PSYCHOLOGICAL SCIENCE

Research Report

The Time Course of Orthographic and Phonological Code Activation

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ABSTRACT—***The present study used event-related potentials (ERPs) to examine the time course of orthographic and phonological priming in the masked priming paradigm. Participants monitored visual target words for occasional animal names, and ERPs to nonanimal critical items were recorded. These critical items were preceded by different types of primes: Orthographic priming was examined using transposed-letter (TL) primes (e.g.,*** **barin-BRAIN*****) and their controls (e.g.,*** **bosin-BRAIN*****); 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, which is 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 obtained repeatedly 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, in press, for review). However, direct comparisons of orthographic and phonological priming are less abundant (e.g., Ferrand & Grainger, 1992, 1994; Grainger & Ferrand, 1996; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). One such study is particularly relevant to the experiment we report here. Using the masked priming paradigm, Ferrand and Grainger (1993) varied both prime exposure duration and the amount of orthographic and phonological overlap between primes and targets. 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).

This time-course pattern is consistent with the results of studies manipulating the relative position of letters shared by prime and target. The primes in these experiments have included subset primes (e.g., *grdn-GARDEN*—Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Peressotti & Grainger, 1999), superset primes (e.g., *gafrsden-GARDEN*—Van Assche & Grainger, 2006), and transposed-letter (TL) primes (e.g., *gadren-GARDEN*—Perea & Lupker, 2004; Schoonbaert & Grainger, 2004). All these studies point to an early phase of orthographic processing that is not influenced by phonology. Thus, Grainger et al. (2006) demonstrated that although 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 in which 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-REVOLUCIÓN*) were compared with effects of orthographic control primes (e.g., *reloducion-REVOLUCIÓN*) and with effects of pseudohomophones of TL primes (e.g., *relobucion-REVOLUCIÓN*; note that *b* and *v* are given the same pronunciation in Spanish). The phonological TL condition (*relobucion-REVOLUCIÓN*) produced response latencies in a lexical decision task that did not differ significantly from those in the orthographic control condition (*reloducion-REVOLUCIÓN*), and were significantly slower than those in the orthographic TL condition (*relovucion-REVOLUCIÓN*).

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The present study combined masked priming with event-related potential (ERP) recordings to further analyze 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, in press) has shown that repetition priming affects a cascade of ERP components that start as early as 130 ms after target onset and continue through to as late as 600 ms. Two of these components are particularly relevant for the present study: the N250 and the N400. Both of these components are more negative-going for targets that are unrelated to the prime than for targets that are repeats of the prime. On the basis of the precise timing of these components and their distinct topographies, we (Holcomb & 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 was that N250 amplitude should be modified by both orthographic primes and phonological primes, and that the onsets of these two effects should be different.

METHOD

Subjects

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 five-letter words and their respective five-letter pseudohomophones. Fifteen subjects (who did not participate in the main experiment) rated each word-pseudohomophone pair for phonological similarity on a scale from 1 (*low*) to 7 (*high*), and the 200 most similar pairs were selected as stimuli for the main experiment (mean rating = 6.52, range = 4.75–7, *SD* = 0.57).

Each of the 200 target words was paired with four prime stimuli: the pseudohomophone that was pretested (e.g., *brane-BRAIN*), a pseudohomophone control prime (e.g., *brant-BRAIN*), a TL prime (e.g., *barin-BRAIN*), and a TL control prime (e.g., *bosin-BRAIN*). Control primes for pseudohomophones were formed by replacing one letter of the pseudohomophone that did not overlap with the target word (e.g., the *e* in *brane* became a *t* in *brant*); the pseudohomophone primes and pseudohomophone control primes were therefore matched in terms of the number of letters shared by prime and target and the position of the shared letters. Control primes for TL primes had two different letters replacing the transposed letters. For purposes of counterbalancing, each participant was tested with one of four lists of prime-target pairings; each list included all four priming conditions, with each target word appearing only once. Thus, each target word was tested in all four priming conditions across different participants.

Sixty noncritical trials were intermixed with the 200 critical trials. Thirty of the noncritical trials contained an animal name in the prime position and a filler word in the target position (e.g., *horse-TABLE*), and 30 contained an animal name in the target position and an unrelated pseudohomophone, TL, or corresponding control prime in the prime position (e.g., *trane-HORSE*, *trian-HORSE*, *troun-HORSE*). Each of 30 animal names was used once as a prime and once as a target 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 button whenever they detected an animal name. Subjects were told to read all other words passively (i.e., critical stimuli did not require an overt response). The trials on which animal names were 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 subjects with the procedure.

