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Research Report

When less is more: Feedback, priming, and the pseudoword superiority effect

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ABSTRACT

The present study combined masked priming with electrophysiological recordings to investigate orthographic priming effects with nonword targets. Targets were pronounceable nonwords (e.g., STRENG) or consonant strings (e.g., STRBNG), that both differed from a real word by a single letter substitution (STRONG). Targets were preceded by related primes that could be the same as the target (e.g., streng–STRENG, strbng–STRBNG) or the real word neighbor of the target (e.g., strong–STRENG, strong–STRBNG). Independently of priming, pronounceable nonwords were associated with larger negativities than consonant strings, starting at 290 ms post-target onset. Overall, priming effects were stronger and longer-lasting with pronounceable nonwords than consonant strings. However, consonant string targets showed an early effect of word neighbor priming in the absence of an effect of repetition priming, whereas pronounceable nonwords showed both repetition and word neighbor priming effects in the same time window. This pattern of priming effects is taken as evidence for feedback from whole-word orthographic representations activated by the prime stimulus that influences bottom-up processing of prelexical representations during target processing.

1. Introduction

In languages that use alphabetical orthographies, strings of letters that do not correspond to a real word (i.e., nonwords) can vary in terms of the amount of orthographic and phonological structure they carry. Consider, for example, a pronounceable string of letters such as “toble” compared with a random string of consonants such as “tfblg” that is barely pronounceable. Examining how skilled readers process such nonword stimuli provides a window onto the earliest phases of visual word recognition, involving the processing of prelexical orthographic and phonological information. Indeed, some of the very first studies in experimental psychology investigated the processing of nonsense strings of letters using tachistopscopic presentation (Cattell, 1886). Since the early work of Cattell, much of this research has focused on differences between word and nonword processing, applying improved methodologies designed to rule-out guessing biases and superior memory for real words as opposed to nonwords (Reicher, 1969; Wheeler, 1970). The present study focuses on processing of nonword stimuli, contrasting orthographically regular and pronounceable letter strings with orthographically

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irregular unpronounceable strings. Most critically, in the present study both types of nonword were orthographically similar to real words, differing only by a single letter (e.g., "streng" and "strbng," with respect to "strong" or "string"). This will allow us to separate out prelexical effects resulting from differences in orthographic and phonological regularity, from effects due to feedback from whole-word orthographic representations. These two influences have been typically confounded in prior research, such as when comparing a pronounceable nonword such as "streng" with a consonant string such as "stpfm." In this example, not only is the first type of nonword more orthographically and phonologically regular than the second but it is also orthographically similar to a real word, whereas the second is not.

Indeed, there is a large literature examining the performance of skilled readers in behavioral experiments using exactly these two kinds of nonword stimuli. For example, when asked to reject these stimuli as nonwords in a lexical decision task, participants are faster and more accurate at rejecting consonant strings than pronounceable nonwords (e.g., Ratcliff et al., 2004). Differences are also observed even when participants only have to identify a single letter in the stimulus, in a post-cued letter-in-string identification task (Reicher, 1969; Wheeler, 1970). In studies using this paradigm, not only is letter identification found to be better in word stimuli compared with nonwords (the "word superiority effect") but it is also found to be more accurate in pronounceable nonwords than consonant strings—the so-called "pseudoword superiority effect" (e.g., Adams, 1979; Baron & Thurston, 1973; Grainger et al., 2003; Grainger & Jacobs, 1994; Spoehr & Smith, 1975). Although the precise mechanisms underlying the pseudoword superiority effect remain to be clarified, it seems clear that pseudoword stimuli benefit from multiple additional sources of information that are present to a lesser extent in consonant strings. This additional information could be provided by the familiarity of letter combinations, the quality of the phonological code, or the ability to make contact with whole-word representations.

One standard interpretation of the pseudoword superiority effect is that it is primarily driven by top-down feedback from whole-word orthographic representations (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). This has the advantage of parsimony, in that the same mechanism is used to explain both word superiority and pseudoword superiority effects. According to this explanation, pronounceable nonword stimuli partially activate whole-word orthographic representations that in turn send excitatory feedback to all compatible letter representations that are activated by the pronounceable nonword stimulus. This therefore generates improved letter identification in these stimuli compared with consonant strings that can only weakly activate whole-word orthographic representations. Key evidence in favor of this interpretation was provided by Rumelhart and McClelland (1982). These authors compared letter identification in consonant strings which were similar or not to real words (e.g., SPCT vs. SPCJ; where SPCT is similar to SPAT, SPIT and SPOT). The results revealed a significant advantage for consonant strings which were similar to real words compared to letter strings which were not. Furthermore, performance to consonant strings that were similar to real words was found to be the same as that found with pronounceable nonwords (e.g., SPET). These results suggest that feedback from partially activated whole-word representations to letter representations provides one source of improved letter identification in strings of letters that are not real words.

Grainger and Jacobs (2005), on the contrary, provided evidence against the role of top-down feedback in the pseudoword superiority effect. Grainger and Jacobs manipulated the number of orthographic neighbors of pronounceable nonword stimuli that were compatible with the target letter (e.g., PABLE—target "B", has compatible word neighbors such as TABLE, CABLE, FABLE). They found clear evidence for improved letter identification when the pronounceable nonword had at least one compatible word neighbor, but they failed to find evidence for any influence of increasing the number of compatible word neighbors over and above one, an effect that was predicted by the interactive-activation model (McClelland and Rumelhart, 1981). This led Grainger and Jacobs to conclude that the pseudoword superiority effect is best captured by a process of word misperception, whereby the pseudoword stimulus is misperceived as a real word, such as misperceiving "pable" as "table." Thinking that they saw the word "table," participants would then correctly respond that the letter B was at the 3rd position. Top-down feedback was therefore deemed unnecessary in order to account for the pseudoword superiority effect.

