On the Time Course of Visual Word Recognition: An Event-related Potential Investigation using Masked Repetition Priming

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Abstract

■ The present study used event-related potentials (ERPs) to examine the time course of visual word recognition using a masked repetition priming paradigm. Participants monitored target words for occasional animal names, and ERPs were recorded to nonanimal critical items that were full repetitions, partial repetitions, or unrelated to the immediately preceding masked prime word. The results showed a strong modulation of the N400 and three earlier ERP components (P150, N250, and the P325) that we propose reflect sequential overlapping steps in the processing of printed words. ■

INTRODUCTION

Understanding how literate adults read single words has been one of the major objectives of cognitive science since the beginning of the field. For most of the literate world, reading is an everyday activity and a prerequisite skill for successful integration into modern society. The speed and apparent ease with which individual words can be identified from around 50,000 or so possibilities in less than half a second has provided a continuing challenge for theorists interested in understanding the architecture of the word recognition system. Moreover, tying the various underlying perceptual and cognitive processes involved in word recognition to the specific brain areas involved has proven even more difficult, in part because of the lack of suitable methods with the requisite resolution to adequately determine the location, timing, and interactivity of the brain systems involved.

In the behavioral literature, much has been learned about the processes underlying word recognition by using the masked priming technique. In this procedure, a prime word is briefly presented and is rapidly followed by a second fully visible target word. The target serves as a pattern mask for the prime making the prime virtually impossible to identify. Participants are usually unaware that the prime was even presented. Evidence from single-cell work in monkeys (e.g., Lamme, Zipser, & Spekreijse, 2002; Lamme & Roelfsema, 2000) and recent magnetoencephalogram work (Rieger, Braum, Bulthoff, & Gegenfurtner, 2005) in humans suggests that this sort of backward masking works by allowing the initial feed-forward volley of prime processing, up

to the point of the mask, to proceed through the visual system up to very high levels. However, all recurrent processing (feedback and lateral inhibition) of the prime is then blocked throughout the system because of the mask overwriting the sensory representation initially set up by the prime. So, although the mask does block certain elaborative processing of the prime due to recurrent processing, it does not stop the initial cascade of processing that precedes unimpeded. Lamme et al. (2002) and Lamme, Supèr, and Spekreijse (1998) argue that it is this blocking of recurrent processing that normally occurs for fully visible items, which impedes awareness of the masked item.

Substantial evidence suggests that even subtle manipulations of the overlap of features of the prime and target stimuli can produce reliable changes in target performance in the masked priming paradigm (e.g., Segui & Grainger, 1990; Forster & Davis, 1984). For example, although the largest effects of repetition occur when the target word is a full repetition of the prime compared with when the prime and target are unrelated words (i.e., no letter overlap), smaller but significant priming effects occur under certain circumstances when the prime and target share only some letters (e.g., Ferrand & Grainger, 1992, 1994; Grainger & Jacobs, 1993). This pattern of effects has been interpreted as reflecting the sensitivity of lexical processing to the overlap of orthographic features in the prime and target items and as evidence in favor of an interactive hierarchical processing architecture such as the interactive activation model (Grainger & Jacobs, 1996, 1999; McClelland & Rumelhart, 1981). Grainger and van Heuven (2003) proposed an extended framework for orthographic processing based on the interactive activation model. In this

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framework, a bank of letter detectors performs parallel, independent detection of a set of simultaneously presented letter identities. Each letter detector receives visual feature information from a specific location along the horizontal meridian of the retina (for horizontally written languages with alphabetical orthographies). Grainger and van Heuven called this bank of letter detectors the "alphabetic array." Location-specific detection of letter identities is then transformed into a location-independent orthographic code by letter combination detectors that receive input from appropriately ordered location-specific letter identities in the alphabet array. Letter combination detectors then activate whole-word orthographic representations, which provide the central gateway to semantic representations.

In a number of recent studies, Dehaene et al. (2004) and Dehaene, Le Clec'H, Poline, Le Bihan, and Cohen (2002) have coupled functional magnetic resonance imaging (fMRI) with the masked priming technique in an effort to isolate the location and sequence of early visual word processing areas such as those described above. In one study (Dehaene et al., 2002), they demonstrated that regions in the right occipital cortex are sensitive to low-level visual features (repetition effects were found only for physically identical stimuli), whereas left occipital–temporal areas revealed sensitivity to more abstract features (repetition was found across upper- and lowercase letters, which were not physically similar). In a subsequent study, they further showed that this temporal–occipital area could be subdivided into a bilateral more posterior subregion that was sensitive to retinal location (the prime and target had to occur in the same location to get priming) and a more anterior left hemisphere subregion that was location invariant. They argued that it is this latter region that contains lexical representations.

This sequence of processing steps proposed by Dehaene et al. makes sense from both anatomical and processing perspectives. However, the temporal resolution of the blood oxygen level-dependent signal their findings are based on is on the order of seconds (Dale et al., 2000), whereas the lexical and sublexical processes of interest are on the order of a few hundreds of milliseconds. Although the masked priming paradigm they used arguably reflects bottom-up word-based processes (see the arguments above for the functional explanation of masking), it is nevertheless impossible to know the actual time course of these effects without obtaining additional temporal information.

Recently, several studies have reported that event-related potentials (ERPs), a technique with a much higher temporal resolution than fMRI, are sensitive to repetition effects in the masked priming paradigm (Holcomb, Reder, Misra, & Grainger, 2005; Misra & Holcomb, 2003; Schnyer, Allen, & Forster, 1997). All of these studies reported evidence for an attenuation of the N400 component between 300 and 500 msec for target words that

were repeats of an earlier masked prime word compared with when the target and prime are different unrelated words. Surprisingly, none of these studies reported consistent evidence that ERP components before the onset of the N400 are sensitive to repetition priming. Given that the most-frequently cited interpretation of the functional significance of the N400 is that it reflects a postlexical semantic process (e.g., Holcomb, 1993), the question of why earlier ERP effects, in particular ones sensitive to processes that occur before semantic processing, were not found is clearly an important one. This lack of sensitivity would appear to suggest that the use of ERPs in the masked priming paradigm will not likely tell us much about the sequence of early presemantic word processes that should minimally include processing at the level of subletter visual feature representations, subword orthographic representations (i.e., letters and letter clusters), and word representations themselves (Grainger & van Heuven, 2003; Grainger & Jacobs, 1996).

One possibility for the lack of earlier effects in previous ERP masked priming studies is that they used prime-target stimulus-onset asynchronies (SOAs) of 500 msec. These intervals were selected to avoid overlap between prime and target ERPs. With shorter intervals, the ERPs to primes carry over into the target epoch, making it difficult to know whether an effect is because of the prime, the target, or both. However, the logic of the masking technique as implemented in word processing studies requires that targets follow primes in rapid succession. This is because it is the temporal overlap of processing of the two items that drives word-based effects of repetition. As has been shown by Ferrand (1996), at 500 msec, many if not most of the lexical and sublexical effects of priming have dissipated. Perhaps by 500 msec, all that is left of the masked prime is residual semantic activity that serves to generate an N400 effect.

