

The “electrophysiological sandwich”: A method for amplifying ERP priming effects

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Abstract

We describe the results of a study that combines ERP recordings and sandwich priming, a variant of masked priming that provides a brief preview of the target prior to prime presentation (S. J. Lupker & C. J. Davis, 2009). This has been shown to increase the size of masked priming effects seen in behavioral responses. We found the same increase in sensitivity to ERP priming effects in an orthographic priming experiment manipulating the position of overlap of letters shared by primes and targets. Targets were 6-letter words and primes were formed of the 1st, 3rd, 4th, and 6th letters of targets in the related condition. Primes could be concatenated or hyphenated and could be centered on fixation or displaced by two letter spaces to the left or right. Priming effects with concatenated and/or displaced primes only started to emerge at 250 ms post-target onset, whereas priming effects from centrally located hyphenated primes emerged about 100 ms earlier.

Descriptors: Sandwich priming, ERPs, Orthographic priming, Relative-position priming, Location invariance

In the conventional form of masked priming used for the study of visual word recognition, a prime stimulus immediately precedes a word target to which readers respond. The brief presentation of the prime stimulus (typically around 50 ms) allows its processing to occur subliminally with readers being unaware of its presence, and thus preventing the employment of any strategic effects in response to the target. Albeit brief, however, prime presentation is sufficient to potentially influence the processing of the target, and differences in performance to targets are measured as a function of the nature of the preceding prime stimulus, estimating as such the extent of the priming effect. These exact properties rendered the use of masked priming fundamental in the investigation of the fast and highly automatized processing performed by skilled readers during visual word recognition.

Masked priming has been extensively employed to investigate the intricacies involved in lexical processing and orthographic input coding, in particular (e.g., Forster & Davis, 1984; Perea & Lupker, 2004; Peressotti & Grainger, 1999; Segui & Grainger, 1990). A prime that is orthographically related to a given target word is believed to activate, to some extent at least, some of the representations involved in target word processing, hence modifying this processing and generating a priming effect. Essentially, the magnitude of the priming effect can be regarded as an index of the orthographic similarity between prime and target stimuli. Systematic manipulations of this orthographic similarity and measure-

ments of the magnitude of the resulting priming effects have led to important insights into the nature of the orthographic input code. The most important of these masked priming contributions is perhaps the flexibility with which letter identities are associated with a given position in a word (e.g., Davis & Bowers, 2006; Perea & Lupker, 2004; Peressotti & Grainger, 1999; see Grainger, 2008, for a review).

Evidence for this flexibility comes primarily from relative-position and transposed-letter priming effects. Relative-position priming refers to the priming effects obtained when primes and targets share a subset of letters that do not necessarily respect their absolute, length-dependent position in prime and target (Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Humphreys, Evett, & Quinlan, 1990; Peressotti & Grainger, 1999). For example, the prime SLENE facilitates the processing of the target word SILENCE even though only the relative, and not absolute, position of the shared letters in the string is respected. Transposed-letter priming refers to the priming effects observed with primes formed by transposing two letters of the target word that can be adjacent, as in the case of the prime ANWSEER and the target ANSWER or nonadjacent, as in the case of the prime CANISO and the target CASINO (e.g., Perea & Lupker, 2004; Schoonbaert & Grainger, 2004). Together, these findings have provided evidence for the computation of some form of an approximate word-centered position code for letters used to access the orthographic representations of words and have been instrumental in the development of a new class of models of orthographic processing (Davis, 2010; Grainger & van Heuven, 2003; Whitney, 2001). In order to account for the masked priming effects discussed above, these recent models adopt a flexible letter-position coding scheme that differs markedly from the position-specific slot coding schemes that had

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been previously put forward (McClelland & Rumelhart, 1981). In the Grainger and van Heuven (2003) model, which provides the theoretical background for the present study, flexibility in letter-position encoding is achieved by coding for contiguous and non-contiguous (i.e., open) bigrams independently of their precise location in the letter string.

Sandwich Priming

Despite its many merits, and just like any other measurement technique, conventional masked priming has limited sensitivity. As noted by Grainger (2008), for example, priming effects obtained by contrasting double substitution primes (e.g., galpen–GARDEN) with completely unrelated primes (e.g., tolpan–GARDEN) are generally not robust. Findings such as these led Grainger (2008) to call for more sensitive measurement conditions in the investigation of orthographic priming, in an attempt to provide stronger tests of the different models. In immediate response to this call, Lupker and Davis (2009) provided an ingenious, theoretically motivated means of increasing the sensitivity of conventional masked priming. Lupker and Davis argued that at least one of the reasons why priming effects are difficult to observe in masked priming is because prime stimuli not only contribute bottom-up support in favor of target words, but they also contribute bottom-up support for other words that compete with the target for identification. Within the framework of an interactive-activation account of visual word recognition (McClelland & Rumelhart, 1981), coactivated word representations compete via lateral inhibitory connections across whole-word representations (see Davis & Lupker, 2006; Segui & Grainger, 1990, for empirical evidence). Thus, the observed priming effects are a combination of bottom-up support for the target (i.e., facilitation) and bottom-up support for nontarget words (i.e., inhibition). Indeed, this hypothesized codetermination of priming effects had already been demonstrated empirically via a

phenomenon referred to as shared neighbor priming (van Heuven, Dijkstra, Grainger, & Schriefers, 2001).

The ingenious methodological move on behalf of Lupker and Davis (2009) was to give a prior boost to target word activation in order to limit the amount of interference generated by coactivated word representations during target word processing. They designed a four-field masked priming paradigm to replace the conventional three-field one described above. This new methodological technique, referred to as “sandwich priming,” introduces an additional presentation of the target itself, very briefly (33 ms), and immediately prior to the presentation of the prime stimulus, again presented briefly (e.g., 50 ms) and followed immediately by the clearly visible target stimulus. Lupker and Davis reported significant effects of double substitution primes with this new technique, which were not significant when conventional masked priming was used. Here we apply the same sandwich priming technique as Lupker and Davis (2009), combined with event-related potential (ERP) recordings in order to provide a more sensitive measure of early orthographic priming effects.