It is possible, however, that Grainger and Jacobs (2005) failure to find evidence for top-down influences on the pseudoword superiority effect was due to a ceiling effect produced by bottom-up orthographic and phonological influences. That is, the pseudoword superiority effect would result from the combined influences of prelexical orthographic and phonological structure and top-down lexical influences, with the former dominating the latter in certain conditions. Here we add two novel features to the study of top-down influences on the pseudoword superiority effect—event-related potential (ERP) recordings and masked priming—in a renewed attempt to find evidence for top-down influences. More precisely, by testing pronounceable nonwords and consonant strings that are equally similar to real words (following Rumelhart and McClelland, 1982) and combining this manipulation with masked priming and ERPs, the present study aims to provide the following information. First, a direct comparison of the ERPs generated by these two types of nonword target will indicate when differences in orthographic regularity and pronounceability can be detected while controlling for top-down influences (and this timing estimate can be compared with prior research where top-down influences were not controlled). Second, finding priming effects that are the same for both types of nonword target can be taken as evidence for top-down influences from whole-word representations during nonword target processing. Finally, finding priming effects for pronounceable nonword targets and not for consonant string targets can be taken as evidence for modulation of prelexical orthographic and/or phonological representations by the prime stimulus.

1.1. ERPs and word/pseudoword superiority

Several studies measuring ERPs have reported differences in the waveforms generated by words and different types of nonword starting around 200 ms post-stimulus onset (e.g., Bentin et al., 1999; Compton et al., 1991; Holcomb & Neville, 1990; see Tarkiainen et al., 1999, for a similar finding with magnetoencephalography). However, estimates of the onset of such differences vary from study to study. For example, Bentin et al. (1999) reported a significant difference between pronounceable and unpronounceable letter string stimuli, peaking at around 320 ms, with more negative-going waves for pronounceable letter strings than for consonant strings. Martin et al. (2006), using a variant of the Reicher–Wheeler paradigm combined with ERP recordings, showed a lexicality effect in the 200–300 ms time window. These authors observed a more negative waveform for words than nonwords over the left temporoparietal regions. More recently, Coch and Mitra (2010) tested pronounceable nonwords and consonant string stimuli in the Reicher–Wheeler task with ERP recordings. They found that consonant strings produced more positive-going waveforms than pronounceable stimuli (words and pronounceable nonwords) starting around 150 ms post-stimulus onset.

Most relevant for the present study is our prior work investigating differences between pronounceable nonwords and consonant strings using masked priming and ERP recordings (Massol et al., 2011). In this prior work, we examined priming effects with pronounceable nonword and consonant string targets that were 7 letters in length (e.g., damopur, dcmfplr). The pronounceable nonwords were more orthographically similar to real words than were the consonant strings. Experiment 2 of this study used exactly the same procedure as in the present study, so we will focus on the results of this experiment. The ERP data revealed a significant difference between the two types of nonword target emerging at around 240 ms. Most important is that effects of repetition priming were mostly visible with pronounceable nonwords, and there was little evidence for priming with consonant strings. The observed absence of repetition priming with consonant string targets was taken as evidence that the very first level of orthographic processing, possibly a retinotopic mapping of visual features onto letter identities (Grainger & van Heuven, 2003; Grainger & Holcomb, 2009), is highly sensitive to masking. Such low-level orthographic representations would not survive the masking influence of the target stimulus, and therefore target processing would be minimally affected by prime–target relatedness. Pronounceable nonwords, on the other hand, would activate higher-level orthographic and phonological representations (possibly including whole-word representations) that would be more resistant to masking and therefore survive the onset of the target stimulus and influence its subsequent processing.

1.2. *The present study*

The present study examined processing of pronounceable nonwords (e.g., STRENG) and consonant strings (e.g., STRBNG) that both differed from a real word (STRONG) by a single letter substitution. Pronounceable nonwords and consonant strings are therefore matched in terms of their similarity to a real word, which was not the case in our prior work (Massol et al., 2011). These nonword targets were preceded by the same prime but in lowercase (e.g., streng–STRENG; strbng–STRBNG), by a word neighbor prime (e.g., strong–STRENG; strong–STRBNG), by an unrelated nonword prime (e.g., knaght–STRENG; knsght–STRBNG), or an unrelated word prime (e.g., bridge–STRENG; bridge–STRBNG). Participants performed a lexical decision task and responded only to non-critical word stimuli (i.e., a go/no-go lexical decision task with button presses only to the word targets). The timing of the divergence between the two types of nonword stimuli seen in the present study compared with that found by Massol et al. (2011) will provide an indication of the relative role of lexical and prelexical factors driving this divergence. Furthermore, effects of orthographic neighbor primes will provide a window on possible lexical influences during the processing of nonword targets.

2. Results

2.1. *Behavioral data*

Participants successfully detected 94.43% (SD=4.85) of probe words.

2.2. *Electrophysiological data*

2.2.1. *Visual inspection of ERPs*

Plotted in Figs. 3 and 4 are the ERPs contrasting the conditions with related and unrelated primes for pronounceable nonword and consonant string targets, for repetition priming (Fig. 3) and orthographic neighbor priming (Fig. 4). As can be seen in these figures, the ERPs in this experiment produced a set of positive and negative deflections consistent with previous masked priming studies using nonword stimuli (e.g., Massol et al., 2011). In examining the ERPs in these figures it is important to keep in mind that the waves to both prime and target stimuli are an amalgamation of overlapping components produced by the rapid succession of mask–prime–target stimuli and therefore the traditional componentry seen in unmasked word processing studies is not apparent here. Holcomb and Grainger (2006) argued that it is more important in interpreting the results for ERP masked priming studies to concentrate on the differences between related and unrelated conditions where all potentially confounding effects of pre-target events have been controlled.

Figs. 3 and 4 show that ERPs produced an early negative peak at about 90 ms (N1), which was followed by a larger positivity peaking around 190 ms (P2). The bulk of priming effects began to emerge on the P2 component in anterior sites and continued into what resembles the N250 component seen in our prior masked priming work with word targets (e.g., Holcomb & Grainger, 2006).[1] Between 300 ms and 400 ms, localized at posterior sites, targets preceded by related primes produced more negativity than targets preceded by an unrelated prime. Following this component, in the traditional

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[1] There is some evidence for an earlier effect in left frontal sites at around 100 ms post-target onset with pronounceable nonword targets and repetition primes (Fig. 3). This might well be an early manifestation of the N/P150 effect seen in our prior masked priming studies (see Grainger & Holcomb, 2009, for review), and thought to reflect feature-level overlap across primes and targets. The fact that primes were in lowercase and targets in uppercase in the present study, thereby reducing prime-target feature overlap, might be the reason for why the effect is not stable across the two types of target.

window of the N400 component, unrelated targets also produced a more negative-going response when targets were pronounceable nonwords.