Current Study

In the current study, we measured ERP masked repetition priming effects in a short prime-target SOA paradigm designed to decompose the temporal sequence of processing steps involved in visual word recognition. Participants were presented with brief (50-msec) visual primes that were masked by a both a forward and backward pattern mask and were rapidly (20 msec later) followed by a target word that was a full repetition of the prime (e.g., *table–TABLE*, *mouth–MOUTH*), a target word that was a partial repetition of the prime (e.g., *teble–TABLE*, *moath–MOUTH*), or a target word that was completely unrelated to the prime (e.g., *mouth–TABLE*, *table–MOUTH*, *moath–TABLE*, *teble–MOUTH*). Participants were instructed to read all stimuli and to press a button to occasional probe words in a particular semantic category (animals). ERPs were time-locked to the

onset of primes and recorded for 800 msec after the onset of target words. There were two main predictions. The first was that shorter prime-target SOAs would serve to boost pre-N400 priming effects occurring early in the target epoch. This prediction is based on behavioral work demonstrating that at SOAs longer than 300 msec, lexical and sublexical mask priming effects are attenuated (Ferrand, 1996), but that at shorter SOAs of 50 to 100 msec, robust lexical effects can be obtained. We were particularly interested in determining if ERP components earlier than the N400 might prove sensitive to variables that are known to directly influence lexical and/or sublexical processes. In this regard, differences in priming effects due to manipulation of the degree of prime-target orthographic similarity were predicted. We reasoned that any ERP components sensitive to lexical or sublexical orthographic processing should be differentially sensitive to the degree of prime-target letter overlap. In other words, targets that share a number of letters with their primes (e.g., *teble–TABLE*) should produce responses intermediate between full repetitions (e.g., *table–TABLE*) and unrelated primes and targets (e.g., *porch–TABLE*).

A second prediction was that following previous work with masked repetition priming, robust masked repetition priming effects would be obtained on the N400. However, given that these earlier studies used relatively long prime-target SOAs, it is possible that in the current experiment N400 effects might be small or even eliminated because of an insufficient amount of time for the prime to establish a context. Another issue is whether partial overlap of prime and target items would produce differential attenuation of the N400. Because these primes are not real words, they should not presumably preactivate the semantic representations of the following orthographically similar real words. However, in one previous study (Holcomb, O'Rourke, & Grainger, 2002), pseudowords derived from words with many lexical neighbors produced larger N400s than pseudowords from sparse lexical neighborhoods. This suggests that wordlike pseudowords do at least initially partially activate similar real words that in turn modulates the N400. This suggests that such items might serve as somewhat effective primes for their real word neighbors and therefore might at least partially attenuate the N400.

Finally, to avoid the problem mentioned above of ERPs from the masks and primes differentially contaminating the ERPs to targets when the various stimuli within a trial are positioned close together in time, we carefully matched mask and prime stimuli, such that across participants, all items occurred in all priming conditions an equal number of times. In other words, the grand average ERPs in the various conditions were formed from both the same target and prime words (the exception being that the partial overlap primes were one letter different). This type of counterbalancing scheme assures that ERPs time locked to the different target conditions are not differentially influenced by low level physical or lexical properties of the different prime stimuli.

METHODS

Participants

Forty-eight volunteers (32 women, mean age = 20.8 years, SD = 2.6) who were all undergraduate students at Tufts University were paid $25 to participate in this experiment. All were right-handed native speakers of English with normal or corrected-to-normal visual acuity.

Stimuli

The critical stimuli for this experiment were 320 pairs of five-letter English words. The noncritical stimulus pairs were formed by combining 80 five-letter animal names with 80 unrelated nonanimal five-letter words. For both the critical and noncritical items, the first member of each pair was referred to as the prime and the second member as the target. Stimulus lists consisted of 480 trials each containing a prime–TARGET pair of items, with the prime presented in lowercase letters and the target in uppercase (this was done to minimize the physical similarity between repeated items). In each of four lists, there were 80 trials where the target was a full repetition of the prime (e.g., *table–TABLE*), 80 trials where the target was a partial repetition of the prime (with prime-target letter consistency in all but one letter position—*teble–TABLE*), and 160 trials where the target was completely unrelated to the prime (e.g., *mouth–TABLE* and *moath–TABLE*). Across lists (and participants), critical target words appeared once in each of the four conditions, and within lists, each target stimulus was presented once. For the 160 noncritical trials, 80 contained animal names in the prime position and a filler word in the target position, whereas another 80 trials contained unrelated filler words in the prime position and animal names in the target position. The same 80 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 in either the prime or target position. Participants were told to read all other words passively (i.e., critical stimuli did not require an overt response). A practice session was administered before the main experiment to familiarize the participant with the procedure.
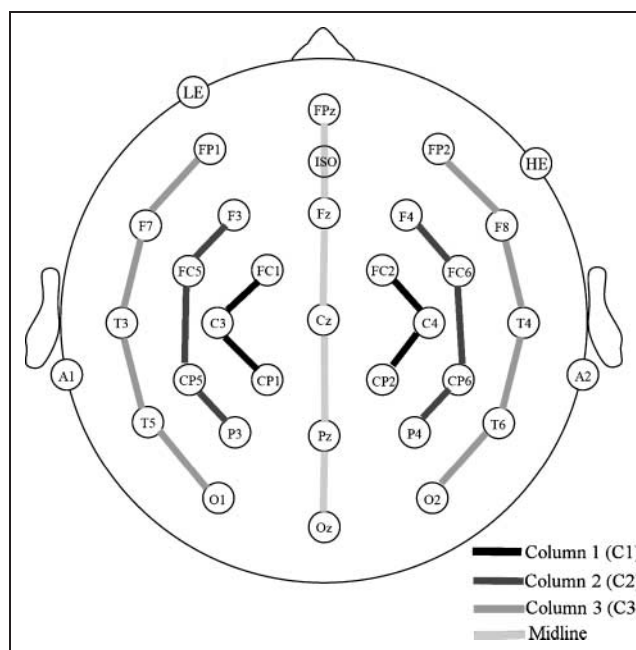
Procedure

Visual stimuli were presented on a 19-in. monitor set to a refresh rate of 100 Hz (which allows 10-msec resolution of stimulus control) and located 143 cm directly 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 by 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 500 msec. The forward mask was replaced at the same location on the screen by a five letter lowercase prime item for 50 msec. The prime was then immediately replaced by a backward mask (#######). The backward mask remained on the screen for 20 msec and was immediately replaced by the visual target in uppercase letters for a duration of 300 msec. All target words were followed by a 900-msec black screen that was replaced by a 2000-msec fixation stimulus marking the end of the trial (see Figure 1 for a schematic of typical trial). Participants were asked to refrain from blinking and moving their eyes except when the fixation stimulus appeared on the screen.

Electroencephalogram 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 (Electro-Cap International, Eaton, OH; see Figure 2). In addition to the 29 scalp sites, additional electrodes were attached 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 kΩ (impedance for eye electrodes was less than 10 kΩ). The EEG was amplified by an SA Bioamplifier (SA International, Encinitas, CA) with a bandpass of 0.01 and 40 Hz, and the EEG was continuously sampled at a rate of 200 Hz throughout the experiment.

Figure 2. Electrode montage and four analysis columns used for ANOVAs.

Data Analysis

Averaged ERPs were formed off-line from trials free of ocular and muscular artifact (less than 10% of trials).

