER	SHIVER
psnila	jtwyuc	hmqcou	uehdwb	SPINAL	SPIRAL
psiltn	wbvjkq	aehxkb	xfckmg	SPLINT	SPRINT
qseula	jrptfn	vcjbdm	cxnrgz	SQUEAL	SQUEAK
qsiutn	zmjxwb	kpovwy	clgpky	SQUINT	SQUIRT
tsrahc	godzvu	ldybfu	jovnqp	STARCH	SEARCH
tsaeym	upkzvo	kxwpuq	ohlfnu	STEAMY	STEADY
nuasdi	owhqtb	gebtcx	mltroe	UNSAID	UNPAID
subael	ivymqx	fxyhki	wrtkjh	USABLE	UNABLE
avlust	qnbjrg	noikre	nohidp	VAULTS	FAULTS
ovtrxe	zmhuij	gakibf	hwjgik	VORTEX	CORTEX
rwtehc	vfzxjp	iolgjv	klvudy	WRETCH	WRENCH
oytush	fpenzq	qgbfkv	lrgvpx	YOUTHS	MOUTHS
acevnr	hqswdg	qpmjgb	xhmwyg	CAVERN	TAVERN
ertcla	oijbzx	muojbz	qifxmb	RECTAL	RENTAL
cserma	klbuop	qbwfdh	kfdboz	SCREAM	STREAM
ofbrdi	jngzwa	exqwyv	gqwktj	FORBID	MORBID
ehbrla	qdyngz	cqztsx	fzxsjd	HERBAL	VERBAL
ehmrti	sawxgz	kcnzjq	bdwokq	HERMIT	PERMIT
ohlwde	nycfpg	rxaiyu	mnargk	HOWLED	BOWLED
eligno	tsacdx	zbjtma	tyxjaz	LEGION	REGION
usklde	rbmaho	wprymf	vxbyrp	SULKED	SUCKED
hciasn	zmvbld	qltxwd	mqgfzp	CHAINS	CHAIRS
iptsno	ufbzek	dweqgx	vdukgx	PISTON	PISTOL
tspael	qxvjgi	gyzdir	wdfjkc	STAPLE	STABLE
rtpiel	jgzahm	jsvknm	hamsoz	TRIPLE	TRIFLE
arsnmo	guctzh	exiqyc	qvlgpw	RANSOM	RANDOM
edotru	cbpsxz	hmfbkc	fsxwlg	DETOUR	DEVOUR
atliro	qhcxzp	ujckgm	ynxezk	TAILOR	SAILOR
imdlwe	ybugko	zhjtop	ysjvqc	MILDEW	MILDER
uoltwa	gdipzh	xgmifp	ifbpsj	OUTLAW	OUTLAY
rwaeht	pxsjvk	fxqcuo	qysonm	WREATH	BREATH

