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## Research Report

# An ERP investigation of orthographic priming with superset primes<sup>☆</sup>



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## ABSTRACT

Prime stimuli formed by inserting unrelated letters in a given target word (called “superset” primes) provide a means to modify the relative positions of the letters shared by prime and target. Here we examined the time-course of superset priming effects in an ERP study using the sandwich-priming paradigm. We compared the effects of superset primes formed by the insertion of unrelated letters (e.g., maurkdet-MARKET), or by the insertion of hyphens (e.g., ma-rk-et-MARKET), with identity priming (e.g., market-MARKET), all measured relative to unrelated control primes. Behavioral data revealed significantly greater priming in the hyphen-insert condition compared with the letter-insert condition. In the ERP signal, letter-insert priming emerged later than hyphen-insert priming and produced a reversed priming effect in the N400 time-window compared with the more typical N400 priming effects seen for both hyphen-insert priming and identity priming. The different pattern of priming effects seen for letter-insert primes and hyphen-insert primes suggests that compared with identity priming, letter superset priming reflects the joint influence of: (1) a disruption in letter position information, and (2) an inhibitory influence of mismatching letters.

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## 1. Introduction

Relative-position priming has played a key role in the investigation of orthographic processing, providing important insights on how letter position information is represented and processed during the early phases of visual word recognition. In relative-position priming, primes and targets share a set of letters that respect their relative but not absolute,

length-dependent position in prime and target. In the majority of prior experiments, relative-position primes were formed by the removal of letters from the target word while preserving the correct letter order (so-called subset primes; e.g., slene-SILENCE). When a subset prime immediately precedes a word target it facilitates target word recognition compared with an orthographically unrelated prime (e.g., Humphreys et al., 1990; Peressotti and Grainger, 1999;

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Grainger et al., 2006). This finding is one of the main pieces of evidence demonstrating the flexibility with which letter identities are associated with a given position in a word (see Grainger, 2008 for a review). It demonstrates that letter positions are not rigidly encoded as in standard slot-based coding schemes, such as implemented in the Interactive Activation (McClelland and Rumelhart, 1981) and the Dual Route Cascaded (DRC) models of word reading (Coltheart et al., 2001). This has given rise to several new models of letter position coding that appeal to positional noise (Gomez et al., 2008; Norris et al., 2010), spatial coding (Davis, 2010), or open-bigram coding (Grainger and Van Heuven, 2003; Whitney, 2001) as a means to accommodate these and other findings.

The present work focuses on a different form of relative-position priming, namely superset priming. In superset priming, orthographically related nonword primes are formed by inserting unrelated letters in target words while preserving the correct order of the shared letters (e.g., silednhce-SILENCE). Superset priming thus allows one to examine the effects of unrelated letters on orthographic priming, in combination with the effects of relative-position priming. While prior research, to be summarized below, has provided behavioural demonstrations of superset priming, this is the first study to combine superset priming with the recording of event-related potentials (ERPs) in order to investigate the time-course of such priming effects.

In a masked priming study, Van Assche and Grainger (2006) were the first to provide evidence for superset priming. They found that superset primes formed by 1-letter and 2-letter insertions facilitated target word recognition to a similar extent as identity primes, compared with unrelated nonword primes that shared no letters with the target words. They further showed that even superset primes made of three-letter insertions produced significant priming compared with unrelated primes, albeit significantly less than identity primes. Welvaert et al. (2008) extended this work, and provided evidence for robust superset priming that varied as a function of the number of inserted letters. Importantly, in a meta-analysis of superset priming effects they found graded effects of number of inserted letters, with a small processing cost associated with each additional letter. The processing cost associated with unrelated letters in superset priming could be due to at least two factors: (1) each unrelated letter provides additional negative evidence with respect to target word identity; and (2) adding unrelated letters increases the mismatch in positional information concerning letters shared by prime and target. In the present study we compare inserted letter superset primes (e.g., maurkdet for the target MARKET) with hyphenated superset primes (e.g., ma-rk-et-MARKET) in order to examine the relative contribution of these two factors. Hyphenated primes are expected to be just as disruptive with respect to positional information, but much less disruptive in terms of negative evidence. Evidence in line with this possibility was provided by Peressotti and Grainger (1999), who found behavioural facilitation with primes formed by replacing the two central letters of 4-letter target words with a plus sign (e.g., F++R-FOUR) compared with different letter substitutions (e.g., FNBR-FOUR). Furthermore, the recording of ERPs will provide

important additional constraints on possible interpretations of these priming effects, given existing knowledge of the time-course of relative-position priming.

Prior research investigating relative-position priming effects using ERPs and subset primes (Carreiras et al., 2009; Grainger and Holcomb, 2009a; Ktori et al., 2012) has shown early priming effects on the N250 ERP component. Most important, with respect to the present study, is that priming effects with hyphenated subset primes (e.g., c-lle-t-COLLECT) emerged during the early part of the N250 ERP component (200–250 ms post-target onset), whereas priming effects with concatenated subset primes (e.g., cllet-COLLECT) emerged during the later part of the N250 component (250–300 ms post-target onset). Furthermore, it was found that displacing prime stimuli horizontally with respect to target stimuli wiped-out the earlier hyphenated priming effects but did not affect the later concatenated priming effects (Ktori et al., 2012). Hyphenated and concatenated subset primes, however, were found to produce a similar pattern of priming effects in the N400 time-window (300–500 ms post-target onset), in line with the behavioural evidence for no difference between these priming conditions (Grainger et al., 2006; Peressotti and Grainger, 1999). These results suggest that hyphens indeed provide positional information that leads to greater subset priming in the early phase of orthographic processing, when letter positions are coded using gaze-centered coordinates (Grainger and Van Heuven, 2003)<sup>1</sup>. They also suggest that the hyphens are not generating significant interference in later phases of orthographic processing, when letter positions are coded using length-independent word-centered coordinates. The hyphenated superset priming condition to be tested in the present study should therefore provide a baseline with which the effects of unrelated letters can be evaluated. Any difference between the hyphenated and inserted letter conditions will provide evidence that the unrelated letters are doing more than just disrupting positional information.