Procedure

Visual stimuli were presented on a 19-in. monitor set to a refresh rate of 60 Hz (which allows 16.67-ms resolution of stimulus control) and located 143 cm in front of the participant. Stimuli were displayed at high contrast as white letters (Arial font) on a black background (letter matrix was 30 pixels tall × 15 pixels wide). Each trial began with the termination of a fixation stimulus in the middle of the screen. After 500 ms, a forward mask of seven pound signs (#######) was presented for a duration of 500 ms. This forward mask was replaced at the same location on the screen by a five-letter prime, presented in lowercase letters for 50 ms. 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 (16.67 ms) and was immediately replaced by the visual target, presented in uppercase letters for a duration of 500 ms. All target words were followed by a 1,000-ms black screen, which was replaced by a 2,000-ms fixation stimulus marking the end of the trial. The next trial followed a 500-ms blank screen. Subjects were asked to blink and move their eyes only when the fixation stimulus appeared on the screen.

Electroencephalogram Recording

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, Eaton, OH). Additional electrodes were attached below the left eye (to monitor for vertical eye movement or 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 kΩ (impedance for eye electrodes was less than 10 kΩ). The EEG was amplified by an SA Bioamplifier with a band pass of 0.01 to 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). Separate waveforms were calculated by averaging compound-stimulus ERPs (i.e., the EEG time-locked to a point 100 ms before prime onset and lasting until 900 ms after target onset) for each of the four priming conditions. In order to carefully quantify the time course of the ERP effects, we measured mean amplitudes in three contiguous windows after target onset: 150 through 250 ms, 250 through 350 ms, and 350 through 550 ms. Repeated measures analyses of variance (ANOVAs) with within-participants factors of prime type (pseudohomophone vs. TL) and repetition (repeated vs. control) were used to analyze the ERP data. The Geisser and Greenhouse (1959) correction was applied to all repeated measures with more than one degree of freedom (corrected p values are reported). Three anterior (FP1, FPz, FP2), three middle (C3, Cz, C4), and three posterior (P3, Pz, P4) electrode sites were chosen for analysis; these sites 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-, TL-, and control-prime conditions are plotted separately in Figures 1a and 1b for the nine electrodes used in the analyses presented here. Figure 2 presents the voltage maps (formed from all 29 scalp sites) for pseudohomophone and TL priming effects in each of the three analysis windows.

150- to 250-Ms Target Epoch

As can be seen in Figures 1 and 2, between about 150 and 250 ms, targets following TL primes showed an early priming effect over the more posterior electrode sites, but targets following pseudohomophone primes showed little evidence of a priming effect. ANOVA results were consistent with this observation: There was a significant interaction among prime type, repetition, anterior-posterior extent, and laterality, $F(4, 76) = 4.59, p = .01$, $\eta^2 = .195$. Follow-up analyses confirmed that in the TL condition, there was a significant priming effect at posterior sites, $F(1, 19) = 4.69, p = .043$, $\eta^2 = .198$, and a marginal effect at the middle sites, $F(1, 19) = 3.41, p = .08$, $\eta^2 = .152$, but no effect at anterior sites ($F < 1$). There was no significant effect of priming for pseudohomophones at any location in this epoch (Fs < 1).

250- to 350-Ms Target Epoch

As can be seen in Figures 1 and 2, between 250 and 350 ms, it was targets following pseudohomophone primes that showed