Location-specific and Location-invariant Orthographic Priming

According to Grainger and van Heuven’s (2003) theoretical framework for orthographic processing, the identities and the positions of the constituent letters of a printed word are encoded by two distinct coding mechanisms. First, a retinotopic location-specific code is computed that maps information about visual features at a given location along the horizontal meridian onto abstract letter representations that signal the presence of a given letter identity at that particular location. A location-independent, word-centered code is then computed that produces a map of the relative positions of the activated letter identities within the word. Figure 1 describes the Grainger and van Heuven model and illustrates our attempts to

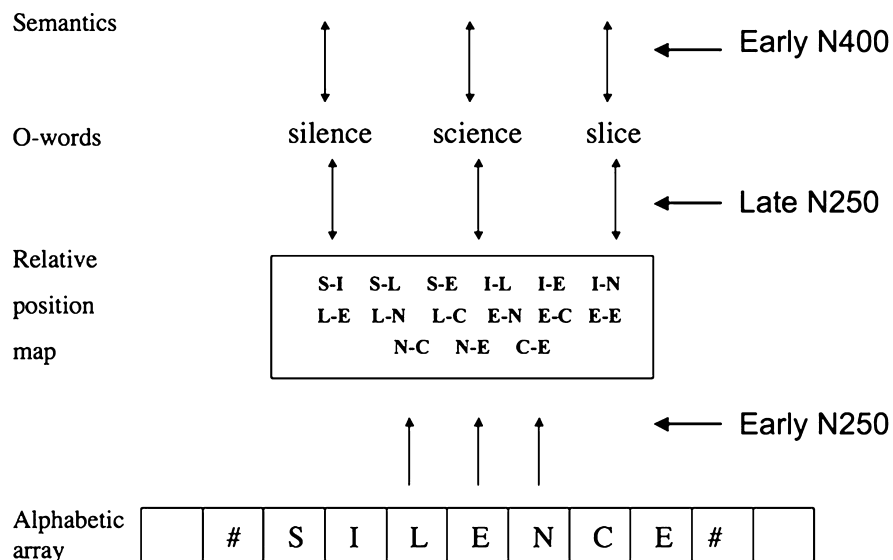


Figure 1. Linking ERP components to orthographic processing within the framework of Grainger and van Heuven’s (2003) model. A bank of parallel, independent, location-specific letter detectors (alphabetic array) send activation onto a location-invariant, word-centered, sublexical orthographic code (relative-position map), and from there onto whole-word orthographic representations. Note that this corresponds to only part of the larger framework for word recognition described in the bimodal interactive-activation model (see Grainger & Holcomb, 2009b; Grainger & Ziegler, 2011; Holcomb & Grainger, 2007).

map priming effects, seen in our research combining masked priming and ERP recordings, onto the different levels of processing described in this model. This research is part of a wider project aimed at mapping ERP masked priming effects onto component processes in word comprehension, including phonological, morphological, and semantic processes (e.g., Grainger, Kiyonaga, & Holcomb, 2006; Holcomb & Grainger, 2006, 2007; Kiyonaga, Grainger, Midgley, & Holcomb, 2007; Midgley, Holcomb, & Grainger, 2009; Morris, Franck, Grainger, & Holcomb, 2007). The overarching rationale behind this research is that the combination of masked priming and ERP recordings provides a privileged window onto the nature and the precise timing of these component processes (see Grainger & Holcomb, 2009b, for a review).

Two specific studies provide the background to the present work. Dufau, Grainger, and Holcomb (2008) examined masked repetition priming with ERP recordings while varying the position of prime stimuli. Targets were always presented centered on fixation, whereas prime stimuli could appear either at the same location as targets, or shifted one letter space to the left or to the right. This prime location manipulation was found to wipe out the earliest ERP repetition effect occurring at around 150 ms post-target onset (N/P150), but did not influence priming effects observed on two later components, the N250 and N400, peaking at around 250 ms and 400 ms post-target onset, respectively. It was therefore concluded that the transition from location-specific to location-invariant orthographic processing was occurring somewhere in between the early N/P150 effect and the following N250 effect.

Grainger and Holcomb (2009a) used a different manipulation of relative position of prime and target stimuli. Rather than shifting prime stimuli, they manipulated the alignment of letters shared by prime and target. To do so, they used primes formed of a subset of the target's letters (letters 1, 3, 4, 5, 7 of 7-letter targets) while maintaining the order of the letters either in concatenated format (e.g., cllet—COLLECT) or in hyphenated format (e.g., c-lle-t—COLLECT) where the hyphens replaced the missing letters. In this way, shared letters could overlap in retinotopic location with hyphenated primes (absolute-position priming), or in the case of concatenated primes, only in terms of their relative position in the target (relative-position priming). Grainger and Holcomb found modestly sized but nevertheless significant evidence for priming with hyphenated primes in a time window between 200–250 ms post-target onset, whereas effects of concatenated primes, which were smaller in size, emerged in the 250–300 ms time window. This pattern fits with the proposal, shown in Figure 1, that the early phase of the N250 reflects the mapping of retinotopic letter representations onto a sublexical word-centered orthographic representation, which should still exhibit sensitivity to retinotopic overlap. Complete location invariance would only be reflected in the later phase of the N250 component, during the mapping of the sublexical word-centered orthographic code onto whole-word orthographic representations.

The Present Study

The present study provides a further investigation of the transition from location-specific to location-independent orthographic processing, this time combining ERP recordings and the sandwich priming technique in an attempt to increase the size of priming effects that were found to be particularly small in our prior work. In particular, the fact that the concatenated priming effects were quite small in the late N250 time window could be taken to imply that

there were effects of this variable in the earlier time window, but they were just too small to be observable.

Furthermore, the present study combines the manipulations that were performed in our prior investigations described above: the concatenation versus hyphenated prime manipulation of Grainger and Holcomb (2009a), and the shifting of prime location in Dufau et al. (2008). If the effects of concatenated primes seen in the Grainger and Holcomb (2009a) study reflect processing at the level of location-invariant orthographic representations, then they should be insensitive to shifts in location of prime stimuli. On the other hand, the early priming effects seen with the hyphenated primes in the Grainger and Holcomb (2009a) study, thought to reflect processing at the level of location-specific orthographic representations, should be sensitive to shifts in prime location. We therefore expect to see an interaction between priming and prime location for the hyphenated primes in early phases of target word processing, while there should be no interaction between priming and prime location for the concatenated primes.

Method

Participants

Sixteen volunteers, drawn from the undergraduate and postgraduate population of the Aix-Marseille University, were paid to take part in the experiment. The data of four participants were excluded from analysis because of excessive eye movement artifacts. The remaining twelve participants (8 female, 4 male) ranged in age from 19 to 24 years (mean 20.6, *SD* 1.6). All participants were right-handed native speakers of French and reported having normal or corrected-to-normal vision, and none reported any linguistic or neurological impairment.