## 2. Results

### 2.1. Behavioral data

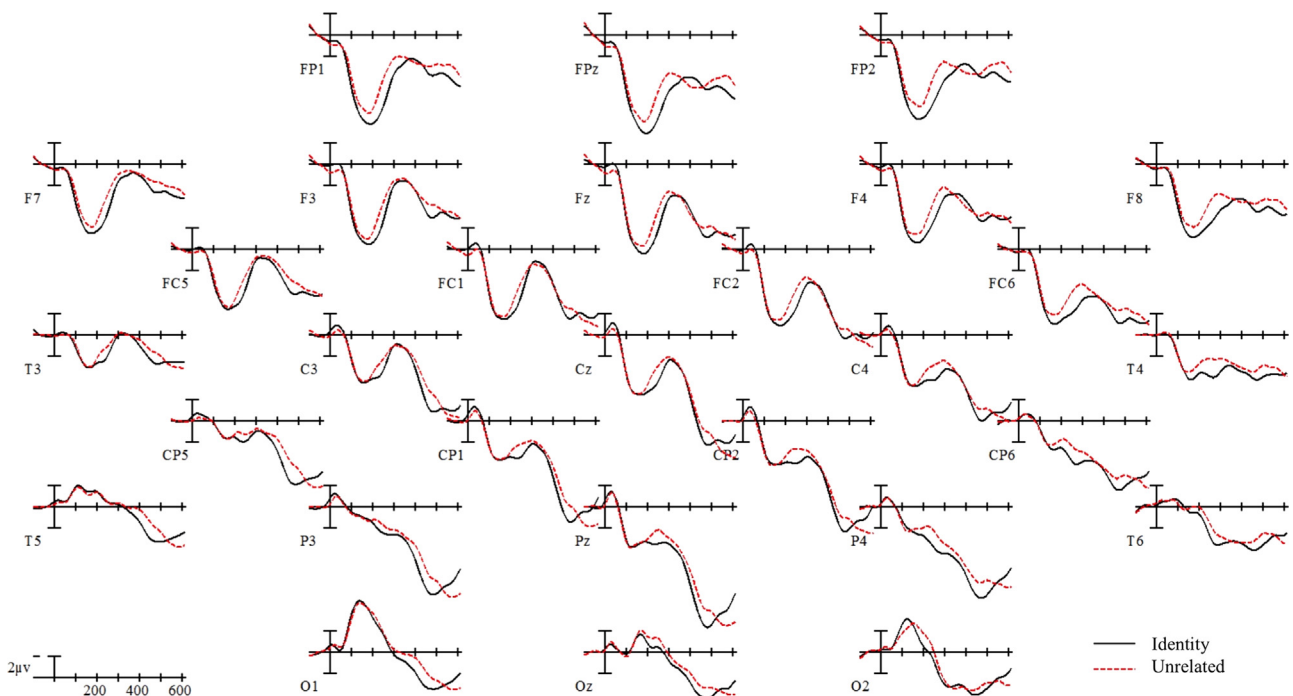
All correct lexical decisions less than 1500 ms post-target onset (92.1% of all data) and response error rate were included in the behavioral analyses. 3 (Prime Type) × 2 (Relatedness) within-groups ANOVAs were conducted separately on the mean RTs and percentage of errors per experimental condition for word and nonword stimuli, with participants ( $F_1$ ) and items ( $F_2$ ) as random variables. Mean RTs and % Errors to words and nonwords for each type of prime (identity, hyphen-insert, letter-insert) across related and unrelated conditions are presented in Table 1.

For words, analyses on mean RT revealed that the main effect of Prime Type ( $F_1(2, 38)=13.46, p<.001; F_2(2, 472)=6.98,$

<sup>1</sup>More precisely, the early phase of the N250 has been linked with the mapping of location-specific letter representations onto location-invariant sublexical representations, while the later phase of the N250 has been associated with the mapping of location invariant sublexical orthographic representations onto whole-word representations (Grainger and Holcomb, 2009b).

**Table 1 – Mean RTs (in ms) and % errors for word and nonword stimuli across experimental conditions; standard errors of the mean (SE) are given in parentheses.**

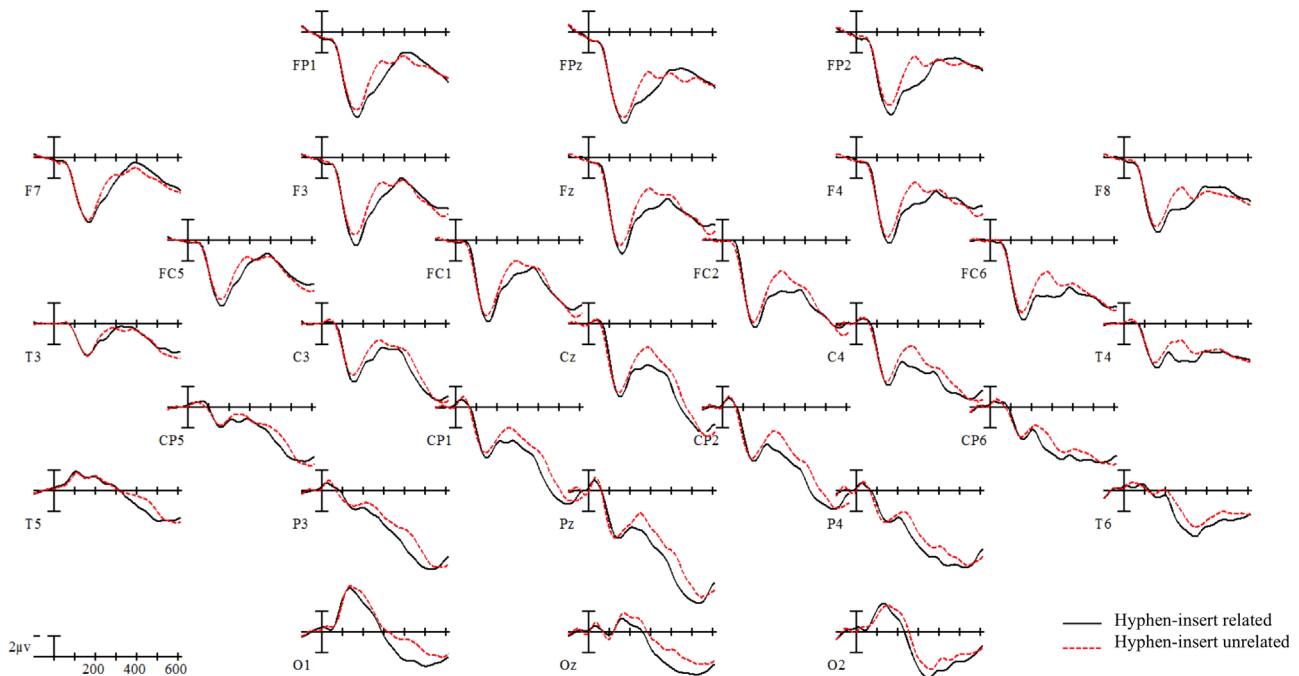
Words				Nonwords			
Prime type	Relatedness	Mean RTs	% Errors	Prime type	Relatedness	Mean RTs	% Errors
Identity	Related	575 (20.0)	2.3 (.6)	Identity	Related	704 (26.1)	10.0 (2.6)
	Unrelated	622 (19.9)	6.8 (1.1)		Unrelated	720 (24.7)	11.5 (2.6)
Hyphen-insert	Related	600 (21.8)	4.1 (.7)	Hyphen-insert	Related	739 (28.3)	9.8 (2.4)
	Unrelated	631 (20.7)	7.5 (1.6)		Unrelated	742 (27.3)	11.13 (2.2)
Letter-insert	Related	609 (19.9)	5.6 (1.1)	Letter-insert	Related	713 (28.1)	9.3 (2.1)
	Unrelated	628 (19.0)	5.8 (1.3)		Unrelated	739 (24.8)	10.8 (2.8)

**Fig. 1 – ERPs time-locked to target onset for all 29 scalp sites in the identity priming condition for word targets overplotted with the respective unrelated control condition. Target onset is marked by the vertical calibration mark, and each tick mark represents 100 ms. Negative values are plotted up.**