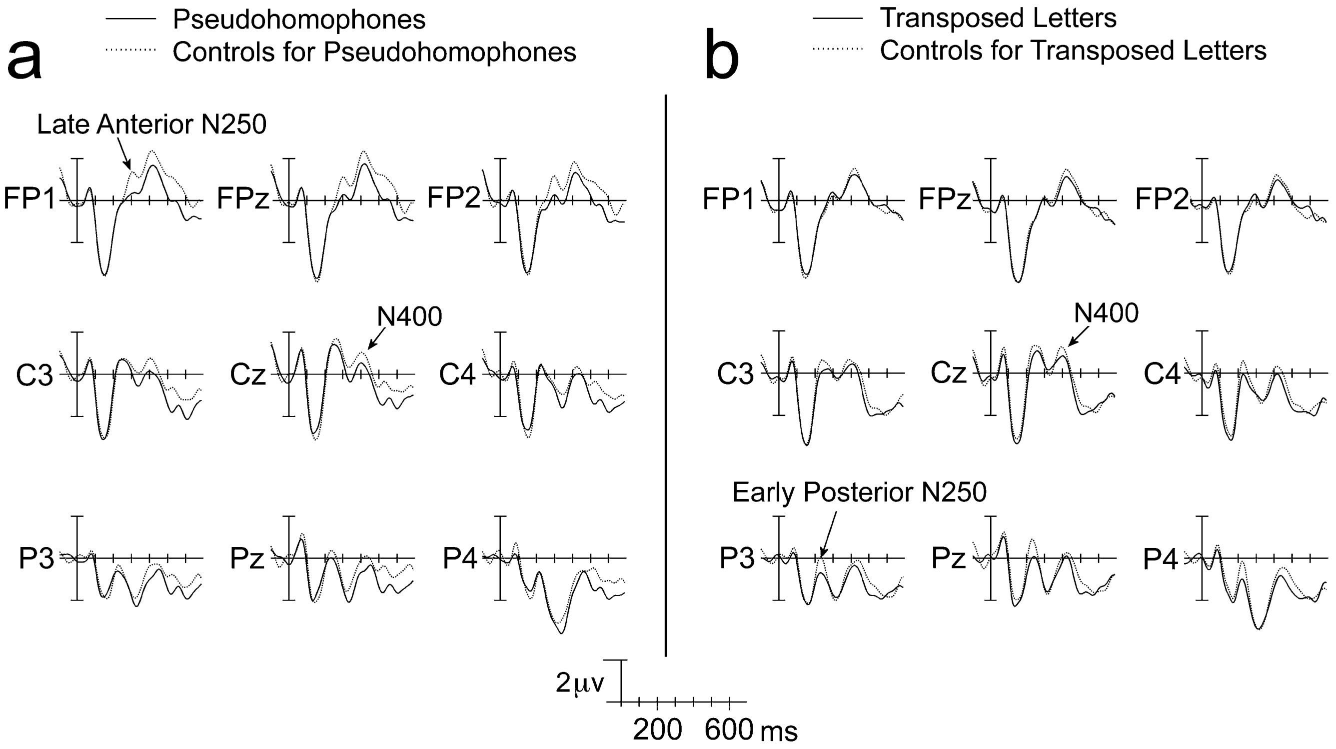

Fig. 1. Event-related potentials time-locked to target onset in the pseudohomophone (a) and transposed-letter (b) conditions, plotted with the waveforms for their respective control conditions.

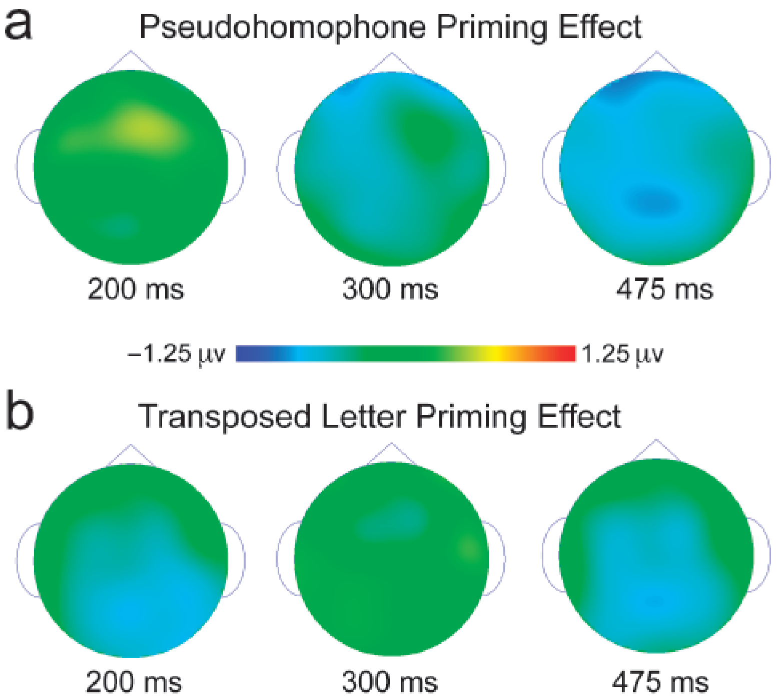

Fig. 2. Voltage maps of the pseudohomophone (a) and transposed-letter (b) priming effects. Each effect was calculated by subtracting event-related potentials (ERPs) to the target in the priming condition from ERPs to the target in the control condition.