Design and Stimuli

All stimuli used were 6 letters long, followed a CVCCVC orthographic structure, and bore no diacritics. A set of 48 words was selected from the French lexical database Lexique (New, Pallier, Brysbaert, & Ferrand, 2004). Word stimuli were disyllabic nouns or adjectives in infinitive form, and their printed frequency ranged between 4 and 145 occurrences per million, with a mean of 24. An additional set of 48 nonwords was selected from the French Lexicon Project (Ferrand et al., 2010) for the purpose of the lexical decision task. In order to ensure the effectiveness of the selected stimuli, mean response accuracy collected from a lexical decision task as part of the French Lexicon Project was taken into consideration and was no less than 92%. Stimuli were paired with an equal number of concatenated and hyphenated primes. Concatenated primes were constructed by removing the second and fifth letter of the stimuli and juxtaposing the remaining four letters (e.g., bskt/BASKET) while hyphenated primes were constructed by replacing the removed letters with hyphens such that the relative spacing between the letters was preserved (e.g., b-sk-t/BASKET). A further set of unrelated concatenated and hyphenated primes was formed by rearranging prime-target associations while minimizing orthographic overlap (e.g., grdn/BASKET, g-rd-n/BASKET; where “grdn” and “g-rd-n” are formed from GARDEN). A $2 \times 2 \times 2$ within-participants factorial design was configured with Prime Relatedness (related and unrelated primes relative to target word), Prime Type (hyphenated and concatenated primes), and Prime Location (primes displayed centrally as the same location as the target and primes displaced equally often by two letter positions

either to the right or the left of the target) as main factors for both word and nonword stimuli. See Figure 2 for examples of prime and word target pairs across the different conditions of the experimental design. Participants saw all target stimuli 8 times, once in each of the 8 experimental conditions. In order to maximize the lag between target repetitions, stimuli were counterbalanced into eight different blocks of 96 trials (i.e., 48 words and 48 nonwords) with different pseudorandomizations such that each target stimulus appeared once in each block and in all the experimental conditions across all blocks. The order of presentation of the blocks was counterbalanced across participants using a standard Latin-square design. It is important to note that with this design the grand average ERPs formed for the related and unrelated prime conditions always involved the same set of prime and target stimuli, and that the same set of target stimuli were involved in comparisons across all 8 experimental conditions. Following a practice session of 16 trials, each participant received all eight blocks and was given the opportunity to rest between blocks.

Procedure

A masked sandwich priming lexical decision task was used. Participants were placed individually in a sound-attenuated and dimly illuminated room after completing informed consent and handedness forms. Each participant sat comfortably 155 cm in front of an 18" monitor. Visual stimuli were displayed at high contrast as white letters on a black background in an 18-point Courier New font. The trial sequence followed in the experiment is illustrated in Figure 2. Each trial began with the presentation of a mask in the middle of the screen for 500 ms. The mask was formed by 12 hash marks, sufficiently long to cover over and beyond primes in both central and displaced conditions. 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 prime comprising the target stimulus itself in upper case for 33 ms. The first prime was immediately followed by the experimental prime in lower case for 50 ms. The target stimulus then appeared in upper case (i.e., identical to the first prime) for 500 ms. Participants were required to indicate as quickly and as accurately as possible whether the target stimulus spelled a French word or not by pressing a response key in their right or left hand, respectively. The trial ended with the presentation of a blank screen for 2,000 ms. On every other trial, a stimulus (in the form of the letter C) appeared in the middle of the screen for 2,500 ms, allowing participants to blink their eyes. The next trial followed a 500-ms blank screen interval.

ERP recording. The electroencephalogram (EEG) activity was recorded continuously through the ActiveTwo BioSemi system from 64 electrodes mounted on an elastic cap (Electro-Cap Inc.) and positioned according to the 10-10 international system (American Clinical Neurophysiology Society, 2006). Two additional electrodes (CMS/DRL nearby PZ) were used as online reference (for a complete description, see Schutter, Leitner, Kenemans, & van Honk, 2006; www.biosemi.com). The montage included 10 midline sites and 27 sites over each hemisphere. In addition to scalp electrodes, two electrodes were used to monitor eye movements and blinks (one attached at the right canthus and one below the left eye), and two electrodes were used for an offline rereferencing (attached to behind the ears on the mastoid bone). EEG activity was amplified using an ActiveTwo BioSemi amplifier (DC 67 Hz band-pass, 3dB/octave) and was continuously sampled (24-bit sampling) at a rate of 256 Hz throughout the experiment. EEG was filtered offline (20 Hz low-pass, 24 dB/octave) using EEGLAB