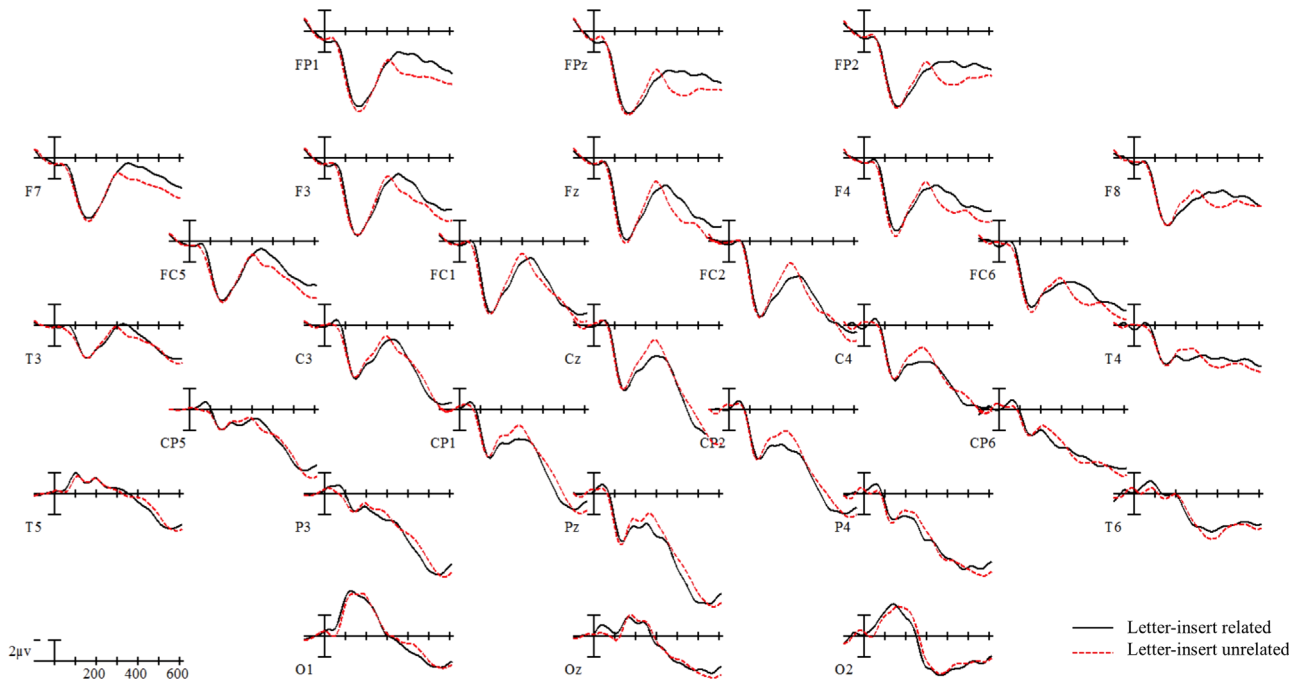
$p < .01$ ) was significant. Overall, across related and unrelated conditions words following identity primes were responded to faster than those following either hyphen-insert ( $F_1(1, 19) = 13.23, p < .01; F_2(1, 236) = 10.27, p < .01$ ) or letter-insert ( $F_1(1, 19) = 22.08, p < .001; F_2(1, 236) = 12.51, p < .01$ ) primes. The main effect of Relatedness was also significant ( $F_1(1, 19) = 41.11, p < .001; F_2(1, 236) = 58.65, p < .001$ ) with related primes producing faster response times than unrelated ones across all types of primes. The interaction between Prime Type and Relatedness was also significant ( $F_1(2, 38) = 4.28, p < .05; F_2(2, 472) = 6.11, p < .01$ ) reflecting a greater priming effect for identity primes ( $F_1(1, 19) = 39.97, p < .001; F_2(1, 236) = 45.46, p < .001; 47$  ms difference), a smaller priming effect for hyphen-insert primes ( $F_1(1, 19) = 14.14, p < .01; F_2(1, 236) = 18.97, p < .001; 31$  ms difference) and an even smaller priming effect for letter-insert primes ( $F_1(1, 19) = 8.51, p < .01; F_2(1, 236) = 3.27, p = .07; 19$  ms difference).

Statistical analyses on error percentages for word stimuli revealed a significant main effect of Relatedness ( $F_1(1, 19) = 7.35, p < .05; F_2(1, 236) = 28.34, p < .001$ ) with related primes producing smaller error rates than unrelated primes across the three different types of primes. Furthermore, the interaction between Prime Type and Relatedness was also significant ( $F_1(2, 38) = 3.60, p < .05; F_2(2, 472) = 4.02, p < .05$ ). While identity primes produced a greater priming effect ( $F_1(1, 19) = 12.41, p < .01; F_2(1, 236) = 23.46, p < .001; 5\%$  difference) than hyphen-insert primes ( $F_1(1, 19) = 4.21, p < .05; F_2(1, 236) = 14.84, p < .001; 3.4\%$  difference), letter-insert primes failed to produce any priming effect on error rates ( $F_1(1, 19) = .01, p = .92; F_2(1, 236) = .45, p = .50$ ).

For nonwords, the main effect of Prime Type ( $F_1(2, 38) = 16.87, p < .001; F_2(2, 472) = 9.11, p < .001$ ) was significant. Overall, across related and unrelated conditions nonwords following



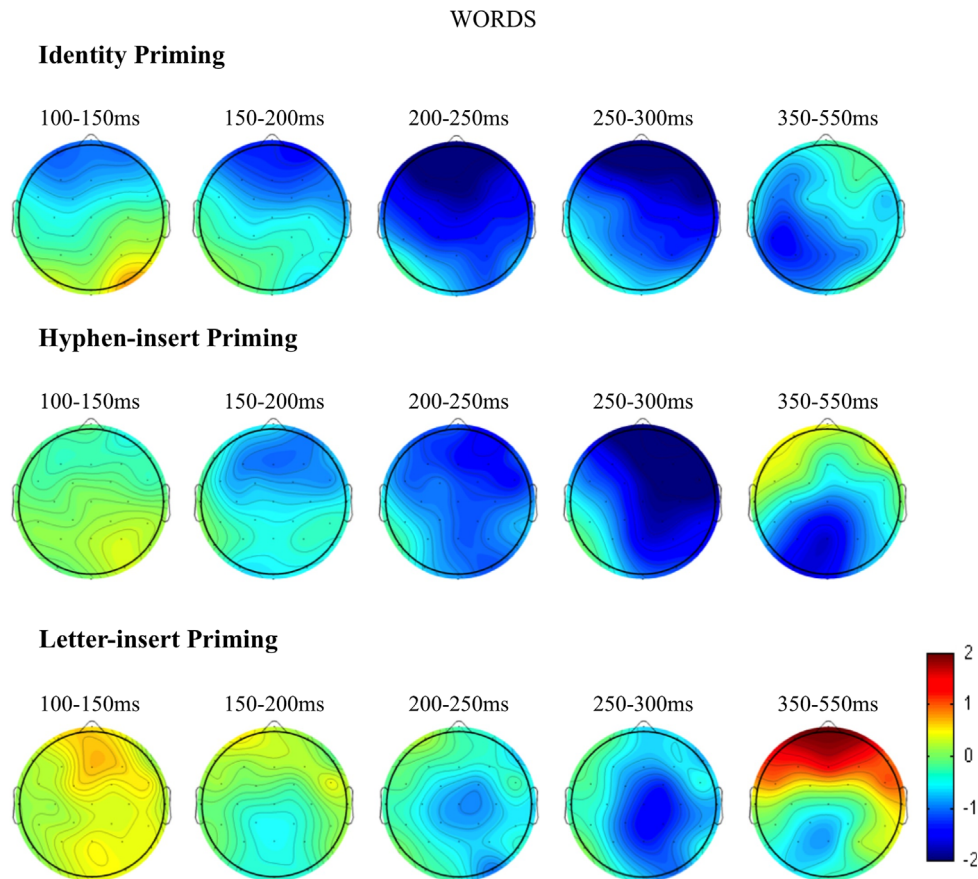
**Fig. 2** – ERPs time-locked to target onset for all 29 scalp sites in the related hyphen-insert priming condition for word targets overplotted with the respective unrelated control condition. Target onset is marked by the vertical calibration mark, and each tick mark represents 100 ms. Negative values are plotted up.