ocvnxe	bzqtrg	qhaurl	dklgjw	CONVEX	CONVEY
Nonword Trials					
nauoes	zykplq	igtykw	qgpydc	ANOUSE	AROUSE
neicgn	axlroh	rlqwhu	prwavz	ENCING	ENDING
rartla	fgcqpn	mguqfo	pbdkzi	ARTRAL	ASTRAL
acines	trvqxu	xturlw	bugplk	CANISE	CANINE
eblasm	ohudjt	tunxov	zgyxkf	BEALMS	REALMS
uckcno	rflmxi	lftbri	tlhfgx	CUCKON	CUCKOO
lbaesk	wcfoqy	gctyxh	hvdwoy	BLEAKS	BREAKS
lfbiel	pzdtum	txpkan	mzdqts	FLIBLE	FOIBLE
lsiues	hdrkqx	ofmgrx	bpfojq	SLUISE	SLUICE
acbrel	hytwqd	oxuisd	gqvzkf	CARBLE	MARBLE
achmte	bwjxvz	igxsyd	dwjynx	CAMHET	CACHET
hctahc	yenjvb	birzmy	ubyjse	CHATCH	THATCH
hcsist	wnvqjp	bgofnq	paqlbx	CHISTS	CHESTS
lctahc	wydbiv	fdviqy	jbzyde	CLATCH	CLUTCH
lclosd	fmwzgx	nwzhfv	kqebtf	CLOLDS	CLOUDS
octaeh	fqkidn	nzivrb	nkmgsb	COATHE	LOATHE
ocaret	fbpzws	npfvjy	bhfznq	CORATE	CURATE
rctieh	npmdvu	upjqyn	qpxoma	CRITHE	WRITHE
edgnht	spuorc	aysbfp	bopxks	DENGTH	LENGTH
tenuci	fxqkmb	mszdjr	wobqag	ETUNIC	ETHNIC
psnayd	vjlber	kuljzr	ulbfiw	SPANDY	SHANDY
iwlasd	onmgfy	bnmyuo	obufxq	WIALDS	WIELDS
rwbose	mxytfc	gtvkjz	mtylni	WROBES	PROBES
rguasn	loehqf	jcehxd	wjhldx	GRAUNS	GRAINS
ivkcye	garoqz	splrqj	uldjrq	VICKEY	MICKEY
ojtnsh	wueabx	rzdplw	kduyax	JONTHS	MONTHS
elopst	ciyznh	hakxrn	yfvcrz	LEPOTS	DEPOTS
afazdr	ptuqcv	ugqpxw	xcnjyi	FAZARD	HAZARD
amonsp	zfxtbw	czfehk	viyhue	MANOPS	MANORS
omtryh	iupvfj	ljvasi	njkucv	MORTHY	WORTHY
anansl	jvuhti	djxifp	xjduhp	NANALS	CANALS
enivel	duxyza	jucbyf	kumdtg	NEVILE	REVILE
apmrht	iknzuo	ixukvo	bidsno	PARMTH	WARMTH
emidhs	jcgabr	tpjfcv	xcjyvl	MEDISH	MODISH
psyadi	bvrfmh	ofqmtn	nkjwrb	SPAYID	SPAYED
lpraec	kwfjns	mxuqjn	ydxjvh	PLARCE	PLAICE
omksyl	vgxbrp	enpgaw	xjefpi	MOSKLY	MOSTLY
oprust	jfahge	dgaejm	ebvqdw	POURTS	COURTS
rpuohc	yvstna	jqbswm	zestaw	PROUCH	CROUCH
httoso	jivbqf	ljrbvm	qgkvwy	THOTOS	PHOTOS

erasep	hyngqk	bntgyo	xgcyuk	RESAPE	RESALE
arptel	cdsjih	nucvbj	giqown	RATPLE	RATTLE
uminyn	zcwbfk	jwkscx	xzgsbe	MUNINY	MUTINY
csarsc	imleqd	gefjuw	ydqhtb	SCRACS	SCRAPS
hsirts	bklxye	xgqleb	ovejgk	SHRIST	SHRIFT
wsdire	khvqnj	cuxobq	mgntaq	SWIDER	SPIDER
psniti	ehjcqd	jwfxqg	mxflcw	SPINIT	SPIRIT
psilsb	fcqxgh	cgmawj	uodmac	SPLIBS	SPLITS
qseule	vtwgnp	gonhkd	xymonb	SQUEEL	SQUEAL
qsiuev	fkybwn	hlopgy	byakop	SQUIVE	SQUIRE
tsraeg	qwjmuh	mifjnl	fynuhb	STARGE	STARVE
tseeyk	jcfbrv	bfzwhx	pomxwq	STEEKY	STEELY
nuisep	dahcyx	jkxhbz	azgbwc	UNSIPE	UNRIPE
tocael	wvshyn	vbgpnq	jhfsyx	OTACLE	ORACLE
avkwde	ixyjsg	ronfmq	sqmpty	VAWKED	HAWKED
ejtrxe	hcvukp	npblgu	qlhnzg	JERTEX	AERTEX
rwnesd	zcipqb	bfozmy	byvcig	WRENDS	TRENDS
nyhcde	pbuxwt	sjukro	urjsxv	YNCHED	INCHED
acedsm	rjkqyp	fhnrpx	bqrjvw	CADEMS	CADETS
erscli	jmybtv	mfwbdg	jdyauh	RECSIL	RECOIL
hterma	pqnycb	lnjpyq	lvfwyz	THREAM	THREAD
ufgrdi	qzxslv	pohcnq	bawlzy	FURGID	TURGID
uhgnla	ivztbx	rpevzj	wyrctj	HUNGAL	FUNGAL
uhmbti	cvnfwz	dzqvoc	koqrlx	HUBMIT	SUBMIT
ohpres	nixtjl	gualqi	vazqxm	HORPSE	CORPSE
elemna	rwfgch	pysouc	zpgyjv	LEMEAN	DEMEAN
usprde	tibmnf	bacjzv	lzxkvt	SURPED	SURGED
hcwasp	nitqoj	iuvyxg	yjfvxn	CHAWPS	CHAMPS
uctsno	qdihly	wehygp	dirvqg	CUSTON	CUSTOM
hcdael	fukomz	xfiznu	nvifxp	CHADLE	CRADLE
rpmiel	wjnocx	hvqusf	dquhav	PRIMLE	PRIMLY
arnnyo	ugbjcl	kxlziw	ldehkq	RANNOY	TANNOY
erogru	qjkxha	vkwypx	azmjkq	REGOUR	RIGOUR
aflcro	qimhkg	iusqwz	xzpdhk	FACLOR	FACTOR
imgdwe	fnrxoy	jknbhv	jzpfax	MIDGEW	MIDGET
uontya	brkmse	xkihvj	vbdkwj	OUTNAY	OUTLAY
msaeht	ruplgy	cdybpn	wyblou	SMEATH	SHEATH
ocfnwe	qvhjax	mljduv	tkuxpz	CONFEW	CONFER