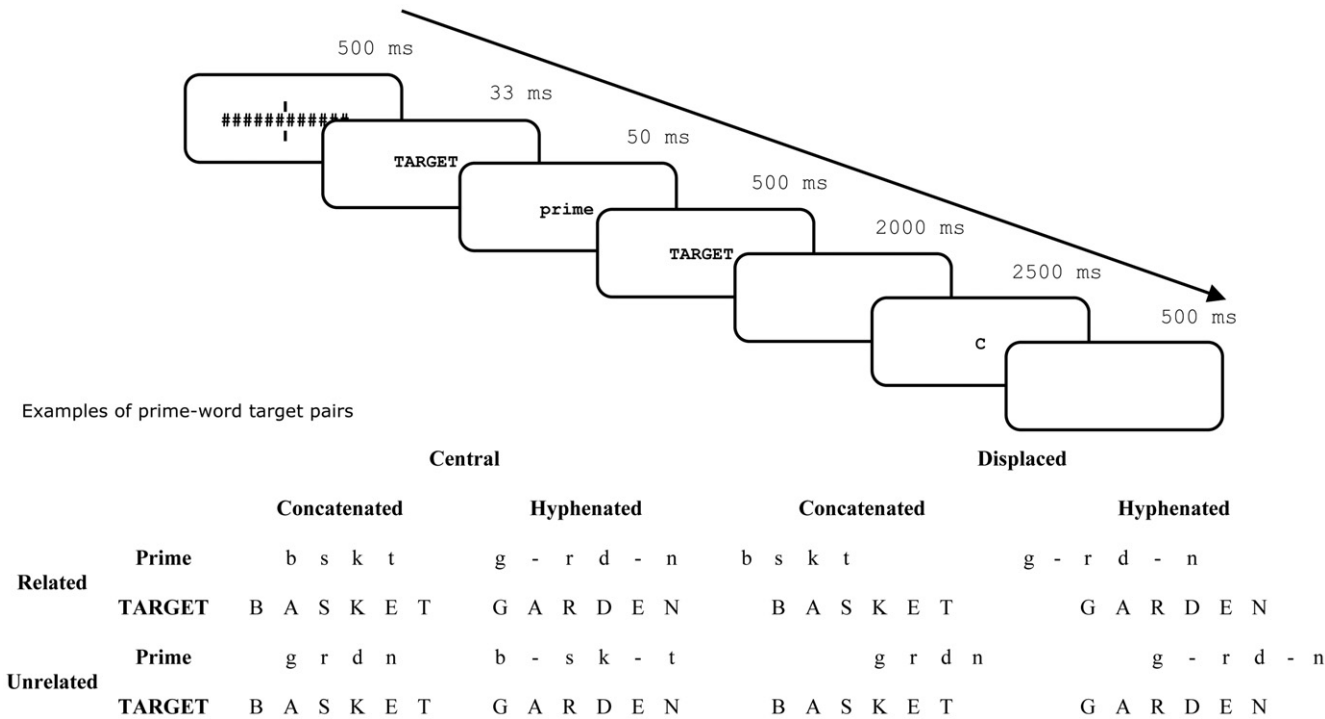


Figure 2. Schematic illustration of the experimental trial sequence in the masked sandwich priming lexical decision task. Examples of stimuli illustrate prime-word target pairs across the different experimental conditions.

Table 1. Mean Correct RT and Percentage of Correct Lexical Decisions for Word and Nonword Stimuli Across Experimental Conditions

Word stimuli		Concatenated			Hyphenated		
Primes		Mean	SE mean	% correct	Mean	SE mean	% correct
Central	Related	536	18.1	97.9	535	17.7	97.0
	Unrelated	574	20.3	95.8	593	23.3	95.5
Displaced	Related	557	20.1	96.2	561	18.1	97.0
	Unrelated	593	18.0	95.5	577	17.8	96.5
Nonword stimuli		Concatenated			Hyphenated		
Primes		Mean	SE mean	% correct	Mean	SE mean	% correct
Central	Related	653	22.6	95.5	661	22.0	95.7
	Unrelated	668	25.1	95.0	678	23.0	96.5
Displaced	Related	646	23.5	96.9	651	21.9	95.3
	Unrelated	666	24.6	95.8	667	25.7	94.6

software (Delorme & Makeig, 2004). All 64 electrode sites were referenced offline to the average of the right and left mastoids.

ERP data and analysis. ERP data were calculated by averaging the EEG time-locked to a point 100 ms pretarget onset and lasting until 700 ms post-target onset. A 50-ms epoch immediately before target onset was used as the baseline. Epochs with eye movements, blinks, or electrical activities greater than $\pm 75 \mu\text{V}$ were rejected. To maintain an acceptable signal-to-noise ratio, a lower limit of 32 artifact-free trials per participant per experimental condition was set. Overall, 8.6% of the trials were rejected.

Separate ERPs were formed for the 8 experimental word conditions defined by the factorial combination of Prime Relatedness (target words related or unrelated to the primes), Prime Type (target words preceded by hyphenated or concatenated primes), and Prime Location (target words preceded either by primes displayed centrally at the same location as the target or primes displaced by two letter positions to the right or the left of the target). The main analysis approach involved measuring mean amplitudes in four consecutive post-target onset latency windows surrounding the repetition ERP effects reported by Dufau et al. (2008) and Grainger and Holcomb (2009a). In particular, these measurement windows were determined from inspection of the grand average waveforms and included 150–200 ms (pre-N250), 200–250 ms (early N250), 250–300 ms (late N250), and 300–500 ms (N400). Repeated measures analyses of variance (ANOVAs) were run in each of these time windows, with mean amplitude as the dependent variable. Three anterior (F3, Fz, F4), three middle (C3, Cz, C4), and three posterior (P3, Pz, P4) electrode sites were chosen for analysis providing as such ANOVA factors of laterality (left vs. center vs. right) and anteroposterior (anterior vs. middle vs. posterior). This analysis approach has been successfully used in several previous studies (e.g., Grainger & Holcomb, 2009a; Grainger, Kiyonaga, & Holcomb, 2006) and, when paired with voltage maps computed across all sites, is believed to offer the best combination of thorough yet easily comprehensible analyses (Grainger & Holcomb, 2009a). In addition, a more complete time-course analysis was performed on the mean amplitude of successive 50-ms latency windows starting at 100 ms and continuing through 500 ms post-target onset. In this analysis, priming effects for each combination of Prime Type and Prime Position at each of the 50-ms time windows are reported.

Results

Behavioral Data

All correct lexical decisions less than 2,000 ms post-target onset (90.4% of the data) and response accuracy were included in the behavioral analyses. Two (Prime Type) \times 2 (Prime Position) \times 2 (Relatedness) within-groups ANOVAs were conducted separately on the mean response times (RTs) and accuracy for word and nonword stimuli. Mean RTs and percentage of correct responses to words and nonwords for each of the two types of primes across central and displaced conditions are presented in Table 1.

For words, the main effect of Prime Type, $F(1,11) = .15$, $p = .70$, was not significant. However, both the main effect of Prime Position, $F(1,11) = 11.64$, $p < .01$, and Relatedness were significant, $F(1,11) = 67.64$, $p < .001$. Overall, participants responded faster to target words when primes were centrally positioned compared to when they were displaced and when primes were related compared to when they were unrelated. Moreover, there was a significant 2-way interaction between Prime Position and Relatedness, $F(1,11) = 11.22$, $p < .01$, which was qualified further by a significant 3-way interaction between Prime Type, Prime Position, and Relatedness, $F(1,11) = 10.20$, $p < .01$. The 3-way interaction is illustrated in Figure 3. Statistical analyses on mean accuracy for word stimuli revealed no significant effects.

Analysis of simple main effects of the 3-way interaction revealed that the interaction between Prime Position and Relatedness was significant for hyphenated, $F(1,11) = 19.15$, $p < .01$, but not concatenated, $F(1,11) = .04$, $p = .85$, primes. This pattern is shown in Figure 3. Participants showed a greater priming effect for central, $t(11) = 6.06$, $p < .001$, compared to displaced, $t(11) = 2.23$, $p < .05$, primes in the hyphenated condition. Further follow-up analyses revealed a marginally significant interaction between Relatedness and Prime Type for centrally located primes, $F(1,11) = 4.05$, $p = .06$, but not for displaced primes, $F(1,11) = 3.60$, $p = .10$. Priming effects were stronger for hyphenated central primes than for concatenated central primes (see Figure 3)¹.

1. An ANOVA performed on the data for only the first presentation of target words obtained from the first eight participants (i.e., a complete counterbalancing of the presentation order of stimulus blocks) produced highly consistent results with the ones reported above.