2.2.2. *Analysis of ERP data*

2.2.2.1. 200–300 ms target epoch. As can be seen in Figs. 3 and 4, targets preceded by an unrelated prime produced a more negative-going wave than targets preceded by a related prime (repetition primes in Fig. 3, and word neighbor primes in Fig. 4), whatever the type of target stimuli. This observation was confirmed by a main effect of RELATEDNESS, which was significant over all electrode sites, $F(1, 23)=19.09$, $MSE=16.78$, $p<.001$. The effect of word neighbor primes was significant across all electrode sites, $F(1, 23)=9.78$, MSE = 16.16, $p<.005$, as was the effect of repetition primes, $F(1, 23)=10.23$, MSE = 15.89, $p=.004$. Inspection of the figures suggests that the priming effect with pronounceable nonword targets are larger than the effects with consonant string targets in this time-window, and there was a marginal two-way interaction between TYPE-OF-TARGET and RELATEDNESS over all electrode sites ($F(1, 23)=3.79$, MSE = 17.35, $p=.064$). Follow-up analyses revealed a significant effect of word neighbor priming for both types of target (pronounceable nonwords: $F(1, 23)=6.22$, MSE = 17.82, $p=.020$; consonant strings: $F(1, 23)=4.39$, MSE = 11.94, $p=.047$), whereas the repetition priming effect was only significant for pronounceable nonword targets, $F(1, 23)=13.58$, MSE = 17.63, $p=.001$.

2.2.2.2. 300–400 ms target epoch. Examination of Fig. 5 reveals that pronounceable nonword targets were associated with more negative-going waveforms than consonant string targets. This observation was confirmed by the presence of a main effect of TYPE-OF-TARGET over all electrode sites, $F(1, 23)=10.64$, MSE = 42.69, $p=.003$. There was also a significant main effect of RELATEDNESS over all electrode sites, $F(1, 23)=4.89$, MSE = 15.97, $p=.037$. Targets preceded by a related prime produced more negative-going waveforms than targets preceded an unrelated prime. The effects of RELATEDNESS did not interact with TYPE-OF-PRIMING or TYPE-OF-TARGET ($ps>.1$).

2.2.2.3. 400–500 ms target epoch. Examination of Fig. 3 and 4 reveals that this interval contains the bulk of the activity similar to the classic N400 component. As can be seen in Fig. 5, pronounceable nonword targets produced a more negative-going wave than consonant string targets. This observation was confirmed by the presence of a main effect of TYPE-OF-TARGET over all electrode sites, $F(1, 23)=8.14$, MSE = 73.43, $p=.009$. Moreover statistical analysis revealed a significant TYPE-OF-TARGET by RELATEDNESS interaction over column 1 ($F(1, 23)=4.81$, MSE = 9.07, $p=.038$) and column 2 ($F(1, 23)=4.4$, MSE = 7.38, $p=.047$). This interaction reflects the fact that the effect of RELATEDNESS was only significant for pronounceable nonword targets over all electrode sites, $F(1, 23)=4.51$, MSE = 20.20, $p=.044$. Pronounceable nonwords following a related prime (repetition or word neighbor) were associated with less negativity than pronounceable nonwords following by an unrelated prime, whereas consonant strings following a related prime did not differ from consonant strings following an unrelated prime ($p>.1$).

2.2.2.4. Onset of effects of target type. In a separate analysis, we compared the ERPs generated at the O1 electrode site for both types of target. This analysis involved averaging ERPs across all pronounceable nonword targets on the one hand and all consonant string targets on the other, across all participants. The corresponding grand averages for pronounceable nonwords and consonant strings are presented in Fig. 5. A repeated measures analysis of variance (ANOVA) was used to analyze the ERPs by using TYPE-OF-TARGET (pronounceable nonwords vs. consonant strings) as a within participant independent variable, and mean amplitude as the dependent variable. O1 was selected as the electrode site showing the earliest systematic divergence. The onset of the divergence between the ERPs generated by pronounceable nonwords and consonant strings was determined when at least 15 consecutive F values were significant ($p<.05$) (Rugg et al., 1995; Thorpe et al., 1996). This was the case at 290 ms post-target onset at electrode O1 ($F(1, 23)=6.13$, MSE = 0.42, $p=.021$).

3. Discussion

The present study combined the masked priming paradigm with electrophysiological recordings in an investigation of lexical influences on the pseudoword superiority effect. Priming effects were evident starting around 200 ms post-target onset, with related primes generating less negative-going waveforms in the 200–300 ms window, more positive-going waveforms in the 300–400 ms time-window, and again less negative-going waveforms in the 400–500 ms time-window, compared with unrelated primes. The onset of priming effects differed, however, as a function of the type of target and type of priming manipulation. Whereas pronounceable nonwords showed priming from both repetition and word neighbor primes in the 200–300 ms time-window, consonant strings, on the other hand, only showed priming in the word neighbor prime condition in that time-window. Consonant string and pronounceable nonword targets showed priming from both types of priming manipulation in the 300–400 ms time-window, but only pronounceable nonwords showed priming effects in the 400–500 ms time-window. A more fine-grained portrayal of the time-course of repetition and orthographic neighbor priming effects for each type of nonword target is shown in Figs. 6 and 7.

3.1. *Top-down influences on pseudoword superiority*

Perhaps the key result of the present study concerns the significant effect of priming from word neighbors seen with consonant strings in the 200–300 ms time-window. The fact that consonant strings were not sensitive to repetition priming in the same time-window, along with the fact that pronounceable nonwords were sensitive to both priming manipulations, is a highly constraining finding with important theoretical consequences. This specific pattern can be accounted for by assuming that both the repetition priming and word neighbor priming effects on consonant strings are mediated by activation of the whole-word orthographic representation of the target's word neighbor. Activation of this whole-word representation would provide excitatory feedback to the letter representations shared with the nonword target, following the dynamics of interactive-activation (McClelland & Rumelhart, 1981). Such feedback would be more readily available when the prime is a word (i.e., in the word neighbor prime condition) compared with when the prime is a nonword (i.e., the repetition prime condition), thus explaining why the effects emerged earlier with the word neighbor primes than the repetition primes (see Figs. 6 and 7). The fact that pronounceable nonword targets were affected by both repetition and word neighbor priming in this time-window, would suggest that these priming effects are mainly driven by prelexical orthographic and/or phonological representations. Furthermore, this account of the pattern of early priming effects seen with consonant strings fits with the explanation for why the divergence between consonant strings and pronounceable nonword targets emerged later in the present study compared with our prior work (Massol et al., 2011).