Figure 1. A typical trial with examples of the various types of items in the prime and target positions. Note that no participant was presented with any word on more than one trial. The bottom row of example items illustrates the two types of probe trials.
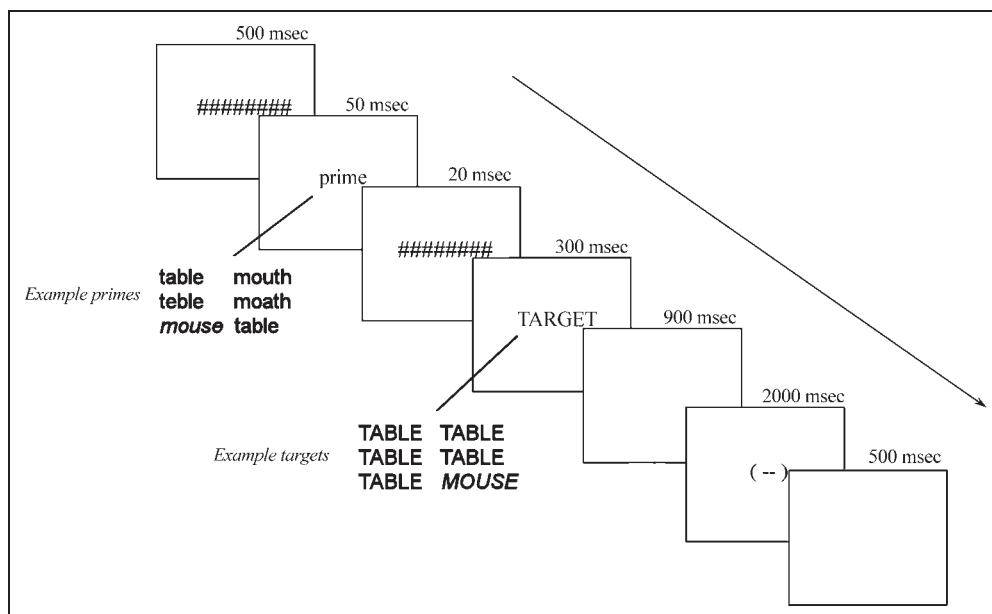
ERPs were calculated by averaging the EEG time locked to a point 100 msec preprime onset and lasting until 800 msec posttarget onset. The 100-msec preprime period was used as the baseline. (Note that we also examined ERPs using baselines calculated during the preforward mask period and during the 100 msec immediately preceding the target [i.e., partly overlapping the prime]. Neither of these alternative baselining procedures produced a different pattern than that reported below for the preprime baseline.) Separate ERPs were formed for the four types of target conditions (targets that were repetitions of their prime words, targets that were unrelated to their prime words, targets that were partial repetitions of their prime pseudowords, and targets that were unrelated to their prime pseudowords). To carefully quantify the time course of repetition effects, mean amplitudes in four contiguous posttarget onset latency windows were measured: 125–175, 175–300, 300–425, and 425–550 msec. We also measured the latencies of three ERP peaks prominent in the waves seen at many sites (see Figure 3A): a negativity peaking between 175 and 325 msec, a positivity peaking between 300 and 405 msec, and the peak latency of the N400 between 350 and 550 msec. Repeated measures analyses of variance (ANOVAs) were used to analyze these data. To directly compare the full and partial repetition conditions with the unrelated condition, we used a single three-level, within-subject factor of repetition in these analyses (full repetition vs. partial repetition vs. unrelated).[1] The Geisser and Greenhouse (1959) correction was applied to all repeated measures with more than one degree of freedom. To balance the need to carefully scrutinize distributional effects in the data while holding down the number of total comparisons, we used an approach to data analysis that we have successfully applied in a number of previous studies (e.g., Holcomb et al., 2005). In this approach, the head is divided up into seven separate parasagittal columns along the anteroposterior axis of the head (see Figure 2). The electrodes in each of three pairs of lateral columns and one midline column are analyzed in separate ANOVAs. Three of these analyses (referred to as Column 1, 2, or 3) involved an anterior/posterior electrode site factor with three (Column 1: FC1/FC2 vs. C3/C4 vs. PC1/PC2), four (Column 2: F3/F4 vs. FC5/FC6 vs. CP5/CP6 vs. P3/P4), or five levels (Column 3: FP1/FP2 vs. F7/F8 vs. T3/T4 vs. T5/T6 vs. O1/O2), as well as a hemisphere factor (left vs. right). The forth "midline" analysis included a single anterior/posterior electrode site factor with five levels (FPz vs. Fz vs. Cz vs. Pz vs. Oz). This approach has a number of advantages over other schemes for analyzing relatively large numbers of scalp sites. First, it provides a thorough analysis of the entire head breaking the scalp up into regions (left and right, front and back) that have proven important in numerous previous studies (e.g., see work by Neville et al., 1992), at the same time allowing single or small clusters of sites

to influence the analysis (using a single electrode factor with a large number of sites can easily mask the effects of a small regional effect). Second, it includes all sites rather than either picking "representative" sites (i.e., regions of interests) or averaging over sites to reduce the number of levels of the electrode factor (these later approaches beg the question of why one would want a high density of sites to begin with). The tradeoff is that with four sets of analyses per measurement, there is an inflated possibility of chance findings. This can be problematic when an effect is significant in a single column. It is therefore important in these cases to use additional caution in interpreting findings.

RESULTS

Electrophysiological Data

Visual Inspection of Event-related Potentials

The compound ERPs spanning the prime and target epochs from 30 electrode sites for the three repetition conditions are plotted in Figure 3A. As can be seen in these plots, ERPs in the target epoch (the part of the waveforms after the vertical calibration bar) anterior to the occipital (O1, Oz, and O2) and posterior–temporal electrode sites (T5 and T6) produced an initial small negative-going potential (occipital N1) peaking at between 40 and 70 msec posttarget onset, which was followed immediately by a much larger positivity (P2) peaking between 140 and 180 msec. At the occipital and posterior temporal sites, in this same time frame, there were similar potentials to those seen at more anterior electrode sites, but their polarity was reversed (i.e., there was a small positivity between 40 and 70 msec and a larger negativity between 140 and 180 msec). These early potentials likely reflect an amalgamation of sensory processes initiated by a combination of the mask, prime, and target stimuli, all of which were present on the stimulus display within the 80-msec period leading up to the beginning of the target epoch. Following these early potentials and starting after the 200-msec point, a series of two negativities and two positivities can be seen at most electrode sites. The first negative-going potential peaks at between 240 and 280 msec and is followed by a small positivity peaking around 325 msec. The positivity is followed in turn by the second negative-going peak between 400 and 500 msec (the N400). Finally, at most sites following the N400, the ERPs go in the positive direction and either stay positive (anterior and central sites) or return toward baseline (posterior and lateral sites).

