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The Time-Course of Orthographic and Phonological Code Activation

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## **Abstract**

The present study used event-related potentials to examine the time-course of orthographic and phonological priming with the masked priming paradigm. Participants monitored visual target words for occasional animal names, and event-related potentials (ERPs) were recorded to non-animal critical items preceded by different types of prime. Orthographic priming was examined using transposed-letter (TL) primes (e.g., barin-BRAIN) and their controls (e.g., bosin-BRAIN), while phonological priming was examined using pseudohomophone primes (e.g., brane-BRAIN) and their controls (e.g., brant-BRAIN). Both manipulations modulated the N250 ERP component hypothesized to reflect sublexical processing during visual word recognition. Orthographic (TL) priming and phonological (pseudohomophone) priming were found to have distinct topographical distributions and different timing, with orthographic effects arising earlier than phonological effects.

Evidence concerning the relative timing of component processes provides a fundamental constraint for models of visual word recognition. Such time-course analyses are an important addition to the many studies that have examined each component process separately. Evidence for rapid activation of phonological codes, for example, has been repeatedly obtained with the masked priming paradigm and brief prime durations (e.g., Carreiras, Ferrand, Grainger, & Perea, 2005; Frost, Ahissar, Gotesman, & Tayeb, 2003; Lukatela & Turvey, 1994; Perfetti & Bell, 1991 - see Rastle & Brysbaert, 2006, for review). However, direct comparisons of orthographic and phonological priming are less abundant (Ferrand & Grainger, 1992; 1994; Grainger & Ferrand, 1996; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). One such study is particularly relevant for the present study. Ferrand and Grainger (1993) varied orthographic and phonological prime-target overlap and prime exposure duration in masked priming. Orthographic priming emerged with a prime duration of 33 ms, whereas phonological priming required 67 ms of prime exposure to be fully established (see Perfetti & Tan, 1998, for a similar pattern in Chinese).

In line with this time-course pattern, studies manipulating the relative position of letters shared by prime and target, such as subset primes (e.g., grdn-GARDEN: Peressotti & Grainger, 1999; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006), superset primes (e.g., gafrsden-GARDEN: Van Assche & Grainger, 2006), and transposed-letter primes (e.g., gadren-GARDEN: Perea & Lupker, 2004; Schoonbaert & Grainger, 2004) all point to an early phase of orthographic processing that is not influenced by phonology. Thus, Grainger et al. (2006) demonstrated that while phonological influences on subset priming effects were detectable at 50 ms prime durations, no such influences were found at 30 ms prime durations in conditions where subset priming was still robust. Furthermore, Perea and Carreiras (2006) have demonstrated that masked TL priming is driven by orthographic, not phonological representations. Effects of TL primes of Spanish words (e.g., relovucion-REVOLUCION) were

compared with orthographic control primes (relocucion-REVOLUCION) and pseudohomophones of the TL prime (e.g., relobucion-REVOLUCION, where “b” and “v” are given the same pronunciation in Spanish). This “phonological TL” condition did not differ from the orthographic control condition, and was significantly slower than the orthographic TL condition.

The present study combines masked priming with ERP recordings in a further analysis of the time-course of orthographic and phonological processing in visual word recognition. Recent work using this combined methodology (Holcomb & Grainger, 2006; Kiyonaga, Grainger, Midgley, & Holcomb, 2006), has shown that repetition priming affects a cascade of ERP components that start as early as 130 ms post-target-onset and continue through to as late as 600 ms. Two of these are particularly relevant for the present study: the N250 and the N400. Both of these components are more negative-going to targets that are unrelated to prime stimuli than those that are repeats of the prime. On the basis of the precise timing of these components and their distinct topographies, Holcomb and Grainger (2006) proposed that the N250 reflects sublexical processing whereas the N400 is primarily sensitive to processing at the interface between word forms and semantic representations. The central prediction of the present study is that N250 amplitude should be modified by both an orthographic and a phonological priming manipulation, with an observable delay between the onset of these two effects.

## **Method**

***Participants.*** Twenty volunteers (14 female, mean age = 20, SD = 1.71) from Tufts University were paid \$25 to participate in this experiment. All reported being right-handed native speakers of English with normal or corrected to normal vision.