3.2. *Pronounceable nonwords vs. consonant strings*

The present study revealed a point of divergence between pronounceable nonwords and consonant strings that was significant at 290 ms post-target onset, with more negative-going waveforms for pronounceable nonword targets. This point of divergence between the two types of nonword is roughly 50 ms later than that seen in our previous work (Massol et al., 2011). This can be attributed to the ability of the consonant strings that were tested in the present study to rapidly make contact with whole-word orthographic representations. These whole-word representations could then feedback information leading to activation in prelexical representations that would otherwise not occur during the processing of consonant strings. In other words, during processing of the consonant strings in the present study, part of the prelexical activation that is typically lacking relative to the activation generated by pronounceable nonwords, could be re-generated via top-down feedback from whole-word orthographic representations.

The estimated point of divergence in the processing of pronounceable nonwords and consonant strings reported in prior ERP research varies considerably from study to study. In one of the first ERP studies to compare these two types of nonword, Ziegler et al. (1997) reported significant differences emerging at 225 ms in left posterior electrode sites in a letter search task. This estimation fits well with that reported in our prior work (Massol et al., 2011) using a letter-in-string identification task. In that work we found a significant difference arising at 200 ms post-target onset in electrode site O1. However, Ziegler et al. (1997) also reported a much earlier difference arising in a semantic categorization task, as early as 25–50 ms post-stimulus onset. This very early effect must be due to participants generating expectancies on the basis of the semantic category that was provided immediately prior to each target stimulus. This is even more likely to have occurred given that fairly narrow semantic categories were tested and only the most typical exemplars were used on positive trials. On the other hand, Bentin et al. (1999) found the earliest difference between pronounceable nonwords and consonant strings in a highly localized negative-going waveform (electrode site T3) peaking at 320 ms post-stimulus onset. Given that this was observed in a rhyme judgment task (decide whether the stimulus rhymes with a given word), it is actually surprising that no earlier differences were seen, given the nature of the task. More recently, however, Coch and Mitra (2010) found evidence for an even earlier dissociation in the ERPs generated to these two types of nonword. Using a post-cued letter identification task, as in experiment 1 of Massol et al. (2011), they found a significant difference on the peak of the P150 component (at 150 ms post-stimulus onset), which was most visible in occipital sites. However, this difference was no longer significant in the following time-window (N200), only to re-emerge at around 300 ms post-stimulus onset. Finally, Rosazza et al. (2009) found a difference between consonant strings and pronounceable nonwords emerging at around 225 ms in a lexical decision task.

It therefore appears that we have three studies showing effects emerging between 200–250 ms post-stimulus onset in a letter search task (Ziegler et al., 1997), a letter-in-string identification task (Massol et al., 2011), and a lexical decision task (Massol et al., 2011; Rosazza et al., 2009), plus one study showing later effects in a rhyme judgment task (Bentin et al., 1999), and one study showing an earlier effect in a letter-in-string identification task (Coch & Mitra, 2010). Results from studies comparing word stimuli with random consonant strings are also in line with this general tendency (McCandliss et al., 1997; Martin et al., 2006). In the McCandliss et al. study, the earliest differences between words and consonant strings were seen over parieto-occipital sites on the peak of the N1 component at around 200 ms post-stimulus onset in a semantic categorization task ("is this something tangible?"). Similarly, in the study by Martin et al., differences between these two types of stimuli were found to emerge over parieto-occipital electrode sites starting around 200 ms post-stimulus onset, this time in a letter-in-string identification task.

Although the general picture is fairly clear, some of the differences across these studies likely lie in the different tasks that participants had to perform. Indeed, Massol et al. (2011) found an earlier onset when participants performed letter-in-string identification with brief target exposures than when they performed a lexical decision task to the same stimuli. However, some of the differences could also be due to the different ability of the consonant strings that were tested in these different studies, to activate whole-word representations. That is, across the different studies it is possible that there was some variation in the level of orthographic overlap between consonant string stimuli and real words. The results of the present study clearly show that it is important to take this factor into consideration when evaluating processing differences between consonant strings and pronounceable nonwords.

3.3. *Effects of orthographic neighbors*

The effects of orthographic neighbor primes seen in the present study can be compared with the effects reported in our prior work (Massol et al., 2010), where we tested word targets and primes that could be word neighbors or nonword neighbors of target stimuli. In this research we found that the lexical status of the prime stimulus had little influence on priming effects up until about 300 ms post-target onset. Before that point in time, both word and nonword neighbor primes generated less negative-going waveforms compared with their respective unrelated control primes. These effects were mostly visible in

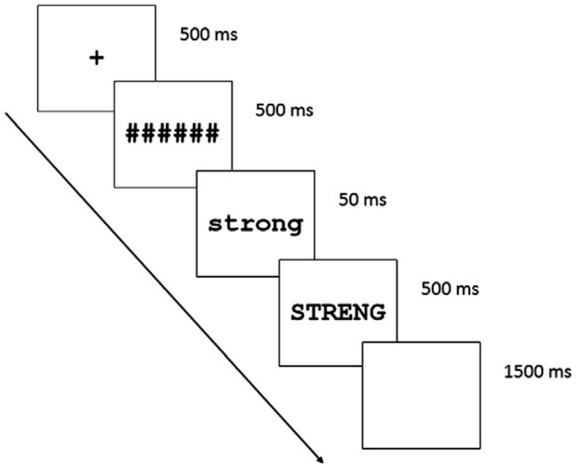

Fig. 1 – Sequence of events on a typical trial with example stimuli for the word neighbor prime and pronounceable nonword target condition.

the N250 component. Starting around 300 ms, and in the time-window of the classic N400 component seen with word targets, we found that nonword neighbor primes continued to produce less negative-going waveforms, whereas the effects of word neighbor primes disappeared. This pattern was taken as support for the hypothesis that the bulk of the N250 component reflects prelexical processing, with lexical level processing starting to kick in around 300 ms post-stimulus onset. The disappearance of effects of word neighbor primes at that point in time was interpreted as reflecting lateral inhibition operating between the prime word's whole-word orthographic representation and that of the target word. Furthermore, in a number of masked priming studies with ERP recordings (Chauncey et al., 2011; Holcomb & Grainger, 2006; see Grainger & Holcomb, 2009 for review), it has been argued that modulation of a component lying between the N250 and N400 components, referred to as the P325, might well be a reflection of activity in whole-word form representations prior to semantic activation reflected in the N400.