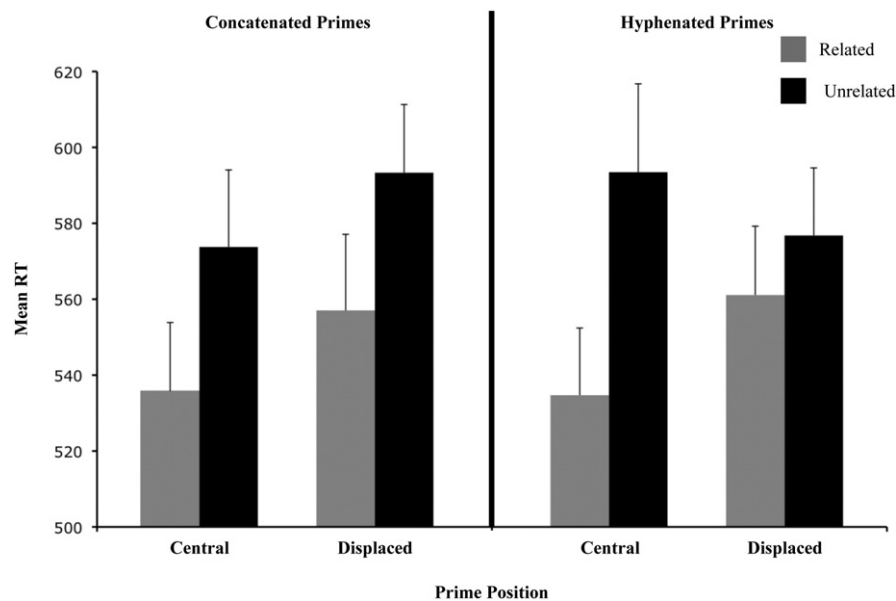


Figure 3. Mean RT (± 1 standard error of the mean) for words across the concatenated and hyphenated prime conditions as a function of prime position and relatedness.

For nonwords, there was a significant main effect of Prime Type, $F(1,11) = 5.11$, $p < .05$, as overall concatenated primes produced faster RTs than hyphenated primes. Furthermore, there was a significant main effect of Relatedness, $F(1,11) = 18.64$, $p < .01$, while the main effect of Prime Position was not significant, $F(1,11) = 2.53$, $p = .14$. Across the conditions of Prime Type and Prime Position, participants responded faster to nonwords when there were related compared to unrelated primes present. None of the 2-way interactions or the 3-way interaction between Prime Type, Prime Position, and Relatedness was significant. Finally, as with the analyses on word stimuli reported above, analyses on the mean accuracy for nonwords revealed no significant effects.

Electrophysiological Data

ERP waveforms for each of the experimental conditions time-locked to target word stimuli² at the nine electrode sites used in the statistical analyses are plotted in Figures 4 and 5. Voltage maps formed from all 64 scalp sites contrasting the different type of priming effects within the four post-target onset latency windows (150–200 ms, 200–250 ms, 250–300 ms, and 300–500 ms) are plotted in Figure 6. For each of these measurement windows, ANOVAs on mean amplitude were conducted separately for the two types of prime (concatenated and hyphenated) following a 2 (Prime Position) \times 2 (Relatedness) \times 3 (Laterality) \times 3 (Anteroposterior) repeated measures design. ANOVAs were performed using the Greenhouse-Geisser epsilon correction for nonsphericity (Jennings & Wood, 1976) to all repeated measures with more than one degree of freedom in the numerator (corrected p values are reported). Table 2 reports the results of the time-course analysis on successive 50-ms latency windows from 100 ms to 500 ms post-target onset.

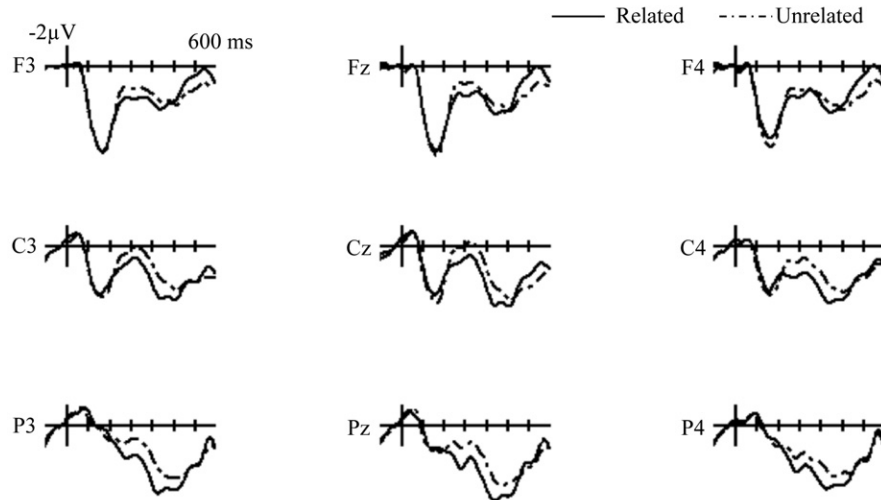
2. We also analyzed the ERP data for nonword targets. However, given that there were no systematic priming effects, these results are not reported but can be obtained from the corresponding author upon request.

150–200 ms target epoch. In this epoch, analyses on concatenated primes revealed no significant results in relation to Relatedness. However, for targets following hyphenated primes there was a significant interaction between Relatedness and Prime Position, $F(1,11) = 4.97$, $p < .05$. Follow-up analyses revealed that priming effects (i.e., the difference between related and unrelated primes) were robust only when hyphenated primes occupied the same central location as did targets, $F(1,11) = 4.53$, $p < .05$, compared to when primes were displaced in relation to targets, $F(1,11) = .52$, $p = .49$. In the central hyphenated condition, targets following related primes produced a more positive-going waveform than the corresponding unrelated ones (See Figure 5A).

200–250 ms target epoch. Similarly, in this epoch targets following concatenated primes produced no significant priming irrespective of the position in which they were presented (central or displaced). However, for targets following hyphenated primes the interaction between Relatedness and Prime Position was once again significant, $F(1,11) = 3.84$, $p < .05$, with robust priming effects for centrally presented primes, $F(1,11) = 3.40$, $p < .05$, and no priming for displaced primes, $F(1,11) < .01$, $p = .99$.