Analyses of Event-related Potential Data

The 125- to 175-msec Target Epoch. There was no main effect of repetition in this epoch, although at the most lateral sites, there was a marginal Repetition × Hemisphere
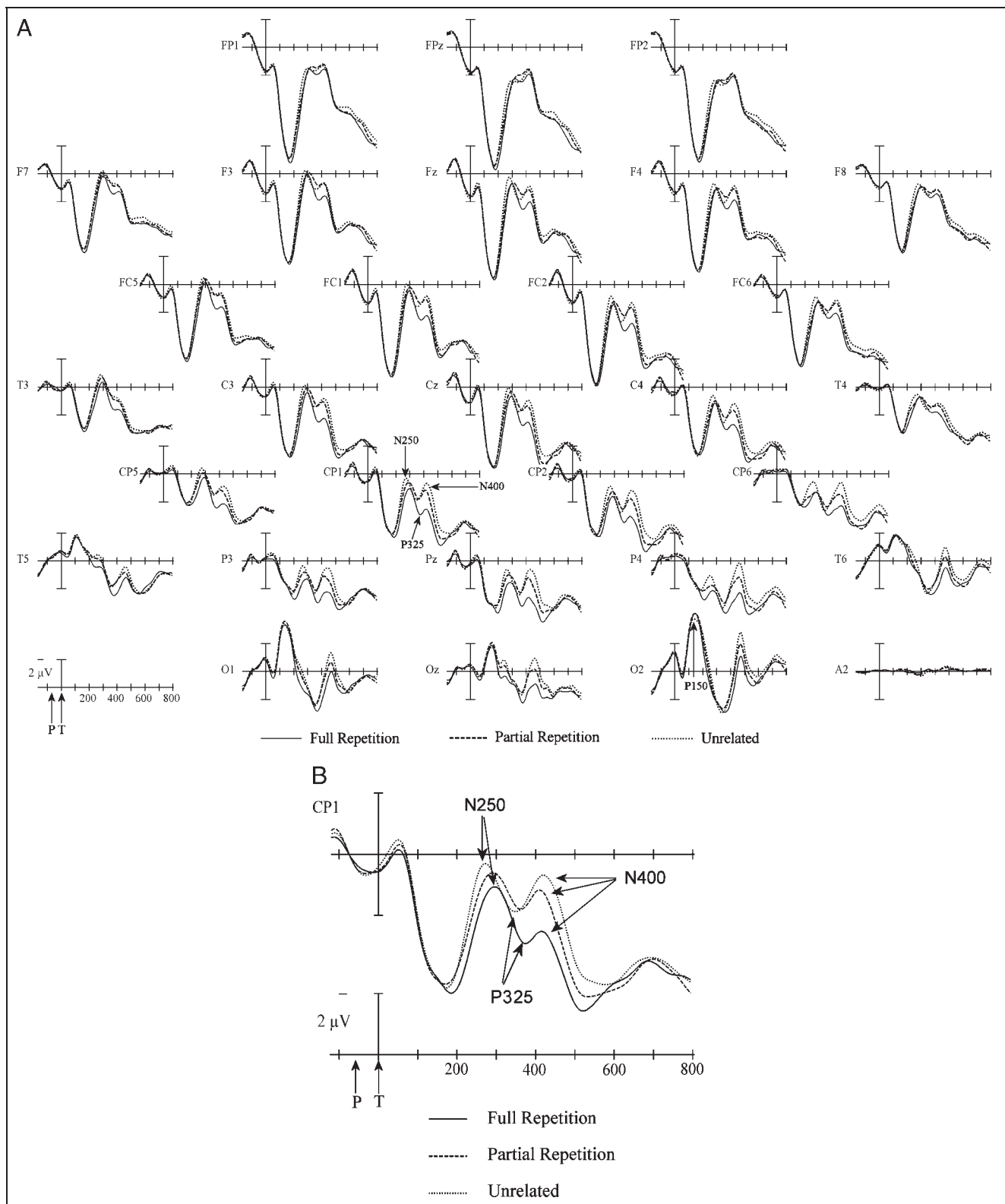
Figure 3. (A) ERPs time locked to target onset in the three repetition conditions. Note the primes' onset at −70 msec (denoted by the "P" arrow in the time legend) and the targets' onset at 0 msec (marked by the vertical calibration bar and the "T" arrow on the time legend). Negative voltages are plotted upward. Refer to Figure 2 for electrode locations. (B) Enlargement of CP1 site from (A).

interaction [Column 3: $F(2,94) = 2.84, p < .067$], suggesting that the effects of repetition differed over the two hemispheres. Follow-up analyses indicated that over the rightmost posterior sites (but not the left), unrelated targets were slightly (but significantly) more positive-going in this epoch than either fully repeated, $F(1,47) = 5.96$, $p = .018$, or partially repeated targets, $F(1,47) = 4.62$, $p = .037$ (see Figure 4), that did not differ significantly from each other ($p > .1$).

The 175- to 300-msec Target Epoch. As can be seen in Figure 3, between about 175 and 300 msec, target words following unrelated primes were associated with a larger negativity than target words following the same prime word (full repetition) or a prime that differed by a single letter (i.e., partial repetition). This observation was confirmed by the presence of a main effect of repetition across all four analysis columns [midline: $F(2,94) = 14.45, p < .001$; Column 1: $F(2,94) = 6.57, p < .004$; Column 2: $F(2,94) = 12.16, p < .001$; Column 3: $F(2,94) = 17.43, p < .001$]. Follow-up analyses contrasting the fully repeated with the partially repeated conditions [midline: $F(1,47) = 9.13$, $p = .004$; Column 1: $F(1,47) = 4.71$, $p = .035$; Column 2: $F(1,47) = 6.06$, $p = .018$; Column 3: $F(1,47) = 10.73, p < .002$] and the partially repeated with the unrelated condition [midline: $F(1,47) = 7.15$, $p = .010$; Column 1: $F(1,47) = 4.10$, $p = .049$; Column 2: $F(1,47) = 6.15$, $p = .017$; Column 3: $F(1,47) = 21.71, p < .001$] showed that both of these contrasts resulted in significant differences. As can be seen in Figure 3, the
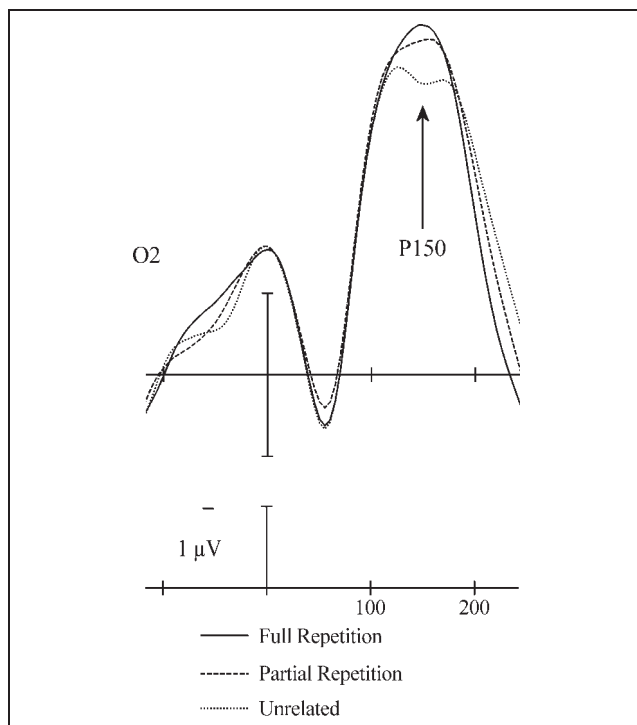
Figure 4. Full repetition, partial repetition, and unrelated targets at the O2 site.

unrelated condition produced the largest negative-going wave in this epoch, followed by the partially repeated and finally the fully repeated condition.

Additional follow-up analyses were run separately for targets that were full repetitions of the prior prime and those that were only partial repetitions to determine if there were differences between the repetition conditions. When contrasted with unrelated targets, partial repetitions tended to produce larger negativities over the right hemisphere than the left [partial repetition, Repetition × Hemisphere interaction: Column 1: $F(1,47) = 3.84, p < .056$; Column 2: $F(1,47) = 6.04, p < .018$; Column 3: $F(1,47) = 6.01, p < .018$] and at anterior than posterior sites [Repetition × Electrode Site interaction: midline: $F(4,188) = 5.01, p < .009$; Column 3: $F(4, 188) = 6.01, p < .008$]. Similar contrast for targets following fully overlapping primes suggested effects on this negativity were more evenly distributed across the scalp [full repetition, Repetition × Hemisphere, and Repetition × Electrode Site interactions: all $Fs < 1.6$].