In the present study we found evidence for such a reversed priming effect starting around 300 ms post-target onset, with related primes generating greater negativities than unrelated primes. Given that all our nonword targets were orthographically similar to at least one real word, this pattern in the ERP waveforms could be the reflection of activation in whole-word representations activated by our nonword targets. As argued in our prior work, this would reflect the stabilization in activation at the level of whole-word representations, and not the earliest activation of such representations. Indeed, the results of the present study suggest on the contrary that whole-word representations have been activated and have started to feedback activation to lower levels of representation well before 300 ms post-target onset. This would explain why no early differences were seen between pronounceable nonwords and consonant strings, plus the priming effects of word neighbor primes during the processing of consonant string targets seen in the 200–300 ms time-window.

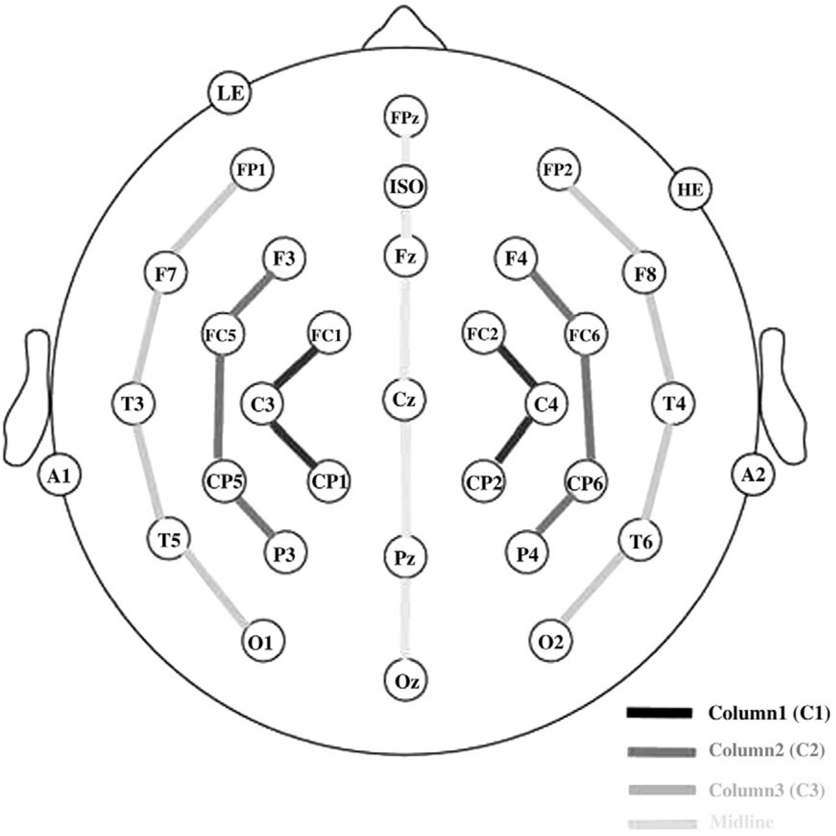

Fig. 2 – Electrode montage and four analysis columns used for ANOVAs.