250–300 ms target epoch. In this time window, the analysis of ERPs to targets following concatenated primes revealed a main effect of Relatedness, $F(1,11) = 10.03$, $p < .01$, across both central and displaced conditions, with unrelated primes producing a more negative-going waveform than related primes (see Figure 4A and B). Furthermore, there was a significant interaction between Relatedness and Laterality, $F(2,22) = 3.23$, $p < .05$. This interaction was due to the priming effect for concatenated primes being more prominent on central electrode sites and over the right hemisphere. For hyphenated primes, there was a significant higher order interaction between Relatedness, Prime Position, and Anteroposterior, $F(2,22) = 3.93$, $p < .05$. Follow-up analyses revealed that central hyphenated primes produced priming effects that were more prominent over anterior sites (Relatedness \times Anteroposterior:

A. Central Concatenated



B. Displaced Concatenated

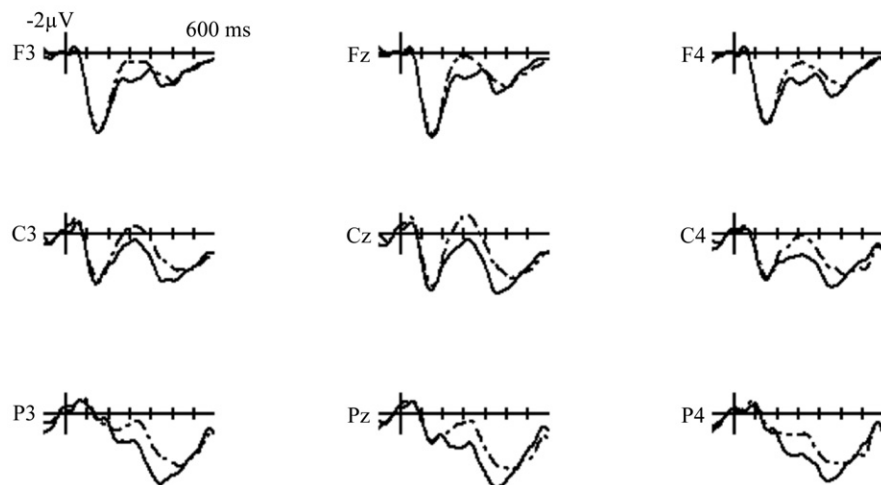


Figure 4. ERPs time-locked to target onset for 9 electrode sites in the central concatenated (A) and displaced concatenated (B) word priming conditions overplotted with their respective unrelated control conditions. Target onset is marked by the vertical calibration bar, and each tick mark represents 100 ms. Negative values are plotted up.

$F(2,22) = 5.65$, $p < .01$). However, targets following displaced hyphenated primes failed to produce any priming effects (Relatedness: $F(1,11) < .05$, $p = .88$).

300–500 ms target epoch. The analyses in this final time window revealed main effects of Relatedness for targets following concatenated, $F(1,11) = 13.63$, $p < .01$, and hyphenated primes, $F(1,11) = 11.78$, $p < .05$. Furthermore, both types of primes produced a significant higher order interaction between Relatedness, Anteroposterior, and Laterality (Concatenated: $F(4,44) = 2.31$, $p < .05$; Hyphenated: $F(4,44) = 2.53$, $p < .05$). Across central and displaced conditions, targets following concatenated primes produced priming effects that were distributed across the middle, left-, and central-posterior, and right-hemisphere electrode sites. Targets following hyphenated primes produced priming effects that were more pronounced at the left-middle and left-posterior scalp sites across central and displaced conditions.

Time-course analysis. The priming effects for each combination of Prime Type and Prime Position at successive 50-ms time windows from 100 ms to 500 ms post-target onset are reported in Table 2. This analysis highlights the earlier onset of central hyphenated primes in the 150–200 ms window, followed by the emergence of priming effects for both central and displaced concatenated primes in the 250–300 ms window. Priming from displaced hyphenated primes only reached significance in the 350–400 ms window.

Discussion

The behavioral results for the word stimuli of the present study replicate prior work showing robust priming from concatenated primes when these are centrally located (Grainger, Granier, et al., 2006; Peressotti & Grainger, 1999). This prior research examined relative-position and absolute-position priming effects using stand-

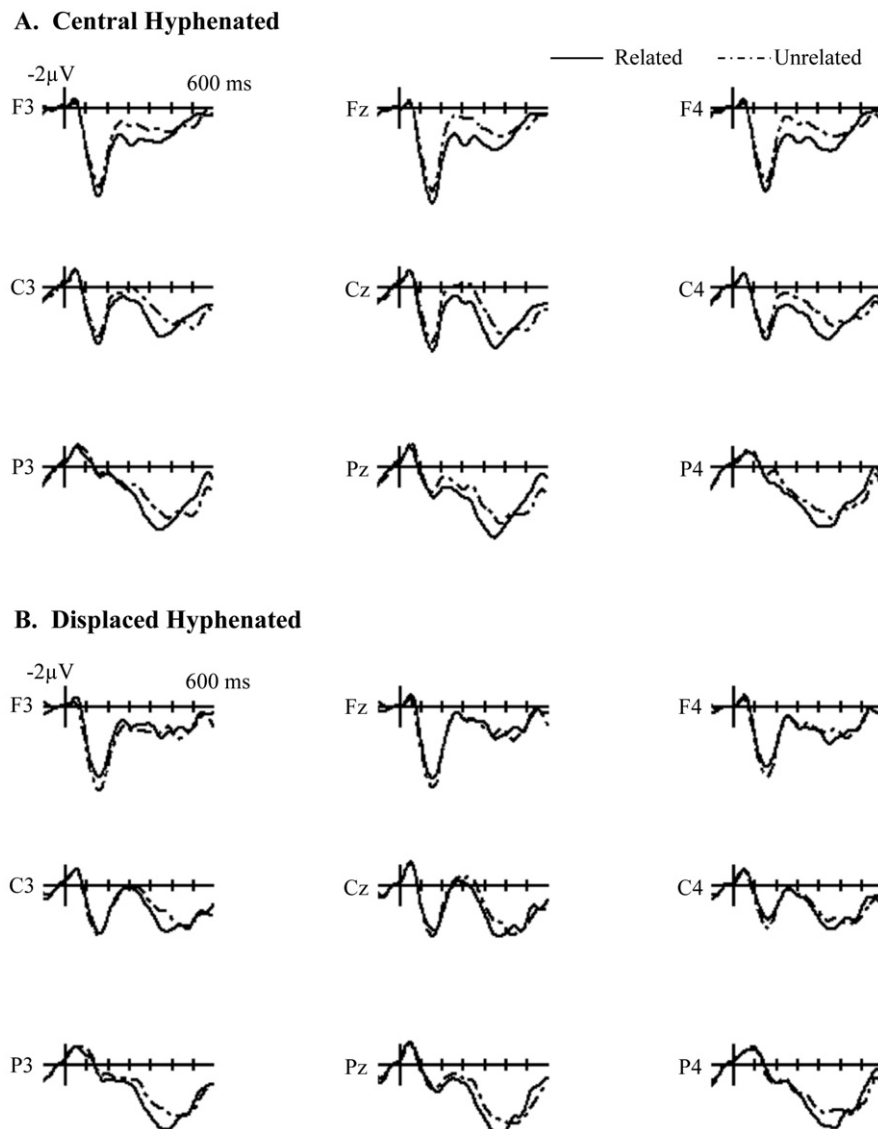


Figure 5. ERPs time-locked to target onset for 9 electrode sites in the central hyphenated (A) and displaced hyphenated (B) word priming conditions overplotted with their respective unrelated control conditions. Target onset is marked by the vertical calibration bar, and each tick mark represents 100 ms. Negative values are plotted up.