***Stimuli.*** The critical stimuli for this experiment were formed from 332 pairs of 5-letter words and their respective 5-letter pseudohomophones. Fifteen participants (who did not participate in the main experiment) rated each pair for phonological similarity on a scale of 1-7 (1=low, 7=high), and the 200

most similar word/pseudohomophone pairs were selected as stimuli for the main experiment (mean rating=6.52, range=4.75-7, SD = 0.57). Each of these 200 target words was paired with four prime stimuli: *pseudohomophone* prime (e.g. brane-BRAIN), *pseudohomophone control* prime (e.g. brant-BRAIN), *transposed letter* prime (e.g. barin-BRAIN), *transposed letter control* prime (e.g. bosin-BRAIN). Control primes for pseudohomophones were matched in terms of the letters shared by prime and target and the position of the shared letters. Control primes for transposed-letter primes had two different letters replacing the transposed letters. Standard counterbalancing was used such that each participant was tested in all four priming conditions but saw each target word once only, and each target word was tested in all four priming conditions across different participants. Sixty non-critical trials were intermixed with the 200 critical trials. Thirty of these contained animal names in the prime position and a filler word in the target position, and 30 contained an animal word changed into a pseudohomophone, transposed letter, or matched control prime for the corresponding animal name in the target position. The same 60 animal names were used once as primes and once as targets in each list. The animal names served as *probe* items in a go/no-go semantic categorization task in which participants were instructed to rapidly press a single button whenever they detected an animal name. Participants were told to read all other words passively (i.e., critical stimuli did not require an overt response). Having animal names in the prime position provided a measure of prime awareness during the course of the experiment. A practice session was administered before the main experiment to familiarize the participant with the procedure.

**Procedure.** Visual stimuli were presented on a 19" monitor set to a refresh rate of 60 Hz (which allows 16.667 ms resolution of stimulus control) and located 143 cm in front of the participant. Stimuli were displayed at high contrast as white letters on a black background in the Arial font (letter matrix 30 pixels tall x 15 pixels wide). Each trial began with the termination of a fixation stimulus in the middle of the

screen. Five hundred milliseconds later, a forward mask of seven hash marks (#####) was presented for a duration of 500ms. The forward mask was replaced at the same location on the screen by a 5-letter lower case prime for 50ms. The prime was immediately replaced by a backward mask of seven random consonants (e.g., CFTRPQB). The backward mask remained on the screen for one retrace interval (16.667 ms) and was immediately replaced by the visual target in upper case letters for a duration of 500 ms. All target words were followed by a 1000ms black screen which was replaced by a 2000ms fixation stimulus marking the end of the trial. Subjects were asked to blink and move their eyes only when the fixation stimulus appeared on the screen. The next trial followed a 500ms blank screen warning interval.

***EEG recording procedure.*** Participants were seated in a comfortable chair in a sound attenuated darkened room. The electroencephalogram (EEG) was recorded from 29 active tin electrodes held in place on the scalp by an elastic cap (Electrode-Cap International). In addition to the 29 scalp sites, additional electrodes were attached to below the left eye (to monitor for vertical eye movement/blinks), to the right of the right eye (to monitor for horizontal eye movements), over the left mastoid bone (reference) and over the right mastoid bone (recorded actively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 5 k $\Omega$  (impedance for eye electrodes was less than 10 k $\Omega$ ). The EEG was amplified by an SA Bioamplifier with a bandpass of 0.01 and 40 Hz and the EEG was continuously sampled at a rate of 200 Hz throughout the experiment.