We also measured the peak latency of the negativity in this time window at the midline and C1 columns (where the component was largest). The mean peak latency of this negativity in the difference waves in Figure 5 was 250 msec. As can be seen in Figure 3B, there were clear differences in latency due to repetition [main effect of repetition, midline: $F(2,94) = 4.96, p = .010$; Column 1: $F(2,94) = 3.26, p = .001$]. Follow-up analyses revealed that partial repetition targets produced significantly later peaks than unrelated targets [midline: $F(1,47) = 9.49$, $p = .003$; Column 1: $F(1,47) = 17.77, p = .001$], but not than full repetition targets ($Fs < 1$).

The 300- to 400-msec Target Epoch. As can be seen in Figure 3, this epoch contains a small positive-going potential as well as the leading edge of the N400 component. There were again significant differences the three target types [main effect of repetition midline: $F(2,94) = 7.62, p < .001$; Column 1: $F(2,94) = 6.57, p < .004$; Column 2: $F(2,94) = 8.09, p < .001$; Column 3: $F(2,94) = 5.37, p < .008$]. Follow-up analyses demonstrated that although partially repeated and unrelated targets did not statistically differ in this epoch ($Fs < 1.6$), full repetition targets were significantly more positive going than partial repetition targets [midline: $F(1,47) = 13.34, p = .001$; Column 1: $F(1,47) = 4.71$, $p = .035$; Column 2: $F(1,47) = 12.22, p = .001$; Column 3: $F(1,47) = 8.96, p = .004$].

There were also distributional differences in this epoch in the contrasts between the full repetition targets and the unrelated targets (see the 325-msec voltage map in Figure 5). The effects of repetition tended to be somewhat larger in a region extending across the right hemisphere and into parietal areas of left hemisphere [Repetition × Hemisphere × Electrode Site, Column 2: $F(3,141) = 3.20, p = .043$; Repetition × Hemisphere interaction, Column 3: $F(1,47) = 7.70, p < .008$] (see Figure 5).

Figure 5. (Top) Voltage maps centered on the four primary measurement epochs. These were formed from difference waves (bottom) calculated by subtracting the full repetition from the unrelated condition.
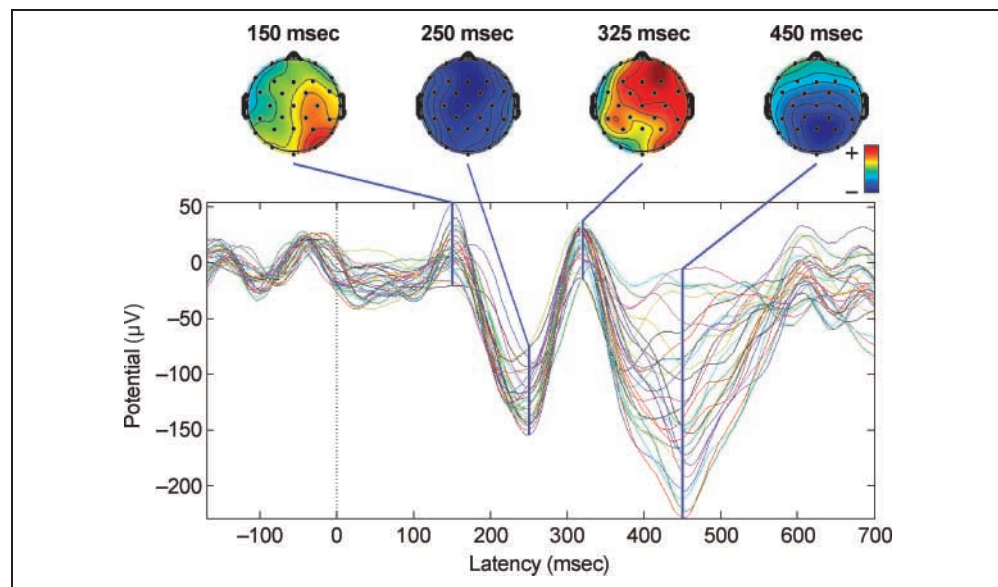
We measured the latency of the positivity in this epoch that had a mean peak latency of 325 msec in the difference waves in Figure 5. There were significant differences in latency due to repetition (main effect of repetition, midline: $F(2,94) = 3.96, p = .023$; Column 1: $F(2,94) = 5.72, p = .005$), which in follow-up analyses revealed that partial repetition targets produced a marginally earlier peak positivity than full repetition targets [midline: $F(1,47) = 2.91, p = .095$] but not unrelated targets ($Fs < 1.5$).

The 400- to 550-msec Target Epoch. Examination of Figure 3 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 effects of repetition across the four analysis columns [midline: $F(2,94) = 9.83, p < .001$; Column 1: $F(2,94) = 10.05, p < .001$; Column 2: $F(2,94) = 8.77, p = .001$; Column 3: $F(2,94) = 6.63, p < .003$]. Follow-up analyses demonstrated that unrelated targets were more negative than partial repetition targets [midline: $F(1,47) = 5.20, p = .027$; Column 1: $F(1,47) = 5.94, p = .019$; Column 2: $F(1,47) = 4.87, p < .032$; Column 3: $F(1,47) = 4.19, p = .046$] and partial repetition targets were more negative than full repetition targets [midline: $F(1,47) = 7.09, p = .011$; Column 1: $F(1,47) = 13.85, p = .001$; Column 2: $F(1,47) = 17.25, p < .001$; Column 3: $F(1,47) = 18.07, p = .001$]. Moreover, these effects of repetition tended to be larger over more posterior than anterior sites [Repetition × Electrode Site interaction, midline: $F(8,376) = 8.75, p < .001$; Column 1: $F(4,188) = 8.92, p < .001$; Column 2: $F(6,282) = 11.08, p < .001$; Column 3: $F(8,376) = 7.10, p < .001$] (see Figure 5) and over the right than the left hemisphere [Repetition × Hemisphere interaction, Column 2:

$F(1,47) = 5.54, p = .023$; Repetition × Hemisphere × Electrode Site interaction, Column 3: $F(4,188) = 3.11, p = .037$].

We also measured the peak latency of the negativity in this epoch, which had a mean peak latency at 450 msec (see Figure 5). As can be seen in Figure 3B, differences in peak latency in this epoch are not nearly as apparent ($Fs < 2.7$).

Behavioral Data

Participants detected 93% of animal probes in the target position and fewer than 10% in the prime position within a window of 200 to 1200 msec postprobe onset.