**Fig. 3** – ERPs time-locked to target onset for all 29 scalp sites in the related letter-insert priming condition for word targets overplotted with the respective unrelated control condition. Target onset is marked by the vertical calibration mark, and each tick mark represents 100 ms. Negative values are plotted up.

identity primes were responded to faster than those following either hyphen-insert ( $F_1(1, 19)=31.54, p<.001; F_2(1, 236)=17.93, p<.001$ ) or letter-insert ( $F_1(1, 19)=7.99, p<.05; F_2(1, 236)=3.12, p=.08$ ) primes, while nonwords following letter-insert primes were responded to faster than hyphen-insert primes ( $F_1(1,$

$19)=9.59, p<.001; F_2(1, 236)=6.01, p<.05$ ). The main effect of Relatedness was also significant ( $F_1(1, 19)=6.58, p<.05; F_2(1, 236)=12.68, p<.001$ ), with related primes producing faster response times than unrelated ones across all types of primes. The interaction between Prime Type and Relatedness was not



**Fig. 4 – Scalp maps for word targets showing the spatial distribution of priming effects expressed as voltage differences (Unrelated-Related) for each of the experimental conditions across the measurement windows used in the statistical analyses. The colorbar features a  $\mu\text{V}$  scale.**

significant ( $F_1(2, 38)=2.26, p=.12$ ;  $F_2(2, 472)=.80, p=.45$ ). Statistical analyses on error percentages rates for nonword stimuli revealed no significant effects.

## 2.2. Electrophysiological data

### 2.2.1. Word stimuli

ERP waveforms for each of the experimental conditions time-locked to target word stimuli from all 29 scalp sites are plotted in Figs. 1–3. Voltage maps formed from all 29 scalp sites contrasting the different types of priming effects within the five post-target onset latency windows used in the analyses (100–150 ms, 150–200 ms, 200–250 ms, 250–300 ms and 350–550 ms) are plotted in Fig. 4. For each of these measurement windows a series of ANOVAs on mean amplitude was conducted following the columnar analysis described in the experimental procedure with Prime Type (3), Relatedness (2), Hemisphere (2 for c1; c2 and c3) and Electrode Site (3 for c1; 4 for c2; 5 for midline and c3) as the main within-groups factors. ANOVAs were performed using the Greenhouse–Geisser epsilon correction for non-sphericity (Jennings and Wood, 1976) to all repeated measures with more than one degree of freedom in the numerator (corrected  $p$  values are reported). Reported are only results concerning the main effect of Relatedness, the interaction of this factor

with Prime Type and any further interactions with these two factors and the two distributional variables (i.e., Hemisphere and Electrode Site).

**2.2.1.1. 100–150 ms target epoch.** In this epoch, analyses on word targets revealed a significant interaction between Prime Type, Relatedness and Electrode Site at Column 3 ( $F(8, 152)=2.91, p<.05$ ). As it can be observed in Figs. 1 and 4 and confirmed by follow-up analyses, Relatedness interacted significantly with Electrode Site for identity primes only ( $F(4, 76)=5.83, p<.05$ ), with a significant negative-going effect on frontal electrodes (elec. Fp:  $F(1, 19)=4.19, p=.05$ ) and a significant positive-going priming effect on occipital electrodes (elec. O:  $F(1, 19)=4.62, p<.05$ ). Analyses on hyphen-insert and letter-insert primes revealed no significant effects in this time window.

**2.2.1.2. 150–200 ms target epoch.** In this time window, the analyses on mean amplitude to word targets revealed a main effect of Relatedness at Column 2 ( $F(1, 19)=6.80, p<.05$ ) and Column 3 ( $F(1, 19)=10.64, p<.01$ ). These effects were qualified further with a significant interaction between Prime Type, Relatedness and Electrode Site for Column 2 ( $F(6, 114)=3.33, p<.05$ ) and between Prime Type, Relatedness, Hemisphere and Electrode Site for Column 3 ( $F(8, 152)=2.31, p<.05$ ).

Follow-up analyses of these interactions showed that for identity primes, relatedness interacted significantly with Hemisphere ( $F(1, 19)=6.88, p<.05$ ) at Column 3. Identity priming at this column was significant over the right hemisphere only ( $F(1, 19)=7.66, p<.05$ ), with unrelated primes producing a more negative-going waveform than identity primes. Hyphen-insert primes produced a significant priming effect at Column 3 ( $F(1, 19)=4.3, p=.05$ ), while at Column 2 Relatedness interacted with Electrode Site ( $F(3, 57)=4.01, p<.05$ ) with priming effects being localized on frontal ( $F(1, 19)=4.19, p=.05$ ) and frontal-central ( $F(1, 19)=5.3, p<.05$ ) scalp sites. There were no significant results for letter-insert primes in this time window.