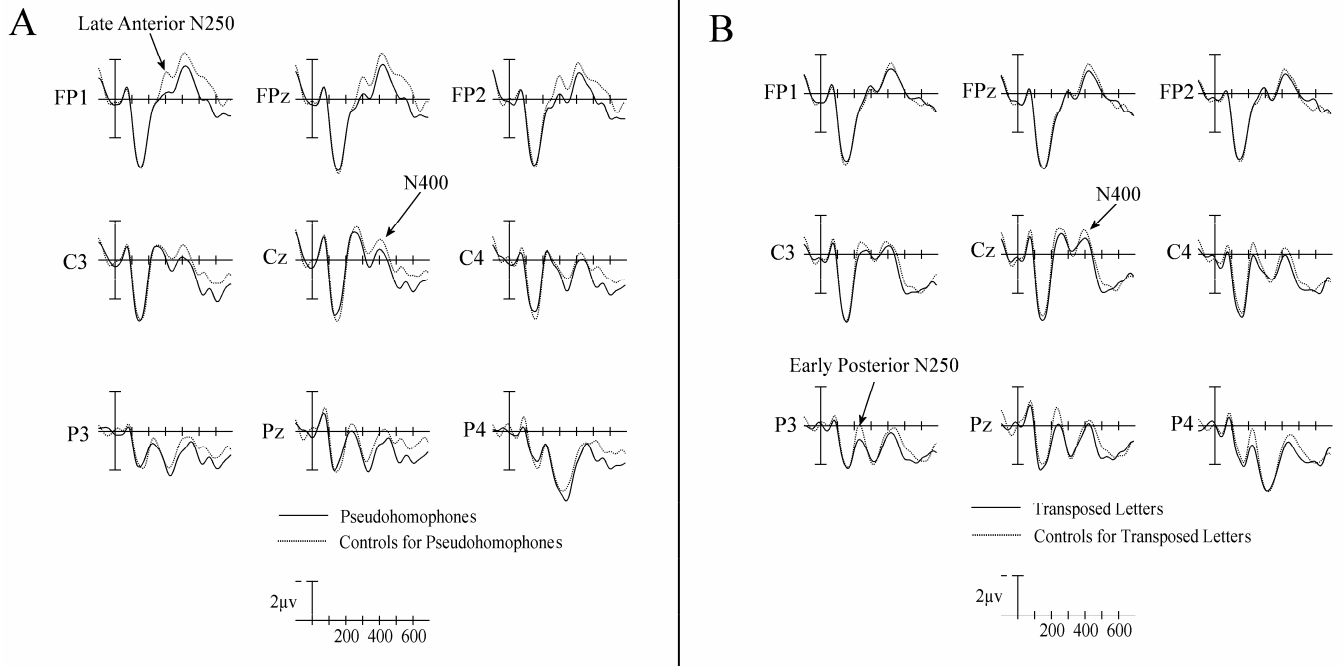
***Data analysis.*** Averaged ERPs were formed off-line from trials free of ocular and muscular artifact (less than 5% of trials in the 20 experimental participants). Separate waveforms were calculated by averaging compound stimulus ERPs (i.e., the EEG time locked to a point 100 ms pre-prime onset and lasting until 900 ms post-target onset) based on the four priming conditions. In order to carefully quantify the time-course of the ERP effects, mean amplitudes in three contiguous post-target onset

latency windows were measured: 150-250 ms, 250-350 ms, and 350-550 ms. Repeated measures analyses of variance (ANOVAs) with within-subject factors of PRIME TYPE (pseudohomophone vs. transposed letter) and REPETITION (repeated vs. control) were used to analyze the ERP data. The Geisser-Greenhouse (1959) correction was applied to all repeated measures with more than one degree of freedom (corrected p values are reported). Three anterior (FP1, Fz, FP2), three middle (C3, Cz, C4) and three posterior (P3, Pz, P4) electrode sites were chosen for analysis which provided ANOVA factors of laterality (left vs. center vs. right) and front-to-back extent (anterior vs. middle vs. posterior).

## Results

ERPs for the pseudohomophone and transposed letter conditions are plotted separately in Figure 1a and 3b for the nine electrodes used in the analyses presented below. Plotted in Figure 2 are the voltage maps formed from all 29 scalp sites contrasting the pseudohomophone and transposed letter priming effects in each of the three analysis windows.