priming effects, whereas targets following TL primes showed little to no priming. This observation was supported by a significant interaction of prime type, repetition, laterality, and anterior-posterior extent, $F(4, 76) = 3.24, p = .045, \eta^2 = .146$. Follow-up analyses demonstrated that whereas pseudohomophones showed a significant priming effect, $F(1, 19) = 4.77, p = .042, \eta^2 = .201$, TL primes did not ($F < 1$). 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- to 550-Ms Target Epoch

Examination of Figures 1 and 2 reveals that the third interval contained the bulk of the activity resembling the classic N400 component. This observation was confirmed by the presence of a 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. The effect of pseudohomophone priming was significant, $F(1, 19) = 7.20, p = .015, \eta^2 = .275$, and remained significant in analyses of anterior sites, $F(1, 19) = 7.24, p = .014, \eta^2 = .276$; middle sites, $F(1, 19) = 5.31, p = .033, \eta^2 = .218$; and posterior sites, $F(1, 19) = 5.89, p = .025, \eta^2 = .237$. In contrast, there was no significant TL priming ($ps < .12$).

Time Course of Priming

To better understand the time course of the effects, we also binned successive 50-ms epochs between 150 and 500 ms for the TL and pseudohomophone primes and their respective controls, and ran separate ANOVAs on each 50-ms epoch. The results are reported in Table 1 separately for anterior, middle, and posterior electrode sites. During the N250 epoch, TL priming began approximately 50 ms earlier (200–250 ms vs. 250–300 ms) than pseudohomophone priming, and the scalp distribution of these earliest effects was posteriorly oriented for TL priming and anteriorly oriented for pseudohomophone priming. During the N400 epoch, it was pseudohomophone priming that started earlier (300–350 ms vs. 450–500 ms), and pseudohomophone priming was generally more robust than TL priming, although in this case the scalp distribution was similar for the two types of priming.

Behavioral Data

Participants detected 91.3% ($SD = 6.1$) of animal probes in the target position and 2% ($SD = 3.3$) of animal probes in the prime position within a window from 200 to 1,200 ms after 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 recognition of the target word. Our orthographic

TABLE 1

Time Course of Priming Effects: Results of Tests of Significance for Three Anterior-Posterior Rows of Electrodes

	Pseudohomophone priming			Transposed-letter priming		
Epoch (ms)	Anterior	Middle	Posterior	Anterior	Middle	Posterior
N250						
150–200	$p > .1$	$p > .1$	$p > .1$	$p > .1$	$p > .1$	$p > .1$
200–250	$p > .1$	$p > .1$	$p > .1$	$p > .1$	$p < .05$	$p < .02$
250–300	$p < .05$	$p > .1$	$p > .1$	$p > .1$	$p > .1$	$p > .1$
N400						
300–350	$p < .05$	$p < .02$	$p < .02$	$p > .1$	$p > .1$	$p > .1$
350–400	$p < .05$	$p < .05$	$p < .02$	$p > .1$	$p > .1$	$p > .1$
400–450	$p > .1$	$p < .1$	$p < .05$	$p > .1$	$p > .1$	$p > .1$
450–500	$p < .05$	$p > .1$	$p > .1$	$p > .1$	$p < .05$	$p < .02$

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, an issue that has been hotly debated over the past decade (e.g., Rastle & Brysbaert, in press). Our ERP recordings not only provide clear evidence for fast phonological priming in conditions in which all possible contamination from strategic factors was eliminated, but 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, not just different levels of overlap on a given dimension.

In previous work, we (Holcomb & Grainger, 2006) applied Grainger and Ferrand's (1994) bimodal interactive-activation model in interpreting the time course of the effects of masked repetition priming on ERPs. In this model, sublexical orthographic processing sends activation to whole-word orthographic representations, on the one hand, and sublexical phonological representations, on the other. TL primes are thought to affect sublexical orthographic processing (Perea & Carreiras, 2006) and therefore to 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.