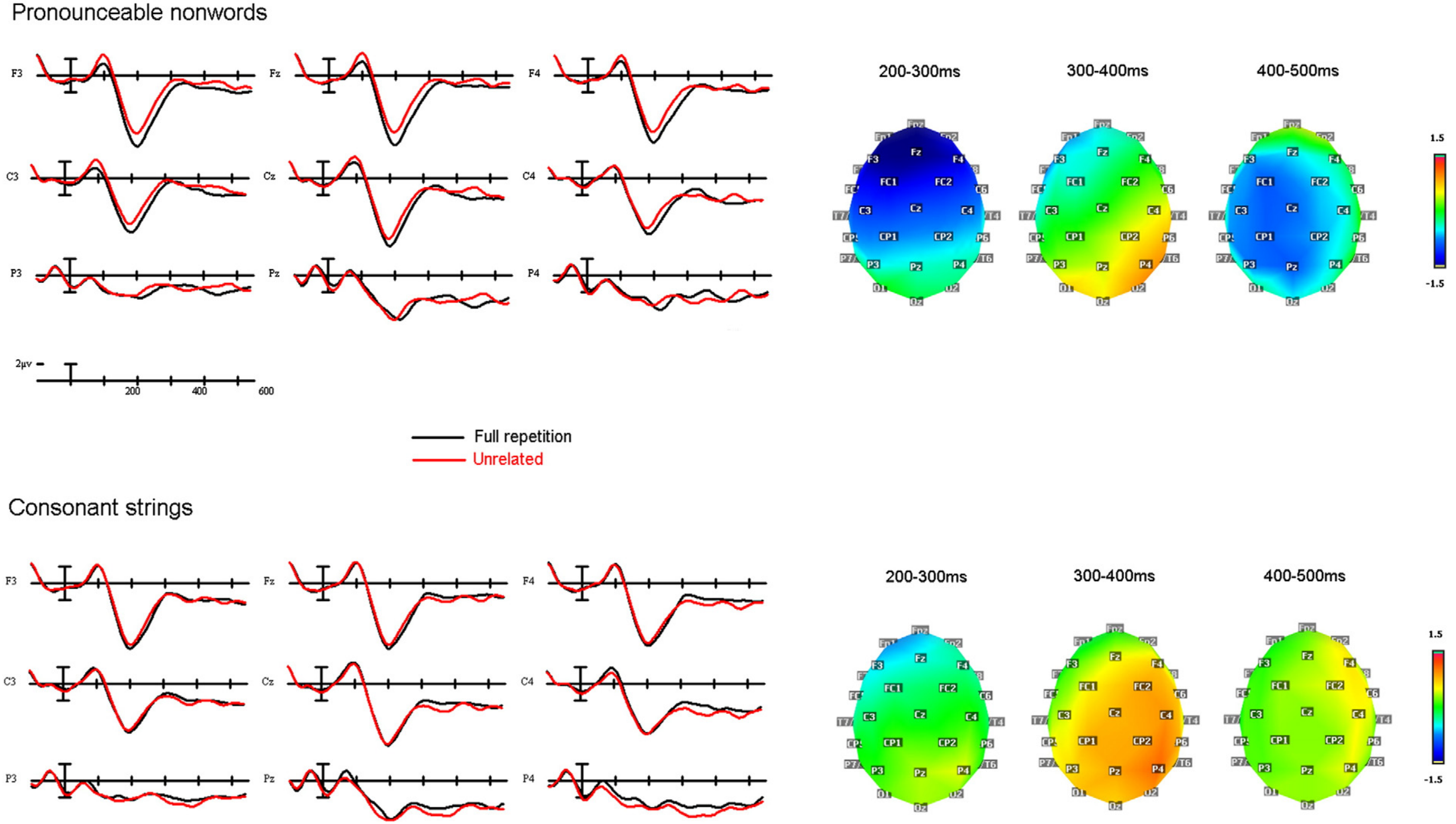

Fig. 3 – Left: ERPs time locked to target onset in two conditions (black line: full repetition; red line: unrelated prime) over 9 electrode sites, for pronounceable nonwords (above) and for consonant strings (below). Right: Voltage maps centered on the three epochs used in the statistical analyses. The maps represent voltage differences at each electrode site calculated by subtracting the voltage values in the related prime condition from the voltage values in the unrelated prime condition.

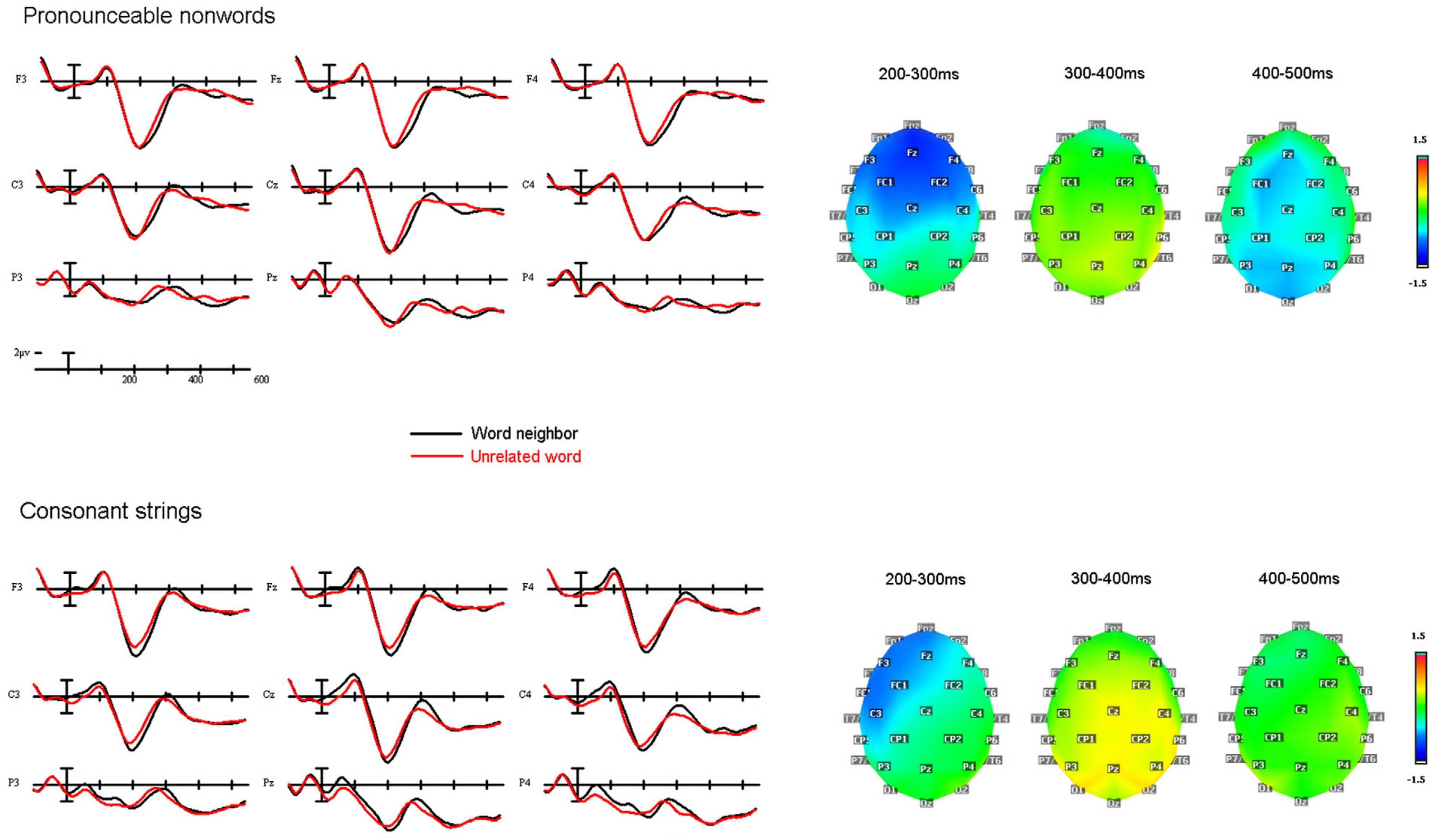

Fig. 4 – Left: ERPs time locked to target onset in two conditions (black line: word neighbor prime; red line: unrelated word prime) over 9 electrode sites, for pronounceable nonwords (above) and for consonant strings (below). Right: Voltage maps centered on the three epochs used in the statistical analyses. The maps represent voltage differences at each electrode site calculated by subtracting the voltage values in the related prime condition from the voltage values in the unrelated prime condition.