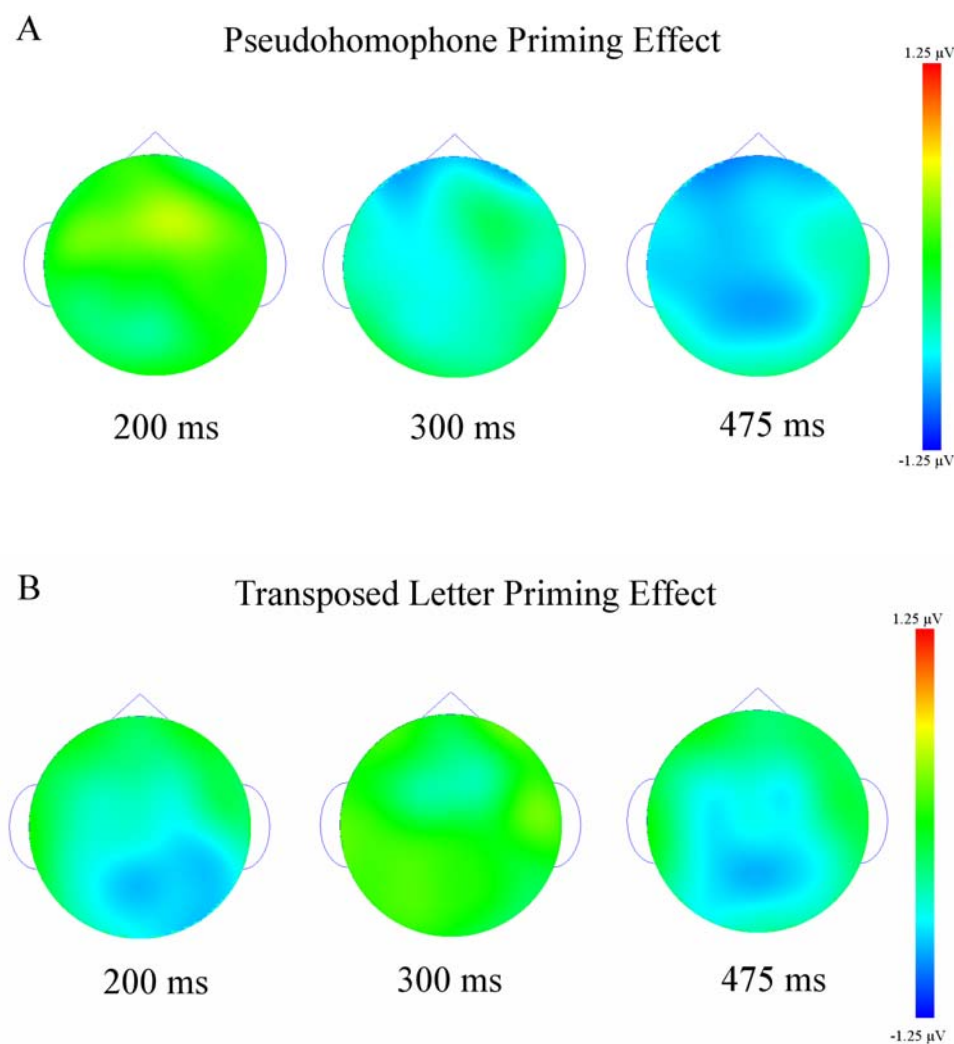
**150-250 ms Target Epoch.** As can be seen in Figures 1 and 2, between about 150 and 250 ms, targets following transposed letters produced an early priming effect over the more posterior electrode sites while targets following pseudohomophone primes produced little evidence of differential activity in this epoch. Consistent with this observation there was a significant interaction between PRIME TYPE, REPETITION, ANTERIOR-POSTERIOR and LATERALITY ( $F(4,76) = 4.59$ ,  $p = .01$ ,  $\eta^2 = .195$ ). Follow-up analyses confirmed that there was a significant priming effect in the transposed letter condition at posterior ( $F(1,19) = 4.69$ ,  $p = .043$ ,  $\eta^2 = .198$ ), a marginal effect at the middle ( $F(1,19) = 3.41$ ,  $p = .08$ ,  $\eta^2 = .152$ ), but no effect at anterior sites ( $F < 1.0$ ). There was no significant effect of priming for pseudohomophones at any location in this epoch ( $F_s < 1$ ).



**Figure 1. ERPs time locked to target onset in the pseudohomophone (A) and transposed letter (B) conditions over-plotted with their respective control conditions.**

**250-350 ms Target Epoch.** As can be seen in Figures 1 and 2 between 250 and 350 ms it was now targets following pseudohomophone primes that produced priming effects while targets following transposed letter primes produced little to no priming. This observation was supported by a significant interaction between PRIME TYPE x REPETITION x LATERALITY x ANTERIOR-POSTERIOR interaction ( $F(4,76) = 3.24, p = .045, \eta^2 = .146$ ). Follow-up analyses demonstrated that while pseudohomophones produced a significant priming effect ( $F(1,19) = 4.77, p = .042, \eta^2 = .201$ ), transposed letters did not ( $F < 1.0$ ). Moreover, the pseudohomophone effect was significant at anterior sites ( $F(1,19) = 5.97, p = .025, \eta^2 = .239$ ) but was not reliable at middle or more posterior sites ( $ps < .1$ ).

**350-550 ms Target Epoch.** Examination of Figures 1 and 2 reveals that this interval contains the bulk of the activity resembling the classic N400 component. This observation was confirmed by the presence of large main effect of REPETITION ( $F(1,19) = 7.78$ ,  $p = .012$ ,  $\eta^2 = .291$ ). Follow-up analyses indicated that priming effects were significant for pseudohomophones across the scalp (main effect of REPETITION:  $F(1,19) = 7.20$ ,  $p = .015$ ,  $\eta^2 = .275$ ; Anterior  $F(1,19) = 7.24$ ,  $p = .014$ ,  $\eta^2 = .276$ ; Mid  $F(1,19) = 5.31$ ,  $p = .033$ ,  $\eta^2 = .218$ ; Posterior  $F(1,19) = 5.89$ ,  $p = .025$ ,  $\eta^2 = .237$ ), but were not significant for transposed letter priming ( $ps < .12$ ).