Finally, orthographic processing and phonological processing converge 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 TL and pseudohomophone primes generate significant activation in the whole-word representations of the corresponding base words (i.e., the word *brain* for the primes *brane* and *barin*). It is this whole-word activation that we hypothesize modulated the N400 in the present study.

Acknowledgments—This research was supported by National Institutes of Health Grants HD25889 and HD043251.

REFERENCES

Carreiras, M., Ferrand, L., Grainger, J., & Perea, M. (2005). Sequential effects of masked phonological priming. *Psychological Science*, *16*, 585–589.

Ferrand, L., & Grainger, J. (1992). Phonology and orthography in visual word recognition: Evidence from masked nonword priming. *Quarterly Journal of Experimental Psychology*, *45A*, 353–372.

Ferrand, L., & Grainger, J. (1993). The time-course of phonological and orthographic code activation in the early phases of visual word recognition. *Bulletin of the Psychonomic Society*, *31*, 119–122.

Ferrand, L., & Grainger, J. (1994). Effects of orthography are independent of phonology in masked form priming. *Quarterly Journal of Experimental Psychology*, *47A*, 365–382.

Frost, R., Ahissar, M., Gotesman, R., & Tayeb, S. (2003). Are phonological effects fragile? The effect of luminance and exposure duration on form priming and phonological priming. *Journal of Memory and Language*, *48*, 346–378.

Geisser, S., & Greenhouse, S. (1959). On methods in the analysis of profile data. *Psychometrica*, *24*, 95–112.

Grainger, J., & Ferrand, L. (1994). Phonology and orthography in visual word recognition: Effects of masked homophone primes. *Journal of Memory and Language*, *33*, 218–233.

Grainger, J., & Ferrand, L. (1996). Masked orthographic and phonological priming in visual word recognition and naming: Cross-tasks comparisons. *Journal of Memory and Language*, *35*, 623–647.

Grainger, J., Granier, J.P., Farioli, F., Van Assche, E., & van Heuven, W. (2006). Letter position information and printed word perception: The relative-position priming constraint. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 865–884.

Holcomb, P.J., & Grainger, J. (2006). On the time-course of visual word recognition: An ERP investigation using masked repetition priming. *Journal of Cognitive Neuroscience*, *18*, 1632–1643.

Holcomb, P.J., Grainger, J., & O'Rourke, T. (2002). An electrophysiological study of the effects of orthographic neighborhood size on printed word perception. *Journal of Cognitive Neuroscience*, *14*, 938–950.

Kiyonaga, K., Grainger, J., Midgley, K., & Holcomb, P.J. (in press). Masked cross-modal repetition priming: An event-related potential investigation. *Language and Cognitive Processes*.

Lukatela, G., & Turvey, M.T. (1994). Visual access is initially phonological: 2. Evidence from phonological priming by homophones, and pseudohomophones. *Journal of Experimental Psychology: General*, *123*, 331–353.

Perea, M., & Carreiras, M. (2006). Do transposed-letter similarity effects occur at a prelexical phonological level? *Quarterly Journal of Experimental Psychology*, *59*, 1600–1613.

Perea, M., & Lupker, S.J. (2004). Can *CANISO* activate *CASINO*? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language*, *51*, 231–246.

Peressotti, F., & Grainger, J. (1999). The role of letter identity and letter position in orthographic priming. *Perception & Psychophysics*, *61*, 691–706.

Perfetti, C.A., & Bell, L.C. (1991). Phonemic activation during the first 40 ms of word identification: Evidence from backward masking and priming. *Journal of Memory and Language*, *30*, 473–485.

Perfetti, C.A., & Tan, L.H. (1998). The time course of graphic, phonological, and semantic activation in Chinese character identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 101–118.

Rastle, K., & Brysbaert, M. (in press). Masked phonological priming effects in English: Are they real? Do they matter? *Cognitive Psychology*.

Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes*, *19*, 333–367.

Van Assche, E., & Grainger, J. (2006). A study of relative-position priming with superset primes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 399–415.

Ziegler, J., Ferrand, L., Jacobs, A.M., Rey, A., & Grainger, J. (2000). Visual and phonological codes in letter and word recognition: Evidence from incremental priming. *Quarterly Journal of Experimental Psychology*, *53A*, 671–692.

(RECEIVED 12/9/05; REVISION ACCEPTED 5/3/06;
FINAL MATERIALS RECEIVED 5/16/06)