DISCUSSION

The task of recognizing and comprehending visually encountered words typically takes less than half a second (Rayner, 1998). However, insights into the mental and neural underpinnings of this task have proven difficult, in part, because few methodologies have the requisite temporal resolution necessary to decompose and examine the elemental processes involved in word recognition. In the current study, we combined the recording of ERPs, a technique with a high temporal resolution, with the short SOA masked repetition priming paradigm that has been used successfully for over a decade by behavioral researchers to study the component processes involved in word recognition (e.g., Kinoshita & Lupker, 2003). We found a series of four electrophysiological effects starting as early as 125 msec postword onset and running through the temporal epoch of the N400 component (550 msec) that were differentially sensitive to manipulations of word process-

ing. The first of these effects took the form of a positivity with a peak at 150 msec, which is almost 100 msec earlier than previous ERP studies of repetition priming. The ERPs at this latency were more positive for target words following masked prime letter strings that shared no letters in common with the target (unrelated targets) than targets words following prime letter strings that were either the same (full repetition targets) or one letter different than their targets (partial repetition targets). The second effect took the form of a negative-going potential that peaked near 250 msec and was largest and earliest in peak latency for targets that shared no letters with their preceding primes, was slightly smaller and later in peak latency for targets that differed by one letter from their primes, and was least negative as well as latest in peak latency for targets that were full repetitions of their primes. The third effect, which we characterize as a positive-going potential with a peak near 325 msec, was most positive-going and latest in peak latency to full repetitions and was less positive and peaked earlier to unrelated and partial repetitions that did not differ from each other. The final effect was a negativity with a peak near 450 msec. This effect, which had many of the characteristics of the classic N400 component, was most negative to unrelated targets, intermediate in amplitude to partial repetitions, and was smallest to full repetitions. The overall timing (125–550 msec) of these effects agrees quite well with previous estimates of the time course of visual word recognition (e.g., Sereno, Rayner, & Posner, 1998), and their sequence coincides with recent suggestions from fMRI studies of visual word processing (e.g., Dehaene et al., 2004; Binder et al., 2002).

Interpreting Event-related Potential Effects in Masked Priming

In the following discussion, we provide a tentative interpretation of the different ERP components observed in this study. At a very general level of analysis, we expect ERPs generated by a target stimulus in the masked prime paradigm to be sensitive to at least two aspects of on-going processing. The first concerns the differential ease with which the target is processed given prior input from the prime. The prime stimulus generates an activation pattern across a given set of representations that are more or less compatible with those generated on presentation of the target word. Level of compatibility will help or hinder target word processing, as documented by the large number of RT studies using masked priming (e.g., Segui & Grainger, 1990; Forster & Davis, 1984). With this category of ERP effects, we expect masked priming to simply exaggerate effects that are already present (although perhaps indiscernible) in unprimed word recognition. In this respect, masked priming can be thought of as a microscope for investigating very-fine-grained processes in visual word recognition.

The second category of ERP effect is hypothesized to be related to the specific testing conditions of masked priming. Given two distinct sources of sequential sensory input, it is possible that the degree of mismatch between the activation patterns generated by these two sources (i.e., prime and target stimuli) is measured in some way during target word processing. This could be achieved by a simple process that looks at the activation pattern generated by the prime stimulus and compares it to that generated by the target for a given level of representation. Such a mismatch evaluation could be involved in determining whether there has been a change in external stimulus (Grainger & Jacobs, 1999; Humphreys et al., 1988).

It is important to note that we consider both types of ERP effect can be useful for inferring the component processes in visual word recognition. We now turn to a closer examination of each of the ERP components identified in our study. These are hypothesized to reflect an orderly hierarchical process that processes the word's component letters, ordered combinations of these letters, whole-word orthographic representations, and finally meaning (Grainger & van Heuven, 2003).[2]

Early Orthographic Processing: P150

The earliest effects of repetition were also the most focal being clearly visible only at a relatively few scalp sites. These relatively small effects (0.5 μV) were present only in the most posterior electrode sites and primarily over the right hemisphere. This early repetition effect took the form of an attenuation of the overlapping N1, and this difference peaked at approximately 150 msec posttarget onset. Consistent with the scheme used to label the N400 (using the direction of the effect on the unrelated trials), we have tentatively referred to this effect as the ''P150.'' One possibility for the functional significance of the P150 is that it reflects processing in an early letter- or form-specific processing system that is sensitive to elemental features of the stimulus. It is important to keep in mind that whatever process this effect reflects, it is one that appears to operate on (or at least is capable of operating on) relatively abstract information. This is because the effect was obtained, although primes and targets were in different cases and were therefore not physically identical in the repeated condition. Given the very early onset of this component, it is possible that it reflects the initial phase of sublexical orthographic processing in visual word recognition where configurations of visual features activate the individual letter representations that compose a word. Grainger and van Heuven (2003) suggested that such processing could be performed by a bank of letter detectors that optimally respond to specific combinations of visual features at a particular location on the horizontal meridian of the retina (for horizontally written languages with alphabetical orthographies). They called

this specialized device for parallel independent letter detection the "alphabetic array."

Dehaene et al. (2002), using fMRI, reported activation in the bilateral occipital cortex that would presumably have a time course similar to the current P150 effect.[3] However, their effect was apparent only when primes and targets were in the same case (i.e., were physically identical). As previously mentioned, the current P150 effect was present even though items in the repeated condition were not physically identical (i.e., primes and targets were in different cases). However, the current study was not designed to examine physical similarity, so it is possible that the P150 would be larger for such items.

Sublexical–Lexical Interface: N250

Another comparatively early (pre-N400) effect of repetition was the occurrence of a negative-going wave that started near 175 msec ended at approximately 300 msec and produced a clear peak near 250 msec. This negativity, which we will tentatively label the N250, was larger and earlier in peak amplitude to targets following primes that did not have any letters in common than to targets that were partial repetitions of their primes in four of five-letter positions. Furthermore, targets that partially overlapped their primes produced significantly larger N250s than targets that were full repetitions of their primes, although in this case, there was no significant difference in peak latency. The N250 had a broad scalp distribution, with the largest effects occurring over more frontal sites.

Because its amplitude and latency seem differentially sensitive to the orthographic overlap of prime and target stimuli presented at short SOAs, we suggest that this ERP component might be directly sensitive to a system that is involved in processing the relative positions of a word's constituent letters as ordered letter combinations are formed (e.g., bigrams, trigrams). These ordered letter combinations are used to generate a sublexical phonological code and access whole-word orthographic representations. At this level of processing, a single-letter mismatch is more damaging than at the level of individual letter processing because the mismatching letter can activate many irrelevant letter clusters and words. It is possible that the N250 reflects the mismatch between representations at this level that were activated by the prime stimulus and those representations receiving activation from the target.[4]

According to this mismatch account, it would be the number of mismatching letters between the prime and target stimuli that controls the amplitude of the N250 in a masked priming experiment—the more mismatching letters, the greater the amplitude. This explanation can also account for the pattern of latency effects, whereby the N250 was significantly earlier for complete mismatches compared with partial mismatches. When all prime and target letters mismatch, there are more opportunities to detect the mismatch than when only a single letter mismatches. On average, this should result in the detections occurring earlier for unrelated targets.

Wang, Cui, Wang, Tian, and Zhang (2004) have reported a similar type of ERP effect on a component they refer to as N250. Their studies have shown that the N250 is sensitive to perceptual mismatches between prime and target stimuli of a variety of different types (e.g., shape, color, orientation) that they have interpreted as support for their statement that "This component represents the activity of the brain for detecting cognitive information mismatches or conflicts" (Wang et al., 2004, p. 22). The emphasis on a more general process for conflict or mismatch processing, one that is "cognitive" in origin would not seem to be consistent with the current N250 effects. In the typical N250 paradigm, both the prime and target stimuli are clearly presented and separated by several hundred milliseconds. Moreover, participants are directed to attend to differences between the prime and target stimuli. These manipulations are consistent with the authors' claims that the N250 reflects a later "cognitive" effect of conflict or mismatch. However, if the N250 effect reported here is related to the N250 of Wang et al., it suggests that this component is unlikely to be as "cognitive" as Wang et al. have characterized. This is because our participants neither made explicit prime-target comparisons nor had enough time between the prime and target events to make clear mismatch judgments. Finally, we are not aware of any previous immediate repetition priming experiments that have shown clear N250 effects with longer SOAs and unmasked primes (e.g., Experiment 2 of Misra & Holcomb, 2003). Because the conditions in these studies more closely approximate the typical N250 paradigm, it is difficult to explain why N250s would not be obtained in these cases but would be in the current masked priming experiment.