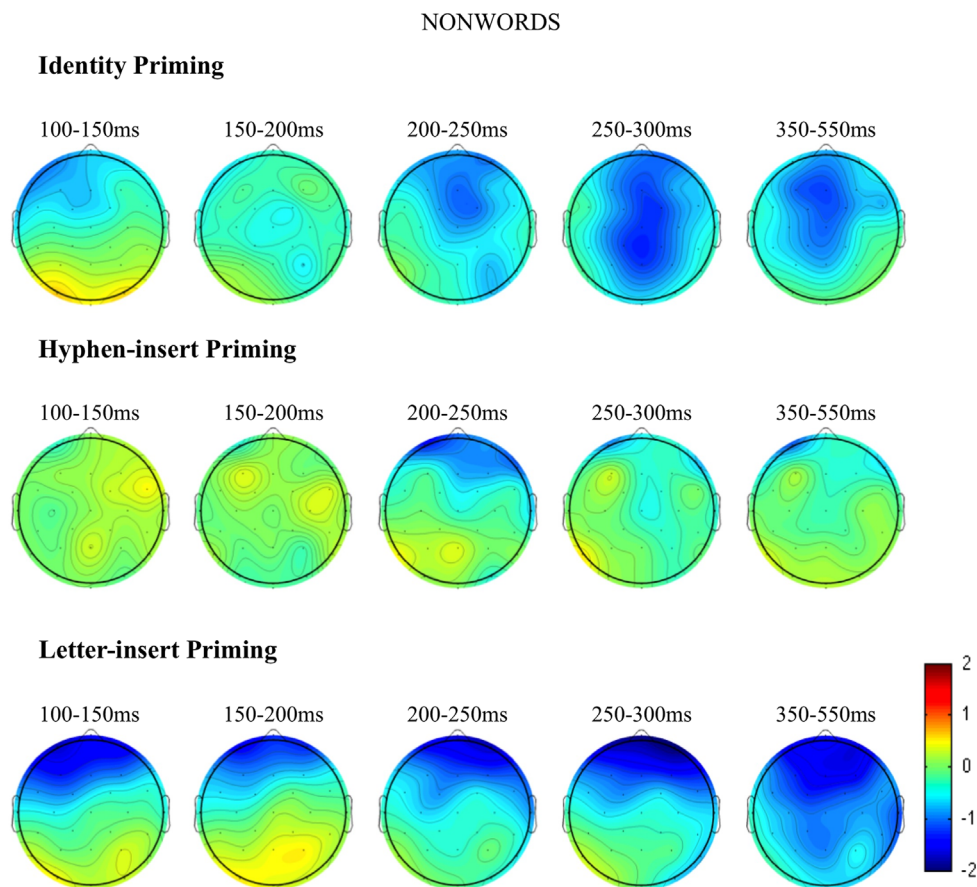
**2.2.1.3. 200–250 ms target epoch.** In this epoch, there was a significant main effect of Relatedness at all columns (midline:  $F(1, 19)=20.33, p<.01$ ; c1:  $F(1, 19)=20.09, p<.01$ ; c2:  $F(1, 19)=19.09, p<.01$ ; c3:  $F(1, 19)=32.32, p<.001$ ) with all types of prime producing priming effects (see Fig. 4). There were not significant interactions with Relatedness in this epoch.

**2.2.1.4. 250–300 ms target epoch.** This time window revealed a significant main effect of Relatedness across all columns (midline:  $F(1, 19)=28.67, p<.001$ ; c1:  $F(1, 19)=19.91, p<.01$ ; c2:  $F(1, 19)=22.16, p<.01$ ; c3:  $F(1, 19)=39.00, p<.001$ ). Furthermore, there was a significant higher order interaction

between Prime Type, Relatedness and Electrode Site at Column 3 ( $F(8, 152)=3.42, p<.05$ ).

Follow-up analyses of this interaction revealed that for identity primes Relatedness interacted significantly with Electrode Site at Column 3 ( $F(4, 76)=8.27, p<.05$ ) with identity primes producing significant priming effect on the frontal (elec. Fp:  $F(1, 19)=29.52, p<.001$ ; elec. F:  $F(1, 19)=22.35, p<.001$ ) and temporal (elec. T:  $F(1, 19)=7.63, p<.05$ ) electrodes only. Hyphen-insert primes also revealed a significant interaction between Relatedness and Electrode Site at Column 3 ( $F(4, 76)=8.14, p<.01$ ) reflecting a more robust priming effect over anterior-temporal sites (elec. Fp:  $F(1, 19)=20.23, p<.001$ ; elec. F:  $F(1, 19)=17.13, p<.001$ ; elec. T:  $F(1, 19)=13.12, p<.01$ ) compared with more posterior-temporal sites (elec. T (5, 6):  $F(1, 19)=3.88, p=.06$ ; elec. O:  $F(1, 19)=6.43, p<.05$ ). Letter-insert primes revealed no priming effects at Column 3.

**2.2.1.5. 350–550 ms target epoch.** In this final time window Relatedness interacted with Electrode Site ( $F(2, 38)=7.63, p<.01$ ) at Column 1, with priming being significant over central-parietal sites only across all prime types ( $F(1, 19)=7.21, p<.05$ ). At midline, the interaction between Prime Type and Relatedness approached significance ( $F(2, 38)=3.34, p=.06$ ) with only hyphen-insert primes producing a significant priming effect at this column ( $F(1, 19)=5.17, p<.05$ ). Prime Type interacted significantly with Relatedness at



**Fig. 5 – Scalp maps for nonword targets showing the spatial distribution of priming effects expressed as voltage differences (Unrelated-Related) for each of the experimental conditions across the measurement windows used in the statistical analyses. The colorbar features a  $\mu\text{V}$  scale.**

Columns 2 ( $F(2, 38)=3.58, p<.05$ ) and 3 ( $F(2, 38)=3.64, p<.05$ ), while at Column 3 these variables interacted further with Electrode Site ( $F(8, 152)=2.88, p<.05$ ). Further analyses exploring these interactions showed that at Column 2 only identity primes produced a significant priming effect ( $F(1, 19)=4.6, p<.05$ ) with unrelated primes showing less positivity compared to identity primes. At Column 3, Relatedness interacted with Electrode Site for both hyphen-insert ( $F(4, 76)=8.81, p<.01$ ) and letter-insert ( $F(4, 76)=8.33, p<.01$ ) primes. Hyphen-insert priming was only present over the temporal-parietal ( $F(1, 19)=3.50, p=.08$ ) and occipital ( $F(1, 19)=17.79, p<.01$ ) electrode sites of this column. Reversed letter-insert priming, however, was present over the frontal scalp sites (elec. Fp:  $F(1, 19)=9.07, p<.01$ ; elec. F:  $F(1, 19)=8.42, p<.05$ ) with related letter-insert primes producing a more negative-going waveform than the corresponding unrelated letter-insert primes (see Figs. 3 and 4).

### 2.2.2. Nonword stimuli

As with the word stimuli, the ERP data for the nonwords were analyzed within the same five post-target onset latency windows and following the same ANOVA repeated measures design and columnar analyses. Voltage maps for nonword stimuli contrasting the different type of priming effects within the five post-target onset latency windows used in the analyses are plotted in Fig. 5.

**2.2.2.1. 100–150 ms target epoch.** In this epoch, analyses on nonword targets revealed a significant interaction between Relatedness and Electrode Site at midline ( $F(4, 76)=5.92, p<.05$ ) with priming being significant over the very frontal electrode Fpz ( $F(1, 39)=5.00, p<.05$ ). Furthermore, Prime Type interacted significantly with Relatedness and Electrode Site at both Column 2 ( $F(6, 114)=3.17, p<.05$ ) and Column 3 ( $F(8, 152)=4.40, p<.05$ ). Further analyses of these interactions revealed that nonword targets following identity primes produced a significant interaction between Relatedness and Electrode Site at this Column 3 ( $F(4, 76)=8.17, p<.01$ ), with a negative-going effect on frontal electrodes that approached significance (elec. Fp:  $F(1, 19)=3.28, p=.09$ ) and a significant positive-going priming effect on occipital electrodes (elec. O:  $F(1, 19)=4.34, p=.05$ ) when the target followed identical primes compared with unrelated primes. Letter-insert primes also showed a significant interaction between Relatedness and Electrode Site at Columns 2 ( $F(3, 57)=9.17, p<.01$ ) and 3 ( $F(4, 76)=10.81, p<.01$ ). Letter-insert priming was significant over the frontal sites of these columns (c2:  $F(1, 19)=5.38, p<.05$ ; c3 (elec. Fp):  $F(1, 19)=12.4, p<.01$ ; c3 (elec. F):  $F(1, 19)=7.15, p<.05$ ; see Fig. 5).