D Stimuli in Experiment 1 Chapter 4

Unrel preprime	Rel prime	Unrel prime	Target
chess	store	guilt	STORM
judge	blast	mayor	BOAST
worth	sharp	jelly	SHARK
brick	stomp	lover	STUMP
boots	stars	hence	STARE
merry	stale	toxic	STALK
myths	spare	clown	SPADE
fools	snake	wider	STAKE
sense	paint	blade	PRINT
grown	skate	mushy	SLATE
power	grace	sting	BRACE
porch	sneak	bribe	STEAK
haunt	tease	snoop	CEASE
towel	sport	prime	SNORT
chose	stray	blend	STRAP
bacon	spoke	flash	STOKE
loose	click	tasty	FLICK
frank	slice	these	SLIME
close	staff	track	STIFF
place	madly	crops	SADLY
bread	mince	chaps	WINCE
taped	worry	clasp	LORRY
brave	sleek	dairy	SLEET
train	sweat	bonus	SWEPT
talks	sheet	block	SHEER
dummy	steer	flare	STEEP
nurse	stint	woken	SKINT
prove	skill	laser	SPILL
creep	foggy	while	SOGGY
mouth	seedy	calms	WEEDY
built	chefs	store	CHEWS
major	fudge	blast	NUDGE
belly	north	sharp	FORTH
cover	brink	stomp	BRISK
fence	booth	stars	BOOTY
topic	ferry	stale	BERRY
blown	moths	spare	MATHS
rider	fouls	snake	FOILS
blame	tense	paint	DENSE
pushy	groin	skate	GROAN

swing	poker	grace	POSER
bride	pouch	sneak	POACH
scoop	taunt	tease	JAUNT
crime	bowel	sport	VOWEL
blind	choke	stray	CHORE
flesh	baron	spoke	BATON
nasty	goose	click	MOOSE
there	crank	slice	PRANK
truck	clone	staff	CLOVE
cross	plane	madly	PLATE
chaos	dread	mince	TREAD
class	tamed	worry	TAXED
daily	grave	sleek	CRAVE
bones	trail	sweat	TRAIT
clock	tanks	sheet	TASKS
flame	mummy	steer	TUMMY
women	purse	stint	CURSE
later	probe	skill	PRONE
whole	creek	foggy	CREED
palms	south	seedy	YOUTH
story	guilt	chefs	QUILT
beast	mayor	fudge	MANOR
share	jelly	north	TELLY
stamp	lover	brink	HOVER
start	hence	booth	PENCE
stall	toxic	ferry	TONIC
space	clown	moths	FLOWN
shake	wider	fouls	CIDER
point	blade	tense	BLAZE
state	mushy	groin	BUSHY
trace	sting	poker	SLING
speak	bribe	pouch	BRINE
lease	snoop	taunt	SWOOP
short	prime	bowel	GRIME
straw	blend	choke	BLAND
smoke	flash	baron	FLUSH
slick	tasty	goose	PASTY
slide	these	crank	THEME
stuff	track	clone	TRICK
badly	crops	plane	CROWS
since	chaps	dread	CHATS
sorry	clasp	tamed	CLASH
sleep	dairy	grave	DAISY