Lexical Form Processing: P325

Immediately after the N250 and overlapping the typical onset phase of the N400 was a third repetition-sensitive ERP effect that took the form of a small positive-going wave that started around 300 msec and peaked between 320 and 350 msec. We tentatively refer to this component as the P325 based on the latency of the positivity seen in the difference waves in Figure 5. Although the N250 had a somewhat central–anterior distribution, the P325 had a more right hemisphere to posterior left distribution (see Figure 5).

Unlike the earlier N250, the P325 did not differentiate the unrelated and partial repetition conditions, but did differentiate partial repetitions from full repetitions. In behavioral lexical decision studies using masked priming, partial repetition primes (*teble–table*) also have

not systematically facilitated target word recognition relative to unrelated primes (e.g., van Heuven, Dijkstra, Grainger, & Schriefers, 2001; Forster, Davis, Schoknecht, & Carter, 1987). Because these behavioral measures are arguably most sensitive to the process of lexical selection, the similarity in the pattern of priming in the behavioral studies and the current P325 suggests that this ERP effect might be differentially sensitive to representations within the lexical level of processing. In particular, it might be sensitive to the outcome of the mismatch process described in the preceding section and its consequences for word-level processing. In both the partial and unrelated prime conditions, a mismatch is detected, and target word processing could be affected by this all-or-none process. On detection of a mismatch, more care would be taken in verifying that activated lexical representations do indeed fit with lower level orthographic activation as target word processing continues. Such a verification process could be part of the normal processes involved in word recognition occurring whenever a mismatch is detected between a selected lexical representation and lower level orthographic representations (e.g., Grossberg, 1987).

The precise timing of the P325 suggests that it might correspond to a point when the lexical processor attempts to settle on a single whole-word representation as a unique interpretation of the input (i.e., lexical selection). At this point in the processing of a printed word, a given whole-word orthographic representation is selected from a number of possible candidates that are compatible with incoming information. In the case of the masked priming paradigm, this would most likely involve primarily bottom-up input, but under normal unmasked reading, it would presumably involve top-down influences as well. This selection process could use mismatching orthographic information to reject different candidate words via a verification type mechanism (as discussed above), or such mismatching representations could be suppressed via lateral inhibition across whole-word representations (McClelland & Rumelhart, 1981). Again, in a masking paradigm, lateral inhibitory influences would presumably be minimal because of the rapid onset of the backward mask (Lamme et al., 2002). Regardless, either type of mechanism leads to enhanced activation of the selected representation and relative suppression of competing representations. At this level of processing, bottom-up sublexical orthographic facilitation generated by primes sharing letters with targets is counteracted by an inhibitory influence of orthographically related primes during the selection process. This explains why the partial overlap primes did not differ from the unrelated primes at this point in processing. Future experimentation could examine whether response times in behavioral tasks (hypothesized to reflect word selection/identification times) correlate with P325 amplitude or latency.

Form–Meaning Interface: N400

Immediately following the P325 was a negative-going potential that peaked near 450 msec. Given its latency, polarity, and scalp distribution (central–parietal), we believe this to be a member of the N400 family. Unlike the P325, the N400 was significantly more negative-going for unrelated targets than for partial repetitions that in turn were significantly more negative-going than full repetitions. Both of these N400 effects were widely distributed across the scalp, although they tended to be largest at more posterior sites and were somewhat larger over the right than the left hemisphere.

One possibility for the sensitivity of the N400 to repetition priming and even partial repetition priming is that it might reflect interactivity at the interface between word representations and meaning (form-meaning interface), such that initial activity between these levels, set in action by the masked prime, makes subsequent interactions of representations activated by the target relatively more or less difficult. Such an explanation of N400 priming effects differs from the mechanism that presumably underlies N400 semantic priming effects where interactions between word meanings rather than between form and meaning mediate priming (in semantic priming, there is no form overlap between the prime and target). Consistent with this interpretation, we recently dissociated the effects of repetition and semantic priming with masked primes (Holcomb et al., 2005). Although the presence of N400 repetition priming effects were not correlated with prime visibility, N400 semantic priming effects were dependent on participant's ability to process primes for meaning.

Perhaps, a bit surprising is the finding that partial repetitions also resulted in the attenuation of the N400. In this case, it is difficult to see how a masked stimulus that does not have a lexical, and therefore semantic, representation (e.g., *teble*) could serve as a context into which the meaning of the target word could be integrated. One possible explanation that follows from our account of earlier processing is that these partially overlapping primes actually do (partially) activate their real word neighbors (i.e., *teble* somewhat activates the meaning for *table*) that then serve as the context for subsequent target word integration (Holcomb et al., 2002). Activation at the level of semantic representations would presumably be less sensitive to the negative effects of selection operating at the level of form representations, thus allowing partially overlapping primes to facilitate processing at this level.

One problem with this explanation is that the intermediate effects of partial primes present for the N250 and N400 were not apparent for the P325. Put another way, if the P325 reflects lexical selection, why would prime items rejected by the selection mechanism (e.g., *teble*) go on to activate semantic representations of their

neighbors (e.g., *table*) as suggested by the existence of a small N400 effect to these items? One possible answer to this apparent conundrum is that recurrent processing may be differentially blocked/impeded across the various subprocesses of word recognition in the masked priming paradigm depending on such factors as prime duration, prime-target SOA, and the nature of the masking stimulus used. Accordingly, the pattern obtained in the current study may be the result of the masking parameters allowing just enough recurrent processing of the prime so that the lexical system was eventually able to suppress incorrect items such as *teble*, but blocked enough feedback processing so that partial primes nevertheless were able to partially activate the semantic representations of their neighbors (e.g., *table*). In other words, what gets blocked at the lexical level nevertheless ends up activating some semantic-level processing. If this assessment is correct, then giving more time between the prime and target or a longer exposure to the prime should result in an increase in the N400 to targets following partial primes such as *teble*. In this case, we would predict an attenuation of both the N400 and P325 components to targets following these primes.

Conclusion

Clearly, much work remains to be done to investigate the above proposals concerning the functional significance of ERP masked priming effects. One particularly important issue is whether any or all of the effects before the N400 are language- or modality-specific. It should be possible to use spoken words and pictures in cross-modal (visual–auditory) and cross-domain (word–picture) designs, as well as pictures in within modality designs to determine this. For example, evidence of P150 and/or N250 masked priming effects for pictures would argue that such effects reflect basic mismatch detection processes, whereas an absence of such effects or a different pattern of effects would suggest that these components reflect visual word-based processes. Likewise, the presence or absence of P150 and/or N250 effects for cross-modal (visual primes and spoken word targets) masked priming would help further constrain the processing locus of such effects. Also, additional studies using more fined-grained manipulations of variables thought to effect processing at the letter, sublexical orthographic, and lexical levels will also be needed to test the specificity of each component.