**Figure 2.** Voltage maps calculated by subtracting target ERPs from the pseudohomophone condition from their control ERPs (A) and the Transposed Letter ERPs from their controls (B).

***Time-course of priming.***

To better understand the time-course of the above effects we also binned successive 50 ms epochs between 150 and 500 ms for the TL and pseudohomophone primes and control ERPs and ran separate ANOVAs on each epoch. These data are reported in Table 1 for each of three bands of anterior to posterior electrode sites. As can be seen, during the N250 epoch TL priming initiated approximately 50 ms earlier (between 200 and 250 ms vs. 250-300 ms) than pseudohomophone priming and the scalp distribution of these earliest effects were more posteriorly oriented for TL and more anteriorly oriented for pseudohomophone priming. Later, during the N400 epoch, it was the pseudohomophone priming effect that started earlier (between 300 and 350 ms vs. 450 and 500 ms) and was generally more robust, although in this case the scalp distribution was similar for the two types of priming.

**Table 1 - Time-course of Priming Effects for 3 Anterior-Posterior Rows of Electrodes**

Epoch ms	Pseudohomophones			Transposed Letters			
	Anterior	Middle	Posterior	Anterior	Middle	Posterior	
150-200	-	-	-	-	-	-	N250 region
200-250	-	-	-	-	*	**	
250-300	*	-	-	-	-	-	
300-350	*	**	**	-	-	-	N400 region
350-400	*	*	**	-	-	-	
400-450	-	+	*	-	-	-	
450-500	*	-	-	-	*	**	

- =  $p > 0.1$ , + =  $p < 0.1$ , \* =  $p < 0.05$ , \*\* =  $p < 0.02$

***Behavioral Data.***

Participants detected 91.3% (SD = 6.1) of animal probes in the target position and 2% (SD = 3.3) in the prime position within a window of 200 to 1200ms post-probe onset.

## Discussion

The present results provide an important confirmation and extension of Ferrand and Grainger's (1993) time-course analysis of orthographic and phonological influences on visual word recognition. In the present experiment prime duration was held constant at 50 ms, and the timing of orthographic and phonological processing was provided by ERP measures of prime influences during target word recognition. Our orthographic and phonological priming manipulation affected the N250 and N400 ERP components, and in line with Ferrand and Grainger's findings, the orthographic effect emerged about 50 ms earlier than the phonological effect.

The results of the present study also provide an important confirmation of early phonological influences on visual word recognition, a point that has been hotly debated over the last decade (e.g., Rastle & Brysbaert, 2006). Our ERP recordings not only provide clear evidence for fast phonological priming in conditions where all possible contamination from strategic factors is eliminated, but they also provide an upper boundary for when phonology starts to have an influence - approximately 250 ms post-target onset in the present study. Furthermore, the distinct topographical distribution of our orthographic and phonological effects suggests that they indeed reflect qualitatively different processes, and not just different levels of overlap on a given dimension.

Holcomb and Grainger (2006) applied Grainger and Ferrand's (1994) bimodal interactive-activation model in interpreting the time-course of masked repetition priming effects on ERPs. In this model, sublexical orthographic processing sends activation onto whole-word orthographic representations on the one hand, and sublexical phonological representations on the other. Transposed-letter primes are thought to affect sublexical orthographic processing (Perea & Carreiras, 2006) and therefore exert the earliest influence on the N250 (a component hypothesized to reflect sublexical

processing). This sublexical orthographic code is then translated into a phonological code, and it is at this moment that pseudohomophone primes can begin to exert their influence. Our results suggest that the sublexical conversion of orthography to phonology takes approximately 50 ms.

Finally, orthographic and phonological processing converges on whole-word representations, and from there on to appropriate semantic representations. The N400 is known to be sensitive to such form-meaning mapping (Holcomb, Grainger, & O'Rourke, 2002). Both transposed-letter and pseudohomophone primes generate significant activation in the whole-word representations of the corresponding basewords (i.e., the word "brain" for the primes "brane" and "barin"). It is this whole-word activation that is hypothesized to modulate the N400 in the present study.

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## AUTHOR NOTE

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