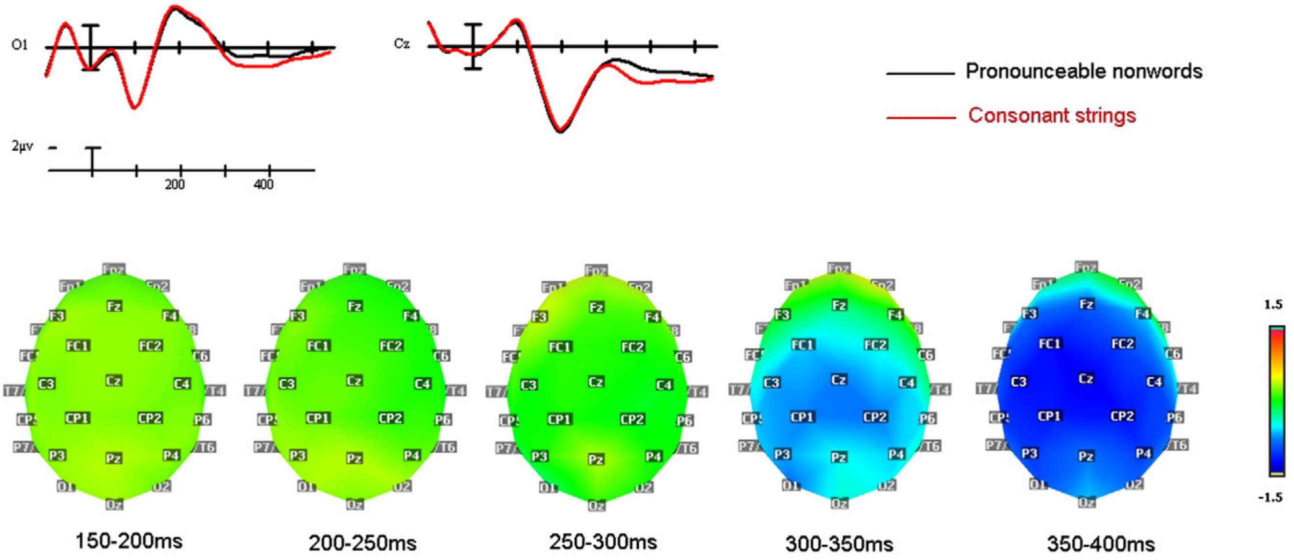

Fig. 5 – Main effect of type-of-target at O1 and Cz electrode sites, and voltage maps representing the voltage differences (pronounceable nonwords vs. consonant strings) at all electrode sites.

3.4. *Conclusions*

In the present study we compared processing of pronounceable nonwords and consonant strings that both differed from a real word by a single letter (e.g., STRENG, STRBNG). The earliest point of divergence in the ERP waveforms generated by these two types of stimuli was found to be at 290 ms post-stimulus onset at electrode site O1. However, differences in the priming effects seen to these two types of target were found to emerge earlier, with pronounceable nonwords showing both repetition priming (e.g., streng-STRENG) and word neighbor priming (e.g., strong–STRENG) between 200 and 300 ms post-target onset, whereas consonant strings only showed priming from word neighbor primes (e.g., strong–STRBNG) in this time window. This pattern of results suggests that feedback from whole-word orthographic representations to sublexical orthographic representations i) reduces the difference between consonant strings and pronounceable nonwords compared to that seen in prior work where the nonword stimuli did not have real word neighbors (Massol et al., 2011) and ii) enables early priming effects to emerge with consonant string targets.

4. Experimental procedures

4.1. *Participants*

Twenty-five undergraduate students (8 women, mean age = 18.9 years, SD = 1.6) were recruited at Tufts University. They received $20 for participation in this experiment. All were right-handed native speakers of English with normal or corrected to normal vision. One of these participants was excluded from analysis because of excessive artifacts during the experiment.

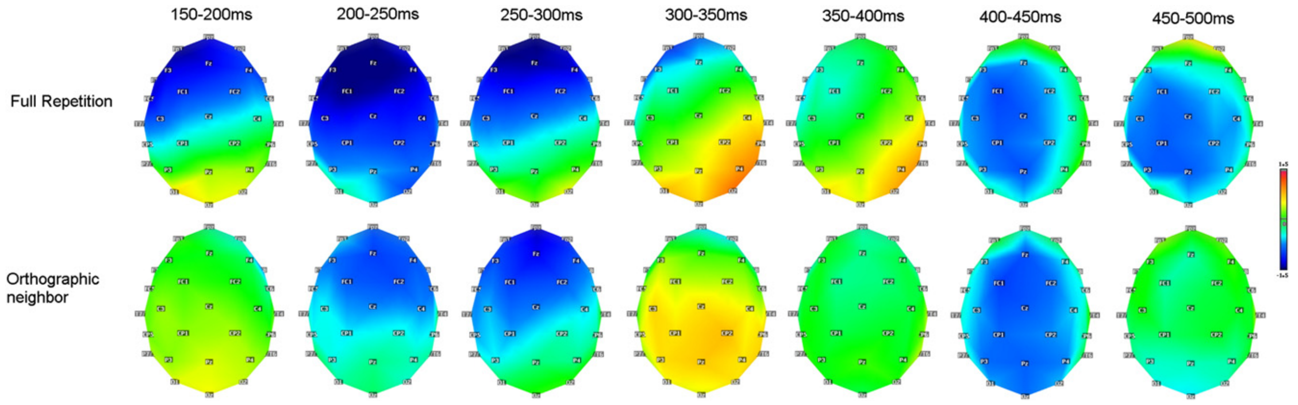

Fig. 6 – Voltage maps subtracting the voltage values in the related prime condition from the voltage values in the corresponding unrelated prime condition for pronounceable nonword targets in seven successive 50 ms time-windows starting from 150 ms post-target onset.

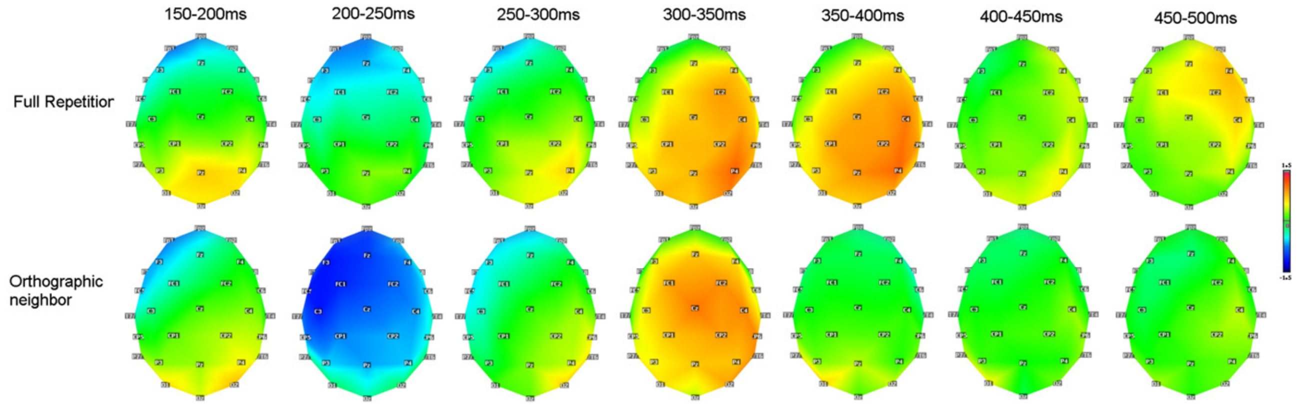

Fig. 7 – Voltage maps subtracting the voltage values in the related prime condition from the voltage values in the corresponding unrelated prime condition for consonant string targets in seven successive 50 ms time-windows starting from 150 ms post-target onset.