On a final note, the results of this experiment support the hypothesis that the earliest effects of priming seen here were not apparent in previous ERP masked repetition priming experiments because of their use of a relatively long prime-target SOAs (Holcomb et al., 2005; Misra & Holcomb, 2003; Schnyer et al., 1997). The most likely explanation for why longer SOAs attenuated the early effects seen in the current experiment is that sublexical and lexical effects of repetition dissipate rapidly over this time period, perhaps in part due to the replacement of the initial representations of the prime by the masking events (Rieger et al., 2005; Ferrand, 1996). On the other hand, robust N400 effects were also found at short SOAs and previously have been reported for longer intervals as well (e.g., Misra & Holcomb, 2003). Therefore, the N400 does not seem to be highly sensitive to the duration of the prime-target interval. This pattern suggests two conclusions: First, context effects set up by the prime in the mask priming paradigm accrue very rapidly; second, unlike the earlier lexical and sublexical effects, the N400 is somewhat impervious to rapid decay. Such a pattern makes sense for a system such as that involved in reading where the ultimate goal is extracting meaning from a text, but which also must rapidly and efficiently activate and then discard a large number of potentially confusing tokens.

Taken together, the above findings suggest that combining the ERP technique with the short SOA masked priming paradigm offers considerable promise as a methodology for helping to further elucidate the temporal dynamics of visual word recognition. One obvious next step is to couple ERP and fMRI experiments using the masked priming paradigm and attempt to merge the resulting data sets in ways that build on the complimentary strengths of both techniques (e.g., as in the work of Dale et al., 2000). The masked priming paradigm may be a particularly good choice for efforts in this regard because masking tends to limit the range of possible effects by mitigating the influence of higher cognitive processing, thus resulting in a smaller and more manageable set of effects to be reconciled.

Notes

1. The ERP data were also analyzed using a two-factor ANOVA that included two levels of prime lexicality (word vs. pseudoword) and two levels of repetition (repeated vs. unrelated). The results of this scheme produced the same basic pattern of effects reported here using the single three-level repetition factor. The advantage of the latter approach is that it allows a more straightforward and direct comparison of the partial and full repetition effects. In the 2×2 analysis approach, this only comes out via the interaction of prime lexicality with repetition.

2. Note that because we did not specifically manipulate prime-target phonological overlap independently of orthographic overlap, we make no claims about the impact of phonological processes during visual word recognition. This is the subject of ongoing research in our laboratory.

3. An alternative way of expressing this mismatch account of the N250 is in terms of resonant activity between sublexical

orthographic representations and whole-word orthographic representations. This resonance, necessary for stable word recognition, would be affected by mismatching information provided by the prime stimulus.

4. Extreme caution must be used in relating ERP effects with specific brain regions because of the low spatial resolution of ERPs and the inherent intractability of the problem of localizing neuronal sources from scalp EEG data (Nunez, 1990). Therefore, we have only made qualitative suggestions concerning the similarly of the effects reported here and in previous functional imaging studies.

REFERENCES

Binder, J. R., McKiernan, K. A., Parsons, M. E., Westbury, C. F., Possing, E. T., Kaufman, J. N., & Buchanan, L. (2002). Neural correlates of lexical access during visual word recognition. *Journal of Cognitive Neuroscience, 15,* 372–393.

Dale, A. M., Liu, A. K., Fischl, B. R., Buckner, R. L., Belliveau, J. W., Lewine, J. D., & Halgren, E. (2000). Dynamic statistical parametric mapping: Combining fMRI and MEG for high resolution imaging of cortical activity. *Neuron, 26,* 55–67.

Dehaene, S., Jobert, A., Naccache, L., Ciuciu, P., Poline, J., Le Bihan, D., & Cohen, L. (2004). Letter binding and invariant recognition of masked words behavioral and neuroimaging evidence. *Psychological Science, 5,* 307–313.

Dehaene, S., Le Clec'H, G., Poline, J. B., Le Bihan, D., & Cohen, L. (2002). The visual word form area: A prelexical representation of visual words in the fusiform gyrus. *NeuroReport, 13,* 321–325.

Ferrand, L. (1996). The masked repetition priming effect dissipates when increasing the interstimulus interval: Evidence from word naming. *Acta Psychologica, 91,* 15–25.

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

Forster, K. I., & Davis, C. (1984). Repetition priming and frequency attenuation in lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10,* 680–698.

Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology, 39,* 211–251.

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

Grainger, J., & Jacobs, A. M. (1993). Masked partial-word priming in visual word recognition: Effects of positional letter frequency. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 951–964.

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review, 103,* 518–565.

Grainger, J., & Jacobs, A. M. (1999). Temporal integration of information in orthographic priming. *Visual Cognition, 6,* 461–492.

Grainger, J., & van Heuven, W. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *The mental lexicon* (pp. 2–23). New York: Nova Science.

Grossberg, S. (1987). Competitive learning: From interactive activation to adaptive resonance. *Cognitive Science, 11,* 23–63.

Holcomb, P. J. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology, 30,* 47–61.

Holcomb, P. J., O'Rourke, T., & Grainger, J. (2002). An event-related brain potential study of orthographic similarity. *Journal of Cognitive Neuroscience, 14,* 938–950.

Holcomb, P. J., Reder, L., Misra, M., & Grainger, J. (2005). Masked priming: An event-related brain potential study of repetition and semantic effects. *Brain Research, Cognitive Brain Research, 24,* 155–172.

Humphreys, G. W., Besner, D., & Quinlan, P. T. (1988). Event perception and the word repetition effect. *Journal of Experimental Psychology: General, 117,* 51–67.

Kinoshita, S., & Lupker, S. J. (2003). *Masked priming: The state of the art.* New York: Psychology Press.

Lamme, V. A. F., & Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neurosciences, 23,* 571–579.

Lamme, V. A. F., Supèr, H., & Spekreijse, H. (1998). Feedforward, horizontal, and feedback processing in the visual cortex. *Current Opinion in Neurobiology, 8,* 529–535.

Lamme, V. A. F., Zipser, K., & Spekreijse, H. (2002). Masking interrupts figure–ground signals in V1. *Journal of Cognitive Neuroscience, 14,* 1044–1053.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review, 88,* 375–407.

Misra, M., & Holcomb, P. J. (2003). The electrophysiology of word-level masked repetition priming. *Psychophysiology, 40,* 115–130.

Neville, H. J., Mills, D. L., & Lawson, D. S. (1992). Fractionating language: Different neural subsystems with different sensitive periods. *Cerebral Cortex, 2,* 244–258.

Nunez, P. L. (1990). Localization of brain activity with electroencephalography. *Advances in Neurology, 54,* 39–65.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124,* 372–422.

Rieger, J. W., Braum, C., Bulthoff, H. H., & Gegenfurtner, K. R. (2005). The dynamics of visual pattern masking in natural scene processing: A magnetoencephalography study. *Journal of Vision, 5,* 275–286.

Schnyer, D. M., Allen, J. B., & Forster, K. I. (1997). Event-related brain potential examination of implicit memory processes: Masked and unmasked repetition priming. *Neuropsychology, 11,* 243–260.

Segui, J., & Grainger, J. (1990). Priming word recognition with orthographic neighbors: Effects of relative prime-target frequency. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 65–76.

Sereno, S., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: Evidence from eye movement and event-related potentials. *NeuroReport, 9,* 2195–2200.

Van Heuven, W. J. B., Dijkstra, A. F. J., Grainger, J., & Schriefers, H. J. (2001). Shared neighborhood effects in masked orthographic priming. *Psychonomic Bulletin and Review, 8,* 96–101.

Wang, Y., Cui, L., Wang, H., Tian, S., & Zhang, X. (2004). The sequential processing of visual feature conjunction mismatches in the human brain. *Psychophysiology, 41,* 21–29.