**2.2.2.2. 150–200 ms target epoch.** In this time window, the analyses on mean amplitude to nonword targets showed that at Column 3, Relatedness interacted significantly with Electrode Site ( $F(4, 76)=4.39, p<.05$ ), with only the very frontal electrode Fp producing significant priming across all prime types ( $F(1, 19)=6.66, p<.05$ ).

**2.2.2.3. 200–250 ms target epoch.** In this epoch, the analyses on mean amplitude to nonword targets revealed a significant main effect of Relatedness at both midline ( $F(1, 19)=6.40, p<.05$ ) and Column 3 ( $F(1, 19)=9.43, p<.01$ ). Over the same

electrode columns Relatedness interacted significantly with Electrode Site (midline:  $F(4, 76)=4.53, p<.05$ ; c3:  $F(4, 76)=6.9, p<.01$ ), as priming effect across all prime types was localized over the frontal sites at midline (elec. Fpz:  $F(1, 19)=12.66, p<.01$ ; elec. F:  $F(1, 19)=6.78, p<.05$ ) and frontal (elec. Fp:  $F(1, 19)=14.05, p<.01$ ; elec. F:  $F(1, 19)=5.32, p<.05$ ) and temporal (elec. T:  $F(1, 19)=6.33, p<.05$ ) scalp sites at Column 3.

**2.2.2.4. 250–300 ms target epoch.** In this time window there was a significant main effect of Relatedness at midline ( $F(1, 19)=12.76, p<.01$ ) and Column 1 ( $F(1, 19)=4.31, p=.05$ ), with unrelated primes producing a more negative-going waveform than the corresponding related ones across all prime types. Furthermore, the main effect of Relatedness was also significant at Column 3 ( $F(1, 19)=6.70, p<.05$ ) and this interacted significantly with Electrode Site ( $F(4, 76)=7.02, p<.01$ ), with only the frontal electrodes exhibiting priming effect across all prime types (elec. Fp:  $F(1, 19)=13.6, p<.01$ ; elec. F:  $F(1, 19)=7.89, p<.05$ ).

**2.2.2.5. 350–550 ms target epoch.** Analyses of nonwords in this final epoch, revealed a significant main effect of Relatedness across all columns (midline:  $F(1, 19)=9.89, p<.01$ ; c1:  $F(1, 19)=6.43, p<.05$ ; c2:  $F(1, 19)=5.47, p<.05$ ; c3:  $F(1, 19)=6.07, p<.05$ ). At Column 3, there was also a significant interaction between Relatedness and Electrode Site, due to priming being localized on the frontal (elec. Fp:  $F(1, 19)=9.19, p<.01$ ; elec. F:  $F(1, 19)=5.52, p<.05$ ) and temporal (elec. T:  $F(1, 19)=4.59, p<.05$ ) sites of this column.

## 3. Discussion

In the present study we found evidence for robust priming effects from superset primes in both the behavioral and the electrophysiological (ERP) data. The facilitatory behavioral priming effects are in line with prior investigations of superset priming that also showed reduced priming effects for superset compared with identity primes (Welvaert et al., 2008). The size of the letter-insert superset priming effect in the present study, measured relative to an unrelated prime condition, is smaller than that predicted by Welvaert et al.'s meta-analysis. However, while the studies reported in the meta-analysis used standard masked priming, sandwich priming was employed in the present study. Sandwich priming has been demonstrated to provide a more sensitive measure of behavioral and ERP priming effects (Lupker and Davis, 2009; Ktori et al., 2012) and could as such capture a heightened interference emanating from the unrelated letters in superset primes compared to what has been previously observed in the literature. Most important, however, is that in the present study we found significantly greater priming in the hyphen-insert priming condition compared with letter-insert priming. This finding suggests that the net effect of letter-insert priming is the result of both the disruption of positional information, which operates for letter-insert and hyphen-insert primes, and the interfering effects of unrelated letters, which only operates for letter-insert primes.

**Table 2 – Summary of priming effects for word targets when analyzed separately for each prime type and electrode column across the time-windows used in the analysis. Significant ( $p < .05$ ) main effects of relatedness are reported, or effects at specific locations when there is a significant interaction between Relatedness and Electrode Site and/or Hemisphere.**

Words		100–150 ms	150–200 ms	200–250 ms	250–300 ms	350–550 ms
Identity	Midline	ns	ns	Main	Frontal; central	ns
	Column 1	ns	ns	Main	Main	Left
	Column 2	ns	ns	Main	Main	Left
	Column 3	Frontal; occipital	Right	Frontal; temporal	Frontal; temporal	ns
Hyphen-insert	Midline	ns	ns	Main	Main	Central; parietal; occipital
	Column 1	ns	ns	ns	right	Central-parietal
	Column 2	ns	Frontal; frontal-central	Main	right	Parietal
	Column 3	ns	Main	Main	Main	Left temporal-parietal; occipital
Letter-insert	Midline	ns	ns	ns	Main	Frontal <sup>R</sup>
	Column 1	ns	ns	Main	Main	ns
	Column 2	ns	ns	ns	ns	Frontal <sup>R</sup>
	Column 3	ns	ns	ns	ns	Frontal <sup>R</sup>

Note. ns = not significant; Main = Main effect; R = reversed priming effect.

Regarding the ERP results (Figs. 1–5), the main findings are summarized in Table 2. The pattern of identity priming effects is similar to what has been found in prior research, with modulation of the early N/P150 with its typical negative-going frontal effect and positive-going occipital effect, followed by modulation of the N250 component with its typical central-anterior spatial distribution, and finally modulation of the N400 component with its more central-posterior distribution. Most important is the distinct pattern of priming effects seen for the two superset priming conditions, both of which emerged later than identity priming. Hyphen-insert priming effects were first seen in the early N250 time-window, and continued to be robust in following time-windows. On the other hand, effects of letter-insert primes emerged even later, and showed a reverse priming effect in the N400 time-window, with related primes generating greater negativity in central and frontal electrode sites. This reversed priming effect seen for letter-insert primes provides further evidence for the interference generated by mismatching letters during target word processing. Within the framework of Grainger and Holcomb's (2009b) account of the time-course of visual word recognition, the timing of the reversed letter-insert priming effect suggests that bottom-up inhibition from mismatching letters takes longer to affect activity in whole-word representations than bottom-up matching information.