and masked priming and reported effect sizes in the order of 20 ms. Here, the priming effects were 38 ms and 59 ms, respectively, for the centrally located concatenated and hyphenated primes. Lupker and Davis (2009) reported a similar increase in the size of behavioral priming effects from 22 ms to 57 ms for single letter substitution priming in their Experiment 2. Sandwich priming clearly boosts the size of masked orthographic priming effects as measured by behavioral responses. However, contrary to the results of this prior work obtained using standard masked priming, the results obtained with sandwich priming suggest that the effects of centrally located concatenated primes are not as large as the effects of centrally located hyphenated primes. This could be due to the fact that primes and targets were the same size in the present study, thus increasing low-level visual overlap with hyphenated related primes, even when primes and targets are in different case. Furthermore, the fact that priming effects were significantly reduced in the displaced hyphenated prime condition is likely due to the

greater eccentricity of outer letters of the prime stimulus in this condition (see Figure 2).

In line with the behavioral results, the ERP results of the present study show that the sandwich priming technique has generated priming effect sizes that are much larger than those found in prior work (Dufau et al., 2008; Grainger & Holcomb, 2009a), in spite of the fact that orthographic overlap was actually lower in the present study (4/6 letters compared with 5/7 in the Grainger and Holcomb study, and complete overlap in the Dufau et al. study). Furthermore, robust priming effects were found with a relatively small number of participants in the present study, again attesting to the increased measurement sensitivity obtained with the sandwich priming technique.

As shown in Figure 7, the timing of the ERP effects is in line with the timing estimates derived from conventional masked priming. Dufau et al. (2008) found that effects of displaced repetition primes started to emerge at around 200 ms post-target onset,

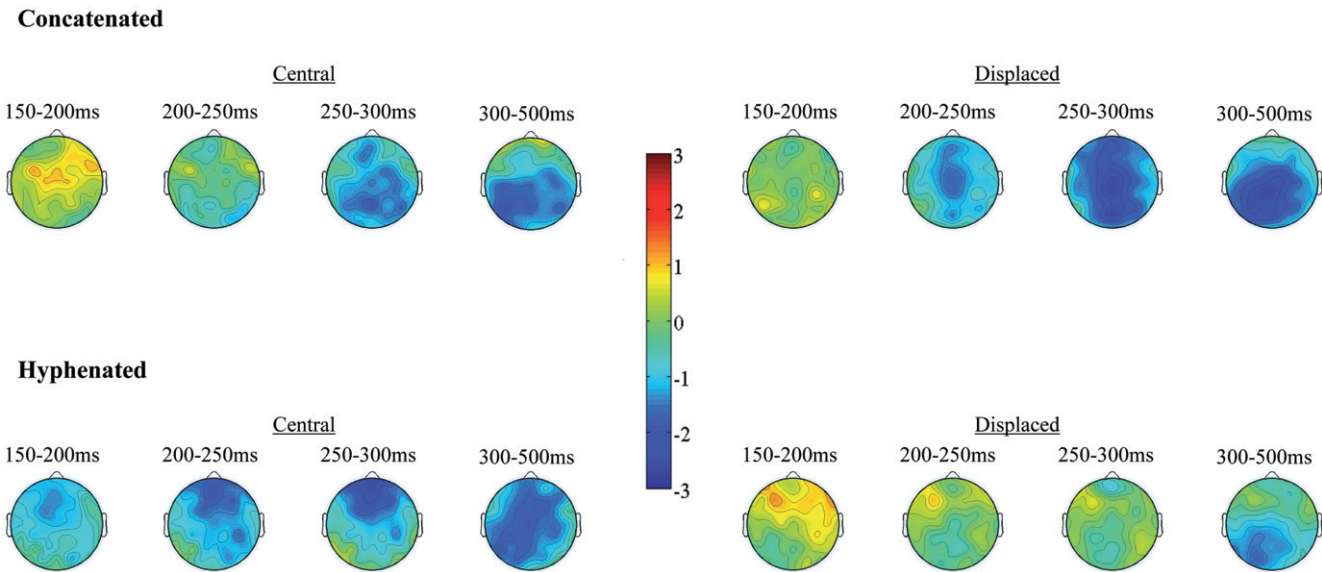


Figure 6. Voltage maps for word stimuli calculated from difference waves (Unrelated-Related) for each of the experimental conditions across the measurement windows used in the statistical analyses. The color bar features a μV scale.

and were robust in the N250 time window analyzed in that study (200–280 ms post-target onset). Grainger and Holcomb (2009a) reported that the effects of concatenated (and centrally located) primes were significant in the late N250 time window analyzed in that study (240–305 ms post-target onset). Taken together, the results of our prior work and the results of the present study all point to location-invariant orthographic processing starting to emerge at around 200 ms post-target onset. The transition from a completely retinotopic encoding of letter position (i.e., the alphabetic array in Grainger and van Heuven’s, 2003, model of orthographic processing) to a word-centered, location-invariant encoding of letter position (i.e., the relative-position map in the Grainger and van Heuven model, see Figure 1) is largely occurring in the time window of what we have referred to as the N250 component.

Thus, the failure to see earlier effects of concatenated primes in our prior work is unlikely to be due to limited measurement sensitivity. This therefore reinforces the proposed association between ERP components and component processes in orthographic processing shown in Figure 1, and more generally in the bimodal interactive-activation model (BIAM—see Grainger & Holcomb, 2009b). Within the overall framework of the BIAM, the earliest priming effects seen in the ERP signal are thought to reflect the mapping of visual features onto location-specific letter detectors, designed to optimize parallel independent letter processing. Our

prior research pointed to around 150 ms post-target onset as the estimated moment in time that such processes should be operating. The contrast between the effects of central hyphenated primes and all other priming conditions seen in the 150–200 ms time window of the present study fits well with this estimated timing. As processing proceeds to location-invariant, word-centered sublexical representations (i.e., letters coded for their position in the word irrespective of their position on the retina), effects of concatenated primes and displaced primes begin to emerge.