sweet	bonus	trail	BONDS
sheep	block	tanks	FLOCK
steel	flare	mummy	FLAKE
saint	woken	purse	WOVEN
still	laser	probe	LAYER
doggy	while	creek	WHALE
needy	calms	south	BALMS
scrub	dealt	bloke	DEALN
float	phase	bring	SHASE
moist	purge	freak	CURGE
chief	fable	meant	RABLE
think	salts	drove	SALEY
scope	grant	marsh	GEANT
worse	avert	drags	ABERT
repay	latin	older	BATIN
silly	bathe	cream	BATHO
aside	shrew	brawl	SEREW
abuse	stair	coral	STAIK
force	inset	muddy	ANSET
magic	count	yield	COUVT
charm	grief	nerve	TRIEF
awake	comas	bully	COMIS
wedge	locus	civic	ROCUS
shift	clean	vogue	CLEIN
cheap	aimed	noisy	ALMED
dozen	slash	award	SEASH
about	ideal	fever	IDEAM
dress	rouge	adapt	ROUVE
perky	snarl	aloud	SNAEL
memos	ratty	chain	VATTY
floor	mango	guest	RANGO
draft	merge	alloy	SERGE
demon	barge	niece	BALGE
bless	anger	decay	ANGEM
naval	alike	crust	ALIME
birth	otter	amble	OLTER
burnt	depth	shelf	DEITH
broke	shrub	dealt	SARUB
being	gloat	phase	SLOAT
break	hoist	purge	ROIST
means	thief	fable	SHIEF
drive	thank	salts	THARK
harsh	slope	grant	STOPE

draws	horse	avert	PORSE
order	reply	latin	REPPY
dream	silky	bathe	SILEY
crawl	abide	shrew	AGIDE
moral	amuse	stair	AGUSE
buddy	forge	inset	FORLE
field	manic	count	MALIC
serve	chart	grief	CHARK
fully	awoke	comas	AWIKE
civil	hedge	locus	PEDGE
rogue	shaft	clean	SHOFT
noise	cheat	aimed	CHEAL
aware	dozed	slash	DOZEL
never	abort	ideal	ABOLT
adopt	press	rouge	BRESS
cloud	porky	snarl	PURKY
chair	demos	ratty	VEMOS
guess	flour	mango	FLOIR
alley	craft	merge	ZRAFT
piece	lemon	barge	SEMON
delay	bliss	anger	BLUSS
trust	nasal	alike	NARAL
ample	birch	otter	BIRSH
shell	burst	depth	BURGT
deals	bloke	shrub	BOOKE
chase	bring	gloat	BAING
surge	freak	hoist	CLEAK
cable	meant	thief	MEANK
salty	drove	thank	DRUVE
giant	marsh	slope	CARSH
alert	drags	horse	DRANS
satin	older	reply	OSDER
baths	cream	silky	VREAM
screw	brawl	abide	TRAWL
stain	coral	amuse	RORAL
onset	muddy	forge	NUDDY
court	yield	manic	PIELD
brief	nerve	chart	ZERVE
combs	bully	awoke	MULLY
focus	civic	hedge	CIVIT
clear	vogue	shaft	LOGUE
armed	noisy	cheat	NOISK
smash	award	dozed	AWART

ideas	fever	abort	TEVER
route	adapt	press	ADIPT
snail	aloud	porky	BLOUD
fatty	chain	demos	CHAIM
tango	guest	flour	GUESE
verge	alloy	craft	ALLBY
badge	niece	lemon	VIECE
angel	decay	bliss	DEMAY
alive	crust	nasal	PRUST
outer	amble	birch	AMSLE
death	shelf	burst	SHELK

E Spatial Coding Model (Davis, 2010) Parameters

Parameter	Value
Position uncertainty (SD)	0.48
Position uncertainty (stimulus length)	0.24
Scaling of word frequency in resting activities	0.046
Resting activity input to activity	1.8
Shunting of net input by current activity	-0.2
Match-dependent decay cutoff	0.4
Match-dependent decay rate	1
Feature-letter input excitation	0.28
Feature-letter input inhibition	6
Net word input excitation	0.4
Net word input power	2.5
Mismatch inhibition	0.04
Word-word inhibition	0.34
Word-word excitation	0.44
Masking field weight	0.35
Length mismatch inhibition	0.06
Word-letter feedback excitation	0.3
Step size: temporal scaling	0.05

F Relative Position Open Bigram Model (Grainger & van Heuven, 2003) Parameters

Parameter	Value
External input inhibition	-2.1
External input excitation[16]	0.07
Bigrams rate	1
Words rate	1
Decay	0.07
Minimum activation	-0.2
Maximum activation	1
Moving average	0.05
Bigram to word excitation	0.28
Bigram to word inhibition (per bigram)	-0.015
Word to bigram excitation	0.3
Word to bigram inhibition	0
External inhibition scale	0
Words resting level multiplier	0.05
Lateral inhibition	-0.21
Lexical decision threshold	0.68

[16] To achieve this in easyNet a parameter of 2.17 was used, as this must counteract the baseline inhibition of -2.1.