Thus, the overall pattern of behavioral and ERP priming seen in the present study suggests that, compared with identity priming, letter-insert priming effects reflect the joint influence of (1) a disruption in letter position information, and (2) an inhibitory influence of mismatching letters. The effect of disrupting letter position information is in line with recent accounts of letter position encoding (e.g., the overlap open-bigram model,

Grainger et al., 2006; the Bayesian-Reader model, Norris et al., 2010; the both-edges coding model, Fischer-Baum et al., 2011; the overlap model, Gomez et al., 2008; the SERIOL model, Whitney, 2001; and the Spatial Coding model, Davis, 2010). All these models allow sufficient flexibility in letter position coding to be able to account for superset priming effects (measured against unrelated control primes), while explaining the difference between superset primes and repetition primes by the imprecise positional information afforded by superset primes. Only an unconstrained open-bigram model, as described by Grainger et al. (2006), incorrectly predicts equivalent priming from superset and identity primes, when the interfering effects of placeholder stimuli are minimized. Nevertheless, although hyphens were chosen to function as placeholders that generate minimal interference, they still might generate an interfering effect on target word identification, albeit less so than inserted letters. Thus, it remains to be seen whether or not superset-priming effects could be increased to a level comparable to that of identity priming, by using placeholder stimuli that generate less interference than hyphens. Such a result would be highly constraining with respect to current approaches to the encoding of letter position information during orthographic processing. Furthermore, regarding the interference of mismatching letters that was observed in letter-insert priming, it should be noted that most of the aforementioned models of orthographic processing do not include an appropriate bottom-up mechanism that could account for the inhibitory influence of unrelated letters in the prime. Such a mechanism is present in the family of interactive-activation models (McClelland and Rumelhart, 1981) in which letter-word connectivity can be both excitatory and inhibitory (see Peressotti and Grainger, 1999, for a simulation study).



**Table 3 – Summary of priming effects for nonword targets when analyzed separately for each prime type and electrode column across the time-windows used in the analysis. Significant ( $p < .05$ ) main effects of Relatedness are reported, or effects at specific locations when there is a significant interaction between Relatedness and Electrode Site and/or Hemisphere.**

Nonwords		100–150 ms	150–200 ms	200–250 ms	250–300 ms	350–550 ms
Identity	Midline	ns	ns	ns	Main	Main
	Column 1	ns	ns	ns	ns	ns
	Column 2	ns	ns	ns	ns	ns
	Column 3	Occipital	ns	ns	ns	ns
Hyphen-insert	Midline	ns	ns	ns	ns	ns
	Column 1	ns	ns	ns	ns	ns
	Column 2	ns	ns	ns	ns	ns
	Column 3	ns	ns	Frontal	ns	ns
Letter-insert	Midline	Frontal	Frontal	Frontal	Frontal	Main
	Column 1	ns	ns	ns	ns	ns
	Column 2	Frontal	ns	ns	Frontal	Main
	Column 3	Frontal	Frontal	Frontal; temporal	Frontal	Frontal; temporal; occipital

Note. ns=not significant; Main=Main effect.

The ERP letter-insert priming effects found in the present study have a similar time-course to the non-adjacent TL priming effects observed in another study of ours (Ktori et al., 2014). What properties might letter-insert and non-adjacent primes share that could be driving this pattern of short-lived ERP priming effects? We would argue that the most likely answer to this question is the amount of mismatching orthographic information carried by these two types of prime. This can be illustrated using an unconstrained open-bigram model, and calculating the number of mismatching bigrams—that is the number of bigrams in the prime stimulus that are not present in the target. In the adjacent TL primes tested by Ktori et al. (2014) there is one mismatching bigram, whereas non-adjacent TL primes have five mismatching bigrams. Now, in the letter-insert primes of the present study there are 13 mismatching bigrams, much more than in the non-adjacent TL primes of Ktori et al. (2014)'s study. This might explain why these non-adjacent TL priming effects did not exhibit the same reversed centro-frontal priming effect as seen with letter-insert primes in the N400 time-window in the present study. That is, the amount of bottom-up mismatching information was enough to cancel N400 priming effects with non-adjacent TL primes, but not enough to reverse the priming effect, as found with letter-insert primes.

The present study did not investigate a possible influence of the consonant–vowel (CV) status of inserted letters on the size of superset priming effects. Past research has demonstrated that relative-position (subset) priming effects are sensitive to the CV status of the letters shared by primes and targets (Carreiras et al., 2009; Duñabeitia and Carreiras, 2011). In particular, across both behavioral and electrophysiological measures it has been shown that while subset primes composed of consonant letters only (e.g., csn–CASINO) produced similar effects to identity primes, subset primes composed of vowel letters only (e.g., aia–ANIMAL) produced priming effects similar to unrelated primes. This pattern is likely due to the fact that consonants are more informative with respect to word identity than vowels are, and hence facilitate lexical access to a greater extent (see Duñabeitia and Carreiras, 2011; for more discussion on the Lexical Constraint Hypothesis). In the current study, the majority of the inserted letter pairs involved at least

one consonant (out of 240 only one vowel–vowel letter pair for words and nine for nonwords), and these pairs were the same across the related and unrelated letter-insert prime conditions. Future research could therefore compare superset priming with only consonant and only vowel insertions in order to enhance our understanding of the contribution of the CV status of letters in orthographic processing.

Finally, we found robust behavioral and ERP priming for nonword targets. The RT data revealed a facilitatory main effect of priming and no interaction with prime type. Nevertheless, Table 1 shows that the numerically largest priming effect was seen for letter-insert primes, and Table 3 and Fig. 5 shows that ERP priming effects were systematically greater for letter-insert than hyphen-insert primes, although the interaction between Prime Type and Relatedness was only significant in the 100–150 ms time-window. Most strikingly, the pattern of letter-insert ERP priming effects seen with nonword targets strongly contrasts with that seen with word targets. Identity priming, on the other hand, showed a qualitatively similar pattern for both words and nonwords, with albeit greatly reduced effects in nonword targets (compare Figs. 4 and 5). We hypothesize that the contrasting effects of letter-insert primes on word and nonword targets might well reflect the inhibitory influence of mismatching letters operating on lexical representations. While this inhibitory influence reduces priming for word targets, it can increase priming for nonword targets by diminishing evidence in favor of a “word” response and, as a consequence, increasing the evidence in favor of a “nonword” response (Dufau et al., 2012). Thus, when processing a nonword target such as “garken”, it is activation of the whole-word representation for “garden” (and possibly other similar words) that slows down the decision process to respond that this is not a word. By inserting unrelated letters in the prime stimulus (e.g., “gamrkven”), there is more negative evidence for the word “garden”, and therefore its activation level is reduced, hence speeding the decision to respond that “garken” is not a word. The same mechanism can therefore explain both the greatly reduced priming (even reversed in the last time window) seen with letter-insert primes and word targets, and the strong priming seen with letter-insert primes and nonword targets.

In conclusion, we found clear differences in priming effects for letter-insert primes compared with hyphen-insert primes, in both behavioral measures and in the ERP results. The behavioral data showed stronger facilitation with hyphen-insert primes than letter-insert primes, and the ERP priming effects on the N400 component suggest that the reduced priming for letter-insert primes might be due to interference generated by the mismatching letters. Overall, the present results suggest that the diminished priming seen with letter-insert superset primes compared with identity primes is due to both a disruption in letter position information and an interfering effect of the inserted letters.