The fact that we obtained similar timing estimates with the sandwich priming technique suggests that this technique is not so much affecting the timing of early bottom-up effects on target word processing, but is having more of an influence on the magnitude of these effects. This fits with the idea that led to the creation of sandwich priming in the first place, that this technique is mostly affecting the amount of lexical inhibition. By reducing the amount of lateral inhibition from coactivated lexical representations (e.g., the word “farmer,” which would receive bottom-up support from the prime “frmr” and the target word “former”), the activation level of the target word will rise in activation more rapidly following a related prime than an unrelated prime, but only once sublexical information starts to feed-forward activation to whole-word representations. This could explain why there is a less pronounced separation between the N250 and N400 components compared with our prior work using standard masked priming (see Figure 7),

Table 2. Time-course of the Priming Effects on Word Stimuli for Concatenated and Hyphenated Primes Across Central and Displaced Conditions

	100–150	150–200	200–250	250–300	300–350	350–400	400–450	450–500
Central concatenated	ns	ns	ns	**	**	**	**	*
Displaced concatenated	ns	ns	ns	**	**	**	**	*
Central hyphenated	ns	*	*	*	*	*	**	*
Displaced hyphenated	ns	ns	ns	ns	ns	*	**	*

Note. Ns = not significant.
* $p < .05$. ** $p < .01$.

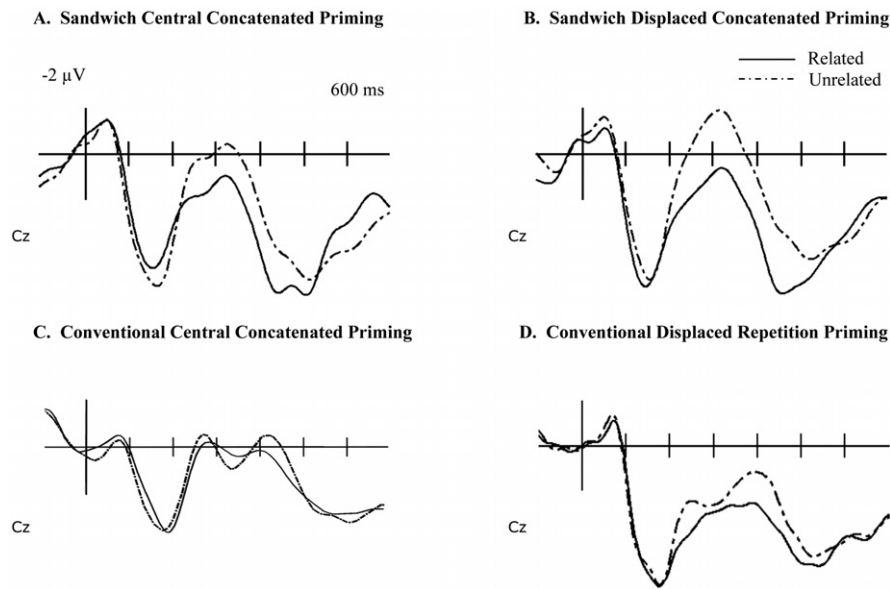


Figure 7. Comparing priming effects seen at one representative electrode site (Cz) obtained with the sandwich priming technique as used in the present study (Panels A & B) and conventional masked priming as used in the Grainger and Holcomb (2009a) study (Panel C) and the Dufau et al. (2008) study (Panel D).

since according to the above reasoning the N400 should be starting earlier with sandwich priming, whereas the timing of the N250 would be less affected. This would lead to a merging of the N250 and N400 components, giving rise to a single negative-going component that starts to rise before 200 ms post-target onset and peaks at around 300 ms. Nevertheless, there is still some evidence for a shift from a more anterior distribution to a more posterior distribution of priming effects, particularly for the central hyphenated primes (see Figure 6), which follows the typical distribution of N250 and N400 priming effects seen in our prior work.

The fact that the earliest effects seen with central hyphenated primes (starting at around 150 ms post-target onset) were found to be much larger with sandwich priming compared with conventional masked priming is in line with the proposal that ERP priming effects that are relatively widely distributed, such as in the present study, reflect a combination of bottom-up and top-down influences (Dell'Acqua et al., 2010; Grainger & Holcomb, 2009b). That is, the reduced lexical inhibition that is hypothesized to be enhancing priming effects obtained with the sandwich priming technique would allow a faster build-up in activation of the whole-word orthographic representation of the target word, which in turn would facilitate processing of sublexical representations associated with the target word via top-down reinforcement. This top-down influence would act to amplify the bottom-up effect without actually changing its time-course. In other words, the priming effects that are reflected in ERP amplitude modulation in the present study, as well as the N250 and N400 priming effects seen in our prior work using standard masked priming, would mainly reflect the stabilization of activation at a particular level of processing via the interplay of bottom-up and top-down processes. The relatively weak ERP priming effects obtained with nonword targets (footnote 1) are also in line with this reasoning, since any lexical representation activated by a nonword target would provide inconsistent feedback to lower levels of processing.

Finally, significant behavioral priming effects were found with nonword targets in the present study. These were relatively small (15–20 ms) compared with the priming effects found with word targets (16–58 ms), and they did not vary as a function of prime position or prime type (hyphenated vs. concatenated). The fact that no systematic priming effects were seen to nonword targets in the ERP analyses suggests that the behavioral nonword priming effects are being driven by decision-making processes that are specific to the lexical decision task (see Dufau, Grainger, & Ziegler, in press, for a recent analysis). The key question is, therefore, by which mechanism could a related prime facilitate nonword decision making? This could be achieved by related primes improving the quality of the information used to estimate target lexicality. Alternatively, related primes could generate greater activation in orthographically similar word representations, thus facilitating a verification process (does the stimulus “girden” match the expected word “garden”) and the subsequent nonword decision. Future research could examine this issue with the sandwich priming technique by replacing initial exposure to the nonword target itself with exposure to an orthographically similar word (e.g., GARDEN-grdn-GIRDEN vs. GARDEN-tlpm-GIRDEN).

In conclusion, we have shown that the sandwich priming technique can be usefully combined with ERP recordings in order to increase the size of priming effects seen not only in behavioral responses, but also in electrophysiological measures. Using this technique, we were able to demonstrate that sensitivity to retinotopic location in orthographic processing was already lost by around 200 ms post-target onset. At that point in time, effects of orthographically related primes did not depend on the precise positional matching of the letters shared by prime and target. Given the increase in measurement sensitivity achieved by the sandwich priming technique, it should enable future research to examine the effects of even more subtle manipulations of prime-target relatedness that cannot be revealed by conventional masked priming.

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