4.2. *Design and stimuli*

The stimulus set for this experiment consisted of 448 pairs of letter strings of 4–7 characters. The first member of each pair was referred to as the prime and the second member as the target. Targets were 224 pronounceable nonwords and 224 consonant strings. These two sets of target stimuli were matched for number of orthographic neighbors (consonant strings, $N = 2.13$ ($SD = 1.25$) and pronounceable nonwords, $N = 2.35$ ($SD = 1.24$), $p > .05$). Stimulus lists consisted of 448 trials each containing a prime–TARGET pair of items, with primes presented in lower case letters and targets in upper case (this was done in order to minimize the physical similarity between repeated items). All pronounceable nonword targets and consonant string targets were used to test for priming from a neighbor word and for effects of repetition priming. These two sets of 224 targets were separated into four lists of experimental stimuli presented to different participants. In each of four lists, there were 56 trials where the target was the full repetition of the prime (e.g., streng–STRENG; strbng–STRBNG), 56 trials where the target was preceded by an orthographic neighbor word (e.g., strong–STRENG, strong–STRBNG), and 112 trials where the target was completely unrelated to the prime (knaght–STRENG, bridge–STRENG, knsght–STRBNG, bridge–STRBNG). Across lists and participants, critical targets appeared once in each of the four conditions, and within lists, each target stimulus was presented once. In this way, participants saw each target only once but were tested in each experimental condition with different targets. However, across participants each item occurred an equal number of times in both related and unrelated conditions. TYPE-OF-TARGET (pronounceable nonword vs. consonant string) was crossed with TYPE-OF-PRIMING (repetition vs. word neighbor) and RELATEDNESS (related vs. unrelated) in a 2×2×2 factorial design. Unrelated prime–target pairs were formed by re-arranging the related prime–target pairs ensuring that there was minimal orthographic overlap between primes and targets in the re-pairings. An additional set of noncritical stimulus pairs was formed by 40 pairs in which the target was an English word. These words were used as probe items in a go/no-go lexical decision task (respond only if the stimulus is a word).

4.3. *Procedure*

Stimuli were presented as white letters centered vertically and horizontally on a black background on a CRT monitor (60 Hz refresh rate), with constant brightness and contrast of the display, using an in-house stimulus presentation program.

As can be seen in Fig. 1, each trial began with the presentation of a fixation cross (+) which remained on screen for 500 ms and was followed by a forward mask composed of 6 hash marks (######) for a duration of 500 ms. The forward mask was replaced at the same location on the screen by a lowercase prime for 50 ms. The prime was replaced by the target in uppercase letters for a duration of 500 ms. Each trial ended with 1500 ms of blank screen. Participants were instructed to rapidly press a response button whenever they detected an English word in the target position and were told to read all others stimuli passively (i.e., the critical stimuli did not require an overt response). Participants were asked to refrain from blinking and moving their eyes when the fixation stimulus appeared on the screen to minimize eye blink artifact during the recorded trials. A short practice session was administered before the main experiment to familiarize participants with the procedure and the lexical decision task.

4.4. *Electroencephalogram recording procedure*

After completing informed consent, participants were seated in a comfortable chair in a sound attenuating room. The electroencephalogram (EEG) was recorded continuously from 29 electrodes mounted on an elastic cap (Electro-cap International—see Fig. 2 for the location of electrodes). An additional electrode placed over the left mastoid (A1) was used as an online reference. Two additional electrodes were used to monitor for eye-related artifact (blinks and vertical or horizontal eye movement), one below the left eye (VE) and one horizontally next to the right eye (HE). A final electrode was placed over the right mastoid (A2), recorded actively to monitor for differential mastoid activity.

For all scalp electrodes impedances were maintained below 5 kΩ. Electrophysiological signals were amplified with an SA

Bio-amplifier with a bandpass filter of 0.01 and 40 Hz and digitized continuously on-line at a rate of 200 Hz. ERPs were time-locked to stimulus onset. Averaging was performed offline. After electrode placement, instructions for the experimental task were given. A short practice session was administered before the main experiment to familiarize participants with the procedure. The experiment required approximately 30 minutes to complete.

4.5. *Data analysis*

ERPs were calculated by averaging the EEG time-locked to target onset and lasting until 700 ms post-target onset. A 100 ms pre-target period was used as the baseline. Any trials with muscle artifact or eye movement/blink activity were excluded from the averaging process (7.67% of trials). The EEG was low-pass filtered offline at 20 Hz. Separate sets of repeated measures ANOVAs were run on the data from each of three time windows (200–300 ms, 300–400 ms and 400–500 ms) with factors of TYPE-OF-TARGET (pronounceable nonword vs. consonant string), TYPE-OF-PRIMING (repetition vs. word neighbor), RELATEDNESS (related vs. unrelated) and ELECTRODE-SITE. We employed an approach to data analysis in which the head is divided up into seven separate parasagittal columns along the antero-posterior axis of the head (see Fig. 2). The electrode sites in each of three pairs of lateral columns and one midline column were analyzed in separate ANOVAs. Three of these analyses (column 1, column 2, and column 3) involved a hemisphere factor (left vs. right). The fourth analysis only involved midline electrode sites (see Fig. 2). Finally, a fifth analysis included an anterior/posterior factor dividing all electrode sites, except those lying on the horizontal central line (T7, C3, Cz, C4 and T6) into two regions (anterior vs. posterior). We used the columnar approach to analyzing the spatial component of the ERP data because it provides a thorough analysis of the entire head breaking the scalp up into regions (left and right, front and back), whereas at the same time allowing single or small clusters of sites to influence the analysis (using a single electrode factor and a large number of sites can easily mask small regional effects). We have used this approach successfully in a number of previous studies (e.g., Holcomb & Grainger, 2006; Massol et al., 2010). The Geisser and Greenhouse (1959) correction was applied to all repeated measures with more than one degree of freedom (corrected *p* values are reported).

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