## 4. Experimental procedure

### 4.1. Participants

Twenty-four individuals were recruited at San Diego State University. All participants were paid volunteers, right-handed, native speakers of English, reported having normal or corrected-to-normal vision, and none reported any linguistic or neurological impairment. The data from four participants were excluded from the analyses due to either a high percentage of errors in the behavioural data or excessive eye movement artifact in the electrophysiological data. The remaining twenty participants (14 females, 6 males) ranged in age from 19 to 25 years (mean 21, *sd* 1.47).

### 4.2. Design and stimuli

A set of 240 words was selected from the English Lexicon Project (ELP) database (Balota et al., 2007). Word stimuli were 6-letter long with no letter repetitions, bore no diacritics, were nouns or adjectives and had a mean CELEX (<http://www.ru.nl/celex>) log frequency of 1.48 (*SD*=.45, range 0.45–2.79). An additional set of 240 nonwords was selected from the ELP database for the purpose of the lexical decision task, and care was taken to avoid any pseudohomophones. In order to ensure the effectiveness of the selected stimuli, mean response accuracy for lexical decisions collected as part of the ELP was taken into consideration and was no less than 91% (mean=98%, *SD*=0.03) for words and 82% (mean=93%, *SD*=0.05) for nonwords. Each of these target stimuli (i.e., words and nonwords) was paired with an equal number of identity primes, hyphen-insert primes, and letter-insert primes. Identity primes were essentially repetitions of the target stimulus (e.g., “market” for the target “MARKET”) while superset primes were formed by either inserting two hyphens (ma-rk-et) or two different letters (maurkdet) in the target stimulus. The consonant–vowel status of the two inserted letters forming the letter-insert primes comprised 53.3% of consonant–consonant pairs, 46.3% of consonant–vowel pairs, and 0.4% of vowel–vowel pairs for words, and 44.6%, 51.6%, and 3.8% respectively for nonwords. An equal number of unrelated primes were also selected to create a set of unrelated prime conditions to correspond to the related conditions above. Unrelated primes had no orthographic overlap with targets, and the additional inserted letters in the unrelated letter-insert prime condition comprised the same letter pairs as in the related condition. Six lists of experimental trials were

created with different pseudo-randomizations using the constraints that each target stimulus appeared once in each list and in all the experimental conditions across all lists. This design ensured that each experimental condition was equally represented throughout the experiment (i.e., 40 repetitions per list) and that the grand average ERP comparisons between conditions always involved the same and the entire set of target stimuli. Following a practice session of 12 trials, each participant was assigned to a stimulus list in a counterbalanced order. Experimental trials were presented in a random order and participants were given the opportunity to rest every 60 trials.

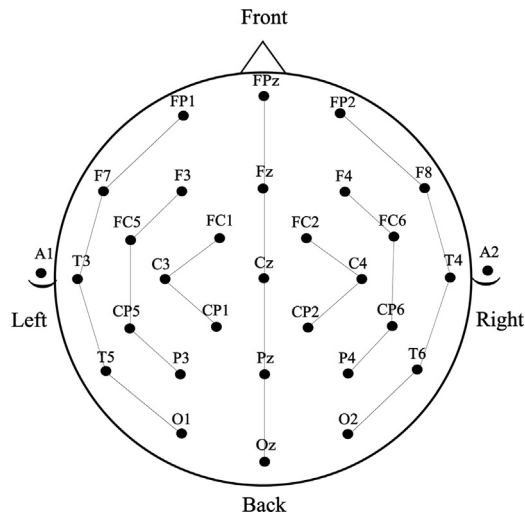
### 4.3. Procedure

Participants were run individually in a sound-attenuated and dimly illuminated room. Each participant sat comfortably 150 cm in front of a 24” LCD monitor with a vertical refresh rate set to 100 Hz. We used an ASUS VG248Q gaming monitor with a 1 ms gray-to-gray response time set at a screen resolution of 1920 × 1080 pixels. The timing of stimuli and time locking to ERP recording was verified using a photo diode and oscilloscope prior to the experiment. Visual stimuli were displayed at high contrast as white letters on a black background in Courier New font (targets and mask 64 × 32 pixels and primes 46 × 28 × 28 pixels per letter/character). All words subtended less than 2 degrees of horizontal visual angle.

A sandwich masked priming lexical decision task was used (Lupker and Davis, 2009). Each trial began with the presentation of a mask in the middle of the screen for 500 ms. The mask was formed by 10 hash marks and therefore sufficiently long to cover over and beyond all primes. Two vertical lines were also positioned centrally above and below the mask indicating the point of fixation. The mask was replaced at the same location with a first presentation of the target stimulus in upper case for 30 ms. This was immediately followed by the prime stimulus in lower case for 50 ms. The target stimulus was then presented again in upper case for 500 ms, following the standard sequence of events for sandwich priming (mask–target–prime–target). Participants were instructed to indicate as quickly and as accurately as possible whether the target stimulus was an English word or not by pressing a response key with the right or left hand respectively. The trial ended with the presentation of a blank screen for 2000 ms. On every other trial, a symbol stimulus (“- -”) appeared in the middle of the screen for 2500 ms allowing participants to blink their eyes. The next trial followed a 500 ms blank screen interval.

### 4.4. ERP recording procedure

The electroencephalogram (EEG) was recorded continuously from 29 electrodes mounted on an elastic cap (Electro-cap International see Fig. 6 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 eye (LE) and one horizontally next to the right eye (HE). A final electrode placed over the right mastoid (A2) recorded actively to monitor



**Fig. 6 – Electrode montage and the four analysis columns used for ANOVAs; midline and extending outwards columns 1 to 3.**

for differential mastoid activity. For all scalp electrodes impedances were maintained below 5 k $\Omega$ . 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 250 Hz throughout the experiment.

#### 4.5. ERP data analysis

Averaged ERPs time-locked to a point 100 ms pre-target onset and lasting until 600 ms post-target onset were formed off-line from trials free of ocular, muscular artifact and response errors (less than 10% of all trials) and were low pass filtered at 0.01 and 15 Hz. Separate ERPs were formed for the six experimental stimuli conditions (words and nonwords separately) defined by the factorial combination of Prime Type (targets stimuli preceded by either identity, hyphen-insert, or letter-insert primes) and Relatedness (target stimuli preceded by primes either related or unrelated to the target).

The main analysis approach involved measuring mean amplitudes in five post-target onset latency windows determined from inspection of the grand average waveforms. These included four successive 50-ms latency windows starting at 100 ms up to 300 ms post-target onset capturing the temporal evolution of the N/P 150 and N250 components, and a final fifth latency window from 350 to 550 ms post-target onset capturing the N400 component.

To thoroughly analyze the full montage of 29 scalp sites, we employed an approach to data analysis that has been successfully applied in a number of previous studies (e.g., Massol et al., 2011). In this scheme, the 29-channel electrode montage is divided up into seven separate parasagittal columns along the anteroposterior axis of the head (see Fig. 6). The electrodes in each of three pairs of lateral columns and one midline column are analyzed in four separate ANOVAs. Three of these analyses (referred to as Column 1/c1, Column 2/c2, or Column 3/c3) involved an anterior/posterior Electrode Site factor with either three, four,

or five levels, as well as a Hemisphere factor (left vs. right). The fourth “midline” analysis included a single anterior/posterior Electrode Site factor with five levels.

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