



# The effects of prime visibility on ERP measures of masked priming

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## Abstract

In two experiments, the effect of the duration (40, 80 and 120 ms) of pattern masked prime words on subsequent target word processing was measured using event-related potentials. In Experiment 1, target words were either repetitions of the prior masked prime (car-CAR) or were another unrelated word (job-CAR). In Experiment 2, primes and targets were either semantically related (cap-HAT) or were unrelated (car-HAT). Unrelated target words produced larger N400s than did repeated (Exp 1) or semantically related (Exp 2) words across the different prime durations and these N400 priming effects tended to be smaller overall for semantic than repetition priming. Moreover, there was only a modest decline in the size of N400 repetition priming at the shortest prime durations, and there was no relationship between this N400 effect and a measure of prime categorization performance. However, the size of semantic priming at the shortest durations was relatively smaller than at longer durations and was correlated with prime categorization performance. The findings are discussed in the context of the functional significance of the N400 as well as a model that argues for different mechanisms during masked repetition and semantic priming.

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## 1. Introduction

Priming has been one of the key tools used to study a variety of word and memory processes. In priming experiments, subjects are usually presented with pairs of items displaced in time. The first item, or “prime”, serves to establish some type of context and the second item, or “target”, is usually manipulated so that it either fits or does not fit into the prime context. Numerous studies have shown that processing of the target can be greatly influenced by the nature of the relationship between the prime and target stimuli. For example, when the prime and target are semantically related words (e.g., knife-FORK) or the same word (e.g., desk-DESK) versus when they are semantically unrelated words (e.g., knife-DESK), subjects are typically

faster and more accurate at making a variety of judgments about the targets [22].

Over the past 20 years, a somewhat different form of priming has been widely investigated, namely *masked priming* (e.g., [4,9,17,18]). In these studies, the prime stimulus is presented very briefly and is then immediately obscured by either a pattern mask (e.g., a series of letters or symbols occupying the same location on the screen as the prime) or the target word itself. When this procedure is used, participants are usually unable to report having seen the prime word, let alone identify it. The typical finding is that clearly visible (i.e., unmasked) target words produce faster reaction times (RTs) and result in fewer errors when they follow primes (both repetition and semantic) that are masked below levels of awareness, although such effects are typically somewhat smaller and shorter-lived than comparable effects measured to targets following supraliminal primes [4,9,17]. The original functional explanation

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proposed by Marcel [17,18] still seems to be the most widely accepted interpretation of the underlying processes that account for this phenomenon; masked priming results from the same set of processes that produce supraliminal priming, with the exception of those that require conscious awareness of the prime (but see [12]). In other words, masked priming results from what are thought to be the automatic components of word recognition processes. Recent work using functional imaging supports this type of interpretation as most if not all of the brain areas that respond to supraliminal words are also active during the processing of masked words, the big difference being that masked words activate these areas to a lesser extent [7].

## 2. Event-related potentials (ERPs)

Many studies have shown that both repetition and semantic priming produce characteristic differences in ERPs. Repeated/related words produce attenuated N400s compared to non-repeated/unrelated words [2,5,10,11,24,26–30,34,36]. Such N400 effects are believed by many to be sensitive to the lexical and/or semantic properties of the stimulus and its context [25]. According to this view, words that are easily integrated with their contextual framework produce an attenuated N400, while those that are impossible or difficult to integrate with the surrounding context generate larger N400s [11,33]. The N400 repetition and semantic priming effects, then, are believed to reflect the greater ease of integrating the target word after presentation of its prime.

There is some controversy, however, as to whether N400 effects might also require conscious processing. Holcomb [10] reported that the N400 effect in a semantic priming task was significantly larger when participants were encouraged to use conscious strategic resources to process prime/target relationships than when instructions and the proportion of related items encouraged subjects to ignore the relationship and process it automatically (see also [5,17,18]). More recently, masked priming paradigms have also been used to evaluate automatic effects on the N400. Recall that behavioral priming studies have established that masked primes speed reaction times and increase accuracy in both semantic and repetition priming experiments, and this pattern has typically been interpreted to indicate that word recognition processes up to and including lexical access are largely automatic [9,17,18]. Brown and Hagoort [3] used this logic to determine if there was an unconscious/automatic, and therefore purely lexical, contribution to the N400. Using both masked and unmasked semantic primes, they found evidence for modulation of target N400s only when primes were not masked. They concluded that the N400 is sensitive to higher order (conscious) lexical integration and not to automatic lexical access. As will be described below, subsequent studies have challenged the view put forth by Brown and Hagoort [3]. Specifically, several authors have now found evidence for masked

priming effects on the N400. The current studies sought to further investigate these effects for both repetition and semantic priming.

## 3. Experiment 1—masked repetition priming

Two recent studies have tried to determine if ERPs are sensitive to masked repetition priming. Schnyer et al. [31] reported a significant N400 masked priming effect in both a recognition memory task and a lexical decision task (LDT) when prime words were flashed for 48 ms and then repeated as visible targets after a masking stimulus. Misra and Holcomb [21] followed up on the Schnyer et al. study in a masked repetition priming paradigm, which allowed for comparisons of masked and unmasked repetition priming within a single test phase and minimized motor artifact during critical trials by using a semantic categorization task. Furthermore, the duration of masked primes was titrated on a subject-by-subject basis, and then prime durations that produced chance performance in the titration procedure were used in the ERP experiment. Priming thresholds were titrated because of the possibility that, at a fixed 48 ms prime duration, a few participants in the Schnyer et al. study might have recognized some or all of the masked primes and their data might have differentially contributed to the observed N400 effect. Even using these very strict criteria for setting prime durations, Misra and Holcomb found that the N400 to target words was significantly attenuated when targets were preceded by the same as opposed to different masked words. This masked priming effect was observed for both immediate repetitions and, to a lesser extent, repetitions over several intervening items. However, the size of this masked N400 repetition effect was significantly smaller than that for unmasked repetitions. This was true in comparisons of delayed masked and unmasked priming effects within the same experiment. It was also true in comparisons of immediate priming effects in a second experiment where prime-target lags were comparable to those in the masking task, but where the prime words were not effectively masked (that is, participants were able to identify them). These results suggest that, while the N400 is sensitive to the contextual framework established by an unidentifiable masked prime, in addition it is also sensitive to additional processes that operate when the prime is visible and identifiable. Misra and Holcomb also reported that, while masked primes resulted in a modulation of only the N400, when primes were visible (unmasked), there was also a later positivity present in the target ERPs to repeated targets. A number of studies using visible primes have reported a similar pattern of late positivities to repeated words and it is generally believed that they reflect the influence of episodic memory (e.g., explicitly remembering that the target was presented earlier as a prime [28–30]). This conclusion is supported by Misra and Holcomb's results since participants were unaware of the primes in the

masked condition and therefore should not have had an intact episodic memory trace of these primes.

One limitation with the Misra and Holcomb [21] study was that their unmasked (identifiable) and masked (unidentifiable) priming data for immediate repetitions (i.e., the trials with the largest effects) were collected in different experiments in different participants. This may have led participants to adopt different strategies for dealing with primes and targets in the two experiments. For example, the larger priming effect in the unmasked experiment may have been due to participants paying more attention to the prime epoch because they had learned that the primes were sometimes predictive of the target while in the masked experiment participants ignored the prime epoch because they did not know words were being presented here. As mentioned above, at least one previous study has demonstrated that attention to the prime epoch can augment the N400 to subsequent target words [10].

Experiment 1 sought to determine if there are different target ERP effects associated with identifiable and unidentifiable primes in immediate masked repetition priming under conditions where differential attention to the prime epoch was not possible. Participants were presented with pairs of items consisting of a brief pattern masked *prime* word and a subsequent clearly visible *target* word. Masked primes could be followed by a clearly visible target word that was either a repetition of the prime word (*repeated targets*) or another unrelated word (*unrepeated targets*). Primes were sandwiched between two pattern masks (forward and backward) and were presented at three different stimulus durations: 40 ms, 80 ms and 120 ms randomly intermixed in a single recording session. These values were selected based on pilot testing which determined them to be of sufficient duration to be rarely identifiable (40 ms), frequently identifiable (80 ms) and almost always identifiable (120 ms), despite the presence of the pattern masks. Participants performed a semantic categorization task in which they were instructed to monitor all stimuli (primes and targets) for occasional exemplars from a designated category of probe words (animal names) and to press a button when such items were detected. No response was required to other (non-animal) stimuli. Use of this task insured that participants attempted to process both the primes and targets at a deep semantic level and that participants focused equal attentional resources on all prime epoch stimuli. In addition, this task provided a measure of the effectiveness of the masking procedure by allowing for comparisons of prime probe detection performance across the three prime durations.

The following predictions were made. First, following Schnyer et al. [31] and Misra and Holcomb [21], it was predicted that, even under conditions of effective prime masking (40 ms prime durations), there would be an attenuation of the N400 to target words immediately preceded by identical masked primes as compared to target words preceded by an unrelated masked prime word. It was hypothesized that this would occur because the N400 is

sensitive to form and semantic processes that are, at least to some degree, automatic or implicit in nature and therefore not entirely reliant on conscious explicit recognition. Second, it was predicted that, as in Misra and Holcomb, the size of the masked repetition effect would vary as a function of prime visibility with the N400 effect getting larger as the duration (and hence visibility) of the prime increased. This should occur if the N400 reflects the influence of both automatic as well as conscious processes and these processes are additive in their effect on the N400 [10]. However, an alternative possibility is that, because prime attention is equated in Experiment 1, there will be no difference in the amplitude of the N400 repetition effect as a function of prime duration. A pattern of effects such as this might indicate that the N400 reflects a single automatic process that is sensitive to the degree of prime epoch attention.

## 4. Methods

### 4.1. Participants

Twenty-two right-handed, native English speaking Tufts University students (10 male, mean age = 19.75) received \$20 compensation for participation in this experiment. We excluded four of these participants due to excessive artifact (three) and experimenter error (one).

### 4.2. Stimuli and procedure

All words used in the current experiment were 4 to 5 letters long. The *critical* stimuli for this experiment were formed from 450 nouns, with frequency less than 30 per million [16]. An additional set of non-critical stimulus pairs was formed by combining 90 different animal names (frequency <30/million) with 90 unrelated non-animal words (nouns; frequency <50/million). For both the critical and non-critical items, the first member of each pair was referred to as the *prime* and the second member as the *target*. Stimulus lists consisted of 360 trials each containing a prime-target pair of words. There were two critical stimulus conditions in each list: repetitions, which contained 135 pairs of repeated words (e.g., chair-*CHAIR*) and non-repetitions, which contained 135 pairs (e.g., table-*UNCLE*) of unrepeated/unrelated words (i.e., 270 unique words). The additional 45 critical non-animal words were used as foils in a subsequent recognition memory test. For the 90 non-critical pairs, 45 contained animal names in the prime position and an unrelated word in the target position, while the other 45 trials contained an unrelated word in the prime position and an animal name in the target position. 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 (response hand counterbalanced) whenever they detected an animal name in either the prime or target position (cf. Misra and Holcomb [21]). Participants were told

to read all other words passively (that is, critical stimuli did not require an overt response).

In addition to the two levels of repetition (repeated/unrepeated), there was another factor of prime duration (40 ms, 80 ms and 120 ms), which resulted in six types of critical trials (45 pairs/condition—see Table 1). These levels of repetition were also applied to the animal trials, such that there were also six types of filler/response trials (15 pairs/condition). Ten different lists were formed so that each critical item appeared once per list, but across lists, each critical item appeared in each of the critical trial positions: (1) 40 ms repeated prime and target, (2) 80 ms repeated prime and target, (3) 120 ms repeated prime and target, (4) 40 ms unrepeated prime, (5) 40 ms unrepeated target, (6) 80 ms unrepeated prime, (7) 80 ms unrepeated target, (8) 120 ms unrepeated prime, (9) 120 ms unrepeated target and (10) recognition test foils.

All stimuli were displayed in the center of a 17 in. monitor as white letters on a black background in the Times Roman font. The schematic of a trial is displayed in Fig. 1. As can be seen, each trial began with the termination of a fixation cross and 400 ms later 1 of 50 unique five letter consonant strings (randomly generated such that there were no immediate letter repetitions in any string) was presented in upper case letters (the forward mask—e.g., QDLMS) for a duration of 200 ms. The mask was immediately replaced at the same location on the screen by a four to five letter lower case prime word (the five letter mask was of sufficient width to extend several pixels past the end of even the longest primes). Primes were presented for either 40, 80 or 120 ms and were immediately replaced by the same five letter upper-case consonant string (backward mask). The backward mask was presented for 200 ms and was followed by a black screen of 180 to 260 ms in duration (40 ms primes = 260 ms blank, 80 ms primes = 220 ms blank, 120 ms primes = 180 ms blank), with the variable post-mask blank screen designed to keep the prime-target SOA constant at 500 ms. Target words were presented for 300 ms in upper case letters immediately following the blank and were followed by a 900 ms black screen, which was, in turn, replaced by a 1200 ms trial

ending fixation cross. The next trial began 400 ms after the offset of the cross. Subjects were asked to blink only when the cross was on the screen to minimize eye blink artifact during the recorded trials.

#### 4.3. EEG recording procedure

Participants were seated in a comfortable chair in sound attenuated darkened room. An electro-cap with tin electrodes was used to record continuous EEG from 29 sites on the scalp including sites over left and right fronto-polar (FP1/FP2), frontal (F3/F4, F7/F8), frontal-central (FC1/FC2, FC5/FC6), central (C3/C4), temporal (T5/T6, T3/T4), central-parietal (CP1/CP2, CP5/CP6), parietal (P3/P4) and occipital (O1/O2) areas and five midline sites over the frontal pole (FPz), frontal (Fz), central (Cz), parietal (Pz) and occipital (Oz) areas (see Fig. 2). In addition, four electrodes were attached to the face and neck area: one below the left eye (to monitor for vertical eye movement/blinks), one to the right or the right eye (to monitor for horizontal eye movements), one over the left mastoid (reference) and one over the right mastoid (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 bandpass of 0.01 and 40 Hz and the EEG was continuously sampled at a rate of 200 Hz.

#### 4.4. Data and analysis

Separate waveforms were calculated by averaging compound ERPs to prime and target words based on the three prime durations and the two target repetition conditions. Only trials without muscle artifact or eye movement/blink activity were included in the averaging process. Mean target amplitudes for the same three latency windows used by Misra and Holcomb [21] were used to quantify the target ERPs in this experiment: 150–300 ms post-target onset, 300–500 ms post-target onset and 500–750 ms post-target onset.

Separate analyses of variance (ANOVAs) were performed using the within-subject factors of prime duration

Table 1  
Experiment 1 trial types

Types of trials	Description	Prime duration	Mask	Prime	Mask	Target
1	Repeated	Short (40 ms)	CRBLT	Posy	CRBLT	POSY
2	Repeated	Medium (80 ms)	RTYQM	Pouch	RTYQM	POUCH
3	Repeated	Long (120 ms)	PLRTB	Twin	PLRTB	TWIN
4	Unrepeated	Short (40 ms)	QSCMJ	Shank	QSCMJ	TONG
5	Unrepeated	Medium (80 ms)	SDPRN	Trunk	SDPRN	GAUZE
6	Unrepeated	Long (120 ms)	MBVTP	Agate	MBVTP	DECK
7	Animal prime	Short (40 ms)	ZGHLN	Moose	ZGHLN	SACK
8	Animal prime	Medium (80 ms)	KJGRW	Flea	KJGRW	CLOUD
9	Animal prime	Long (120 ms)	WQPLM	Tiger	WQPLM	PROP
10	Animal target	Short (40 ms)	FDPRQ	Cork	FDPRQ	LEECH
11	Animal target	Medium (80 ms)	VBMPF	Movie	VBMPF	HIPPO
12	Animal target	Long (120 ms)	FGPHR	Liter	FGPHR	PANDA

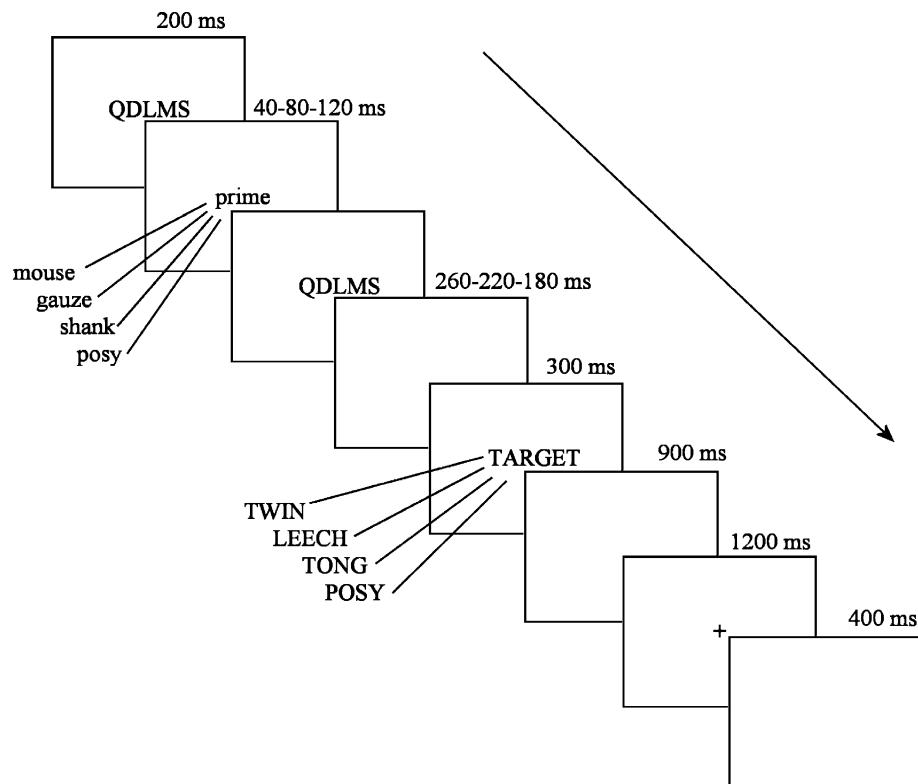


Fig. 1. Schematic of a typical trial in Experiment 1.

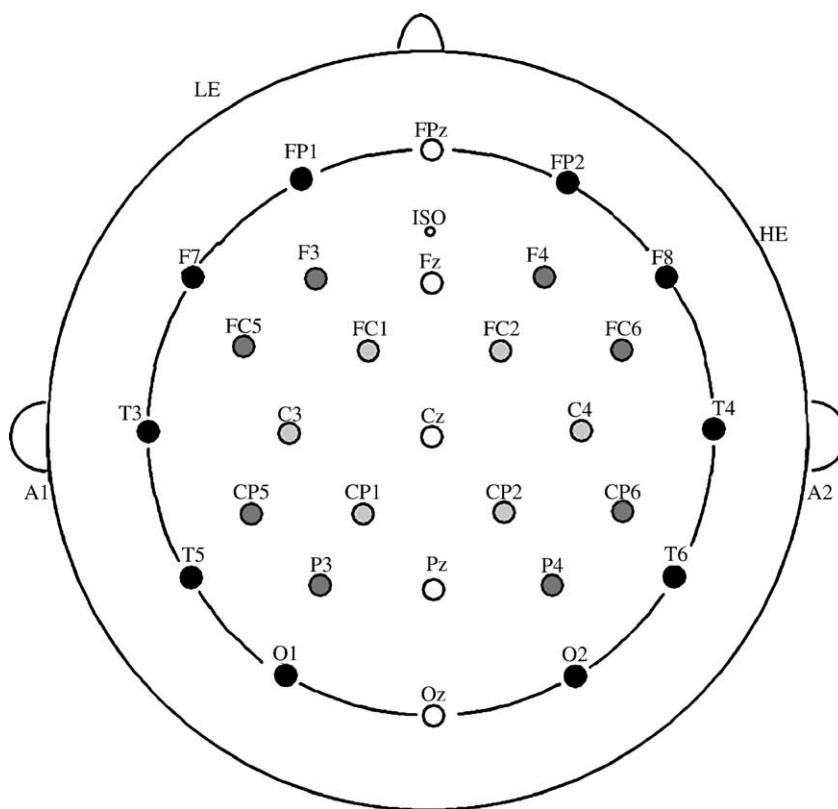


Fig. 2. The electrode montage used in Experiments 1 and 2. The gray scale for the site locations denotes the columnar approach to ANOVA: open circles = midline, light gray = COL1, medium gray = COL2, and black = COL3 (see the text for a more complete explanation of analyses).

(short, medium and long) and repetition (repeated, unrepeated) for each of four sub-montages of electrode site columns: midline (FPz, Fz, Cz, Pz and Oz), COL1 (FC1, C3, CP1, FC2, C4 and CP2), COL2 (F3, FC5, CP5, P3, F4, FC6, CP6 and P4) and COL3 (FP1, F7, T3, T5, O1, FP2, F8, T4, T6 and O2—see Fig. 2 for columns). COL1, COL2 and COL3 also included a factor of hemisphere (left vs. right). We use the columnar approach to analyzing the spatial component of the ERP data because: (a) they allow a complete statistical description of the data set (including a single “site” factor or collapsing across sites can miss subtle distribution effects); and (b) they provide both an anterior/posterior as well as left/right comparison of effects which in numerous previous language studies have proven important in explicating effects [35]. Although this approach does increase the number of comparisons, this is offset by both a more complete description of the data and by a cautious interpretation of analyses where only a single column produces a significant effect.

## 5. Results

### 5.1. Behavioral data

Participants detected an average of 87% of animal probes in the target position within a window of 200 to 1200 ms post-probe onset. In the prime position, participants detected significantly different numbers of animal probes across the three prime durations ( $F(2,32) = 106.09, P < 0.001$ —see Table 2) which translated into a significant difference in the d-prime values ( $F(2,32) = 59.10, P < 0.001$ ; see Table 2). The correlation between target probe hits and 40 ms prime probe hits was not significant ( $r = 0.03$ ), suggesting that the tendency to detect probes in the prime position at short prime durations was not predictive of performance in the overall task of semantic categorization.

To help determine if prime visibility accounted for any of the ERP results (see below), participants were subdivided into two groups based on a median split of their d-prime scores in the 40 ms prime duration condition. D-prime was calculated from the proportion of hits on trials with animal names in the prime position and false alarms on non-animal prime trials. The mean of the low group's d-prime at 40 ms was 0.55 and did not significantly differ from 0 ( $P > 0.07$ ). The mean of the high group's d-prime at 40 ms was 2.1 which did significantly differ from 0 ( $t = 9.2, P < 0.001$ ).

Table 2  
Prime detectability measures

Prime duration	Probability of a hit	Probability of a false alarm	d-prime
40 ms prime	0.18	0.02	1.3
80 ms prime	0.58	0.03	2.4
120 ms prime	0.78	0.02	3.5

### 5.2. Event-related potentials

Plotted in Figs. 3–5 are the ERPs (prime and target) contrasting the conditions with repeated and unrepeated targets at each of the three prime durations. Plotted in Fig. 6 are target ERPs at Cz illustrating the repetition effect for all three prime durations.

As can be seen in these figures, the ERPs in this experiment produced a set of positive and negative deflections. It is important to keep in mind that the early deflections (P1, N1 and P2) to both the prime and target words are an amalgamation of overlapping components produced by the rapid succession of mask-prime-mask-target stimuli. Most important is that through the prime interval (−500 to 0 ms) and the first part of the target interval (0 to approximately 300 ms) the waveforms are remarkably similar for the repeated and unrepeated targets across all three prime durations (Figs. 3–5). For the target interval, these included, most notably, a large central–anterior positivity which peaked at about 200 ms (P2). An earlier negativity (N1) which has been reported in numerous previous word-pair studies [11] was less well defined at most sites and tended, where visible, to be of rather low amplitude at all but the occipital sites where it was the largest of the early components. Across the scalp (with the possible exception of the occipital sites), the P2 wave was followed by a slow negative-going component between 250 and 500 ms (N400). This intermediate latency negative wave appeared to be riding on top of a more prolonged late positivity which had a central–anterior distribution and which persisted during the target interval at most sites until the end of the recording epoch (1200 ms post-target onset).

### 5.3. 150–300 ms target epoch

As can be seen in Figs. 3–5, the effects of repetition began towards the very end of this early target epoch (around 280–300 ms). However, there were no significant effects of repetition or prime duration and no interaction between these variables in any of the columnar analyses of this epoch. Moreover, there were no significant differences between the high and low d-prime groups or interactions between group and any of the within-subjects variables.

### 5.4. 300–500 ms target epoch

As can be seen in Figs. 2–5, there were clear effects of repetition and prime duration across the scalp in this epoch (main effect of repetition, midline:  $F(1,16) = 40.91, P < 0.001$ ; COL1:  $F(1,16) = 46.62, P < 0.001$ ; COL2:  $F(1,16) = 44.10, P < 0.001$ ; and COL3:  $F(1,16) = 36.66, P < 0.001$ ) with repeated target ERPs producing a smaller negativity (N400) than unrepeated targets. There was also a main effect of prime duration (midline:  $F(2,32) = 9.19, P = 0.001$ ; COL1:  $F(2,32) = 8.96, P = 0.001$ ; COL2:  $F(2,32) = 8.99, P = 0.002$ ;

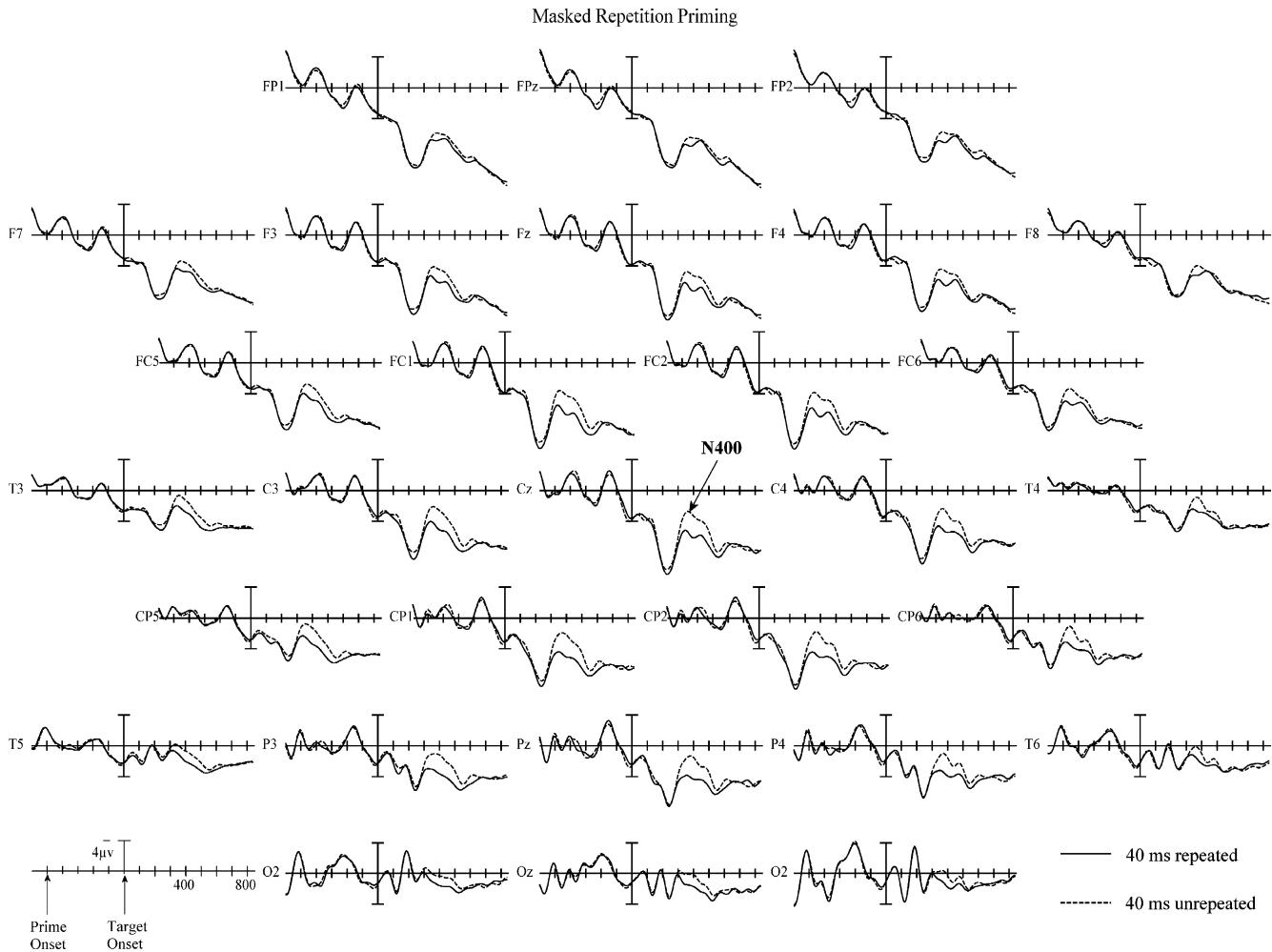


Fig. 3. Compound ERPs time locked to prime onset in the repeated and unrepeated conditions when primes were of 40 ms duration. Note that in this and subsequent figures the prime onset is at the first 100 ms time tic and target onset is the larger vertical calibration bar. Negative voltages are plotted in the upward direction.

COL3:  $F(1,16) = 6.33, P = 0.008$ ), with targets following short duration primes producing the most negative-going ERPs, and targets following long duration primes producing the least negative-going ERPs. Surprisingly, overall differences in the target N400 repetition effect were only marginally different for the three prime duration conditions (prime duration  $\times$  repetition interaction, all  $P$  values  $>0.09$ ). Because of the importance of this interaction, a number of follow-up analyses were run.

In one set of follow-ups, the 40 ms and 120 ms and the 80 ms and 120 ms conditions were directly compared. In a second set, each prime duration condition was analyzed separately. As expected, the repetition effect was significantly larger in the 120 ms than in the 40 ms prime duration condition across much of the head (repetition by prime duration interaction, midline:  $F(1,16) = 5.46, P = 0.033$ ; COL1:  $F(1,16) = 5.10, P = 0.038$ ; COL2:  $F(1,16) = 5.17, P = 0.037$ ; COL3:  $F(1,16) = 4.56, P = 0.049$ ), while there were no comparable significant differences between the 120 ms vs. 80 ms conditions (all  $P$  values  $>0.54$ ). Despite these differences, all three prime duration conditions produced robust repetition

effects across the head (40 ms midline:  $F(1,16) = 24.72, P < 0.001$ ; COL1:  $F(1,16) = 29.23, P < 0.001$ ; COL2:  $F(1,16) = 21.33, P < 0.001$ ; COL3:  $F(1,16) = 11.45, P = 0.004$ ; 80 ms midline:  $F(1,16) = 21.18, P < 0.001$ ; COL1:  $F(1,16) = 24.82, P < 0.001$ ; COL2:  $F(1,16) = 19.96, P < 0.001$ ; COL3:  $F(1,16) = 17.76, P = 0.001$ ; 120 ms midline:  $F(1,16) = 34.34, P < 0.001$ ; COL1:  $F(1,16) = 31.16, P < 0.001$ ; COL2:  $F(1,16) = 31.40, P < 0.001$ ; COL3:  $F(1,16) = 35.75, P < 0.001$ ).

To determine if detectability of masked primes might be responsible for the robust N400 priming effects found in the 40 ms prime duration condition, several comparisons were made, several of which involved comparing participants with high and low 40 ms d-primes. First, there were no significant interactions between d-prime group and repetition or between d-prime group, repetition and prime duration in any of the electrode columns (all  $P$  values  $>0.3$ ). Second, direct comparison of the two d-prime groups at 40 ms did not reveal evidence for a difference in the size of the N400 repetition effect (group by relatedness interaction, all  $P$  values  $>0.6$ ). Third, the repetition effect

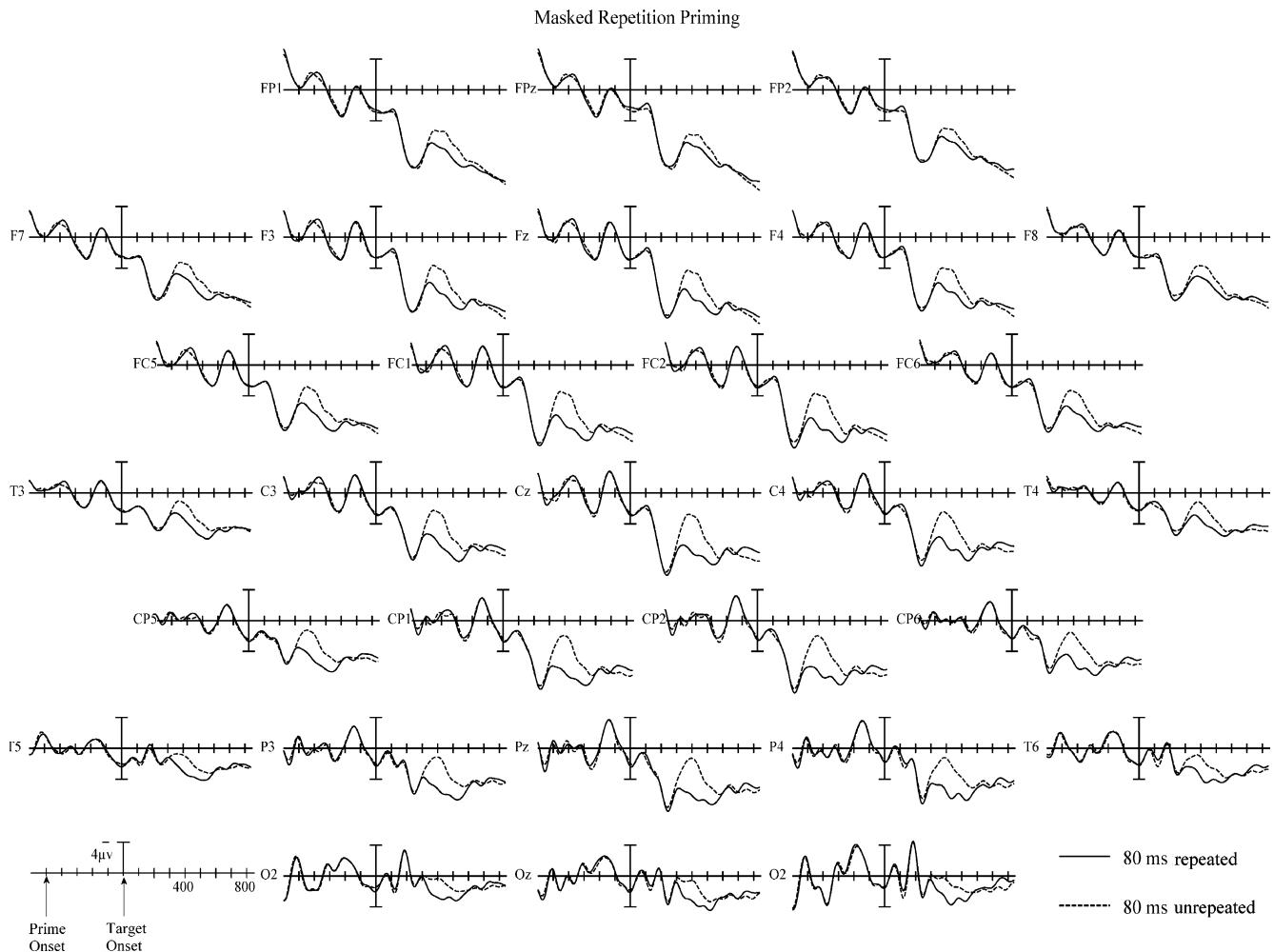


Fig. 4. Compound ERPs in the repeated and unrepeated conditions when primes were of 80 ms duration.

at 40 ms was significant in both groups (relatedness effect at 40 ms low d-prime, midline:  $F(1, 8) = 9.27, P = 0.016$ ; COL1:  $F(1, 8) = 11.80, P = 0.009$ ; COL2:  $F(1, 8) = 9.00 P = 0.017$ ; COL3:  $F(1, 8) = 3.55, P = 0.096$ ; high d-prime, midline:  $F(1, 8) = 17.19, P = 0.003$ ; COL1:  $F(1, 8) = 17.58, P = 0.003$ ; COL2:  $F(1, 8) = 12.39, P = 0.008$ ; COL3:  $F(1, 8) = 9.35, P = 0.016$ —see Fig. 7). Fourth, across all 18 participants, the  $r^2$  with 40 ms d-prime as the predictor variable and the N400 repetition effect at Cz as the dependent variable was 0.07 ( $P = 0.30$ ), suggesting no relationship between these variables. Fifth, across all 18 subjects, the size of the N400 priming effect in the 40 ms condition was 63% of the effect in the 120 ms condition across the midline sites, but based on probe categorization performance, the priming effect at 40 ms should have been only 23% of that at 120 ms. To quantify this difference, we compared the actual 40 ms N400 priming effect to the estimated effect if priming had only occurred on 23% of 40 ms trials. We derived this estimate by taking 23% of the 120 ms N400 effect. Using this procedure at the midline sites, the actual 40 ms effect was significantly larger than the estimated effect ( $F(1, 17) = 5.12, P < 0.037$ ).

### 5.5. 500–750 ms epoch

As can be seen in Figs. 3–6, most of the effects of repetition ended between 500 and 600 ms. Therefore, it is not surprising that the effects of repetition were comparatively weak in this measurement epoch (all  $P$  values  $>0.13$ ). There was a main effect of prime duration on target ERPs, but only at midline sites ( $F(2, 32) = 5.16, P = 0.016$ ). Moreover, there were no signs of a prime duration by repetition interaction (all  $P$  values  $>0.22$ ).

Analyses comparing the two 40 ms d-prime groups found no evidence of a difference in repetition effects across the three prime duration conditions (group by repetition by prime duration, all  $P$  values  $>0.31$ ).

## 6. Discussion

Like several previous studies [21,31], robust effects of repetition in the region of the N400 component were found for target words preceded by very briefly displayed masked prime words. This masked repetition effect was found even

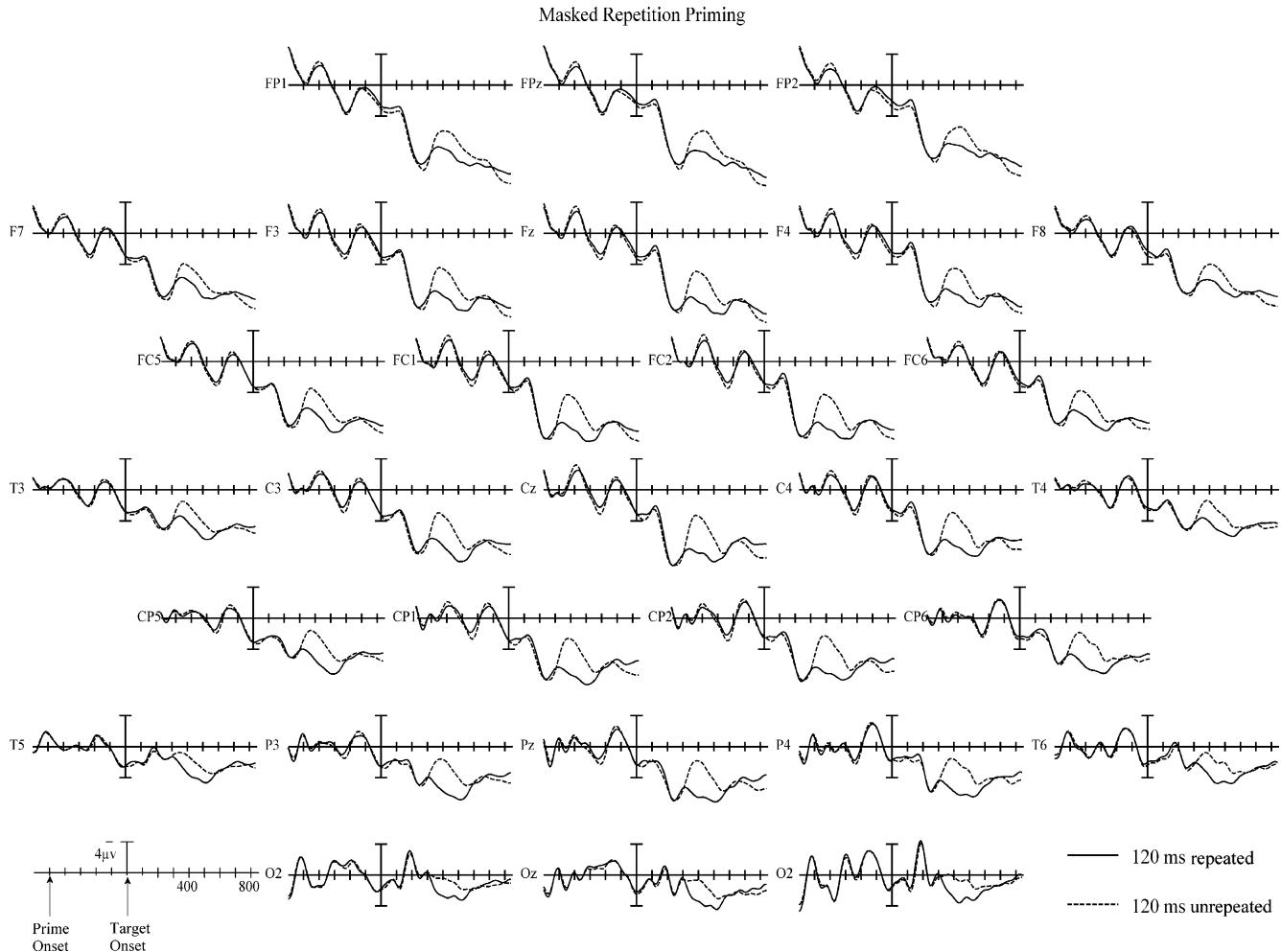


Fig. 5. Compound ERPs in the repeated and unrepeated conditions when primes were of 120 ms duration.

when primes were pattern masked by both a forward and backward pattern mask that varied from trial to trial. Unlike one previous study [21], differences between effectively masked (40 ms) and clearly visible (120 ms) primes produced relatively small differences on the target N400 repetition effect. Misra and Holcomb [21] found differences of approximately 4  $\mu$ V between the two types of priming while the difference in the current study was closer to 1  $\mu$ V averaged across sites. These differences between studies are consistent with the hypothesis that strategic factors that can exist when prime visibility is blocked across sessions as opposed to mixed within a session are an important contributor to N400 masked priming effects. In particular, it seems likely that including trials where prime stimuli could be clearly seen and categorized (120 ms prime duration) encouraged participants to pay closer attention to the prime epoch in general which enhanced the effects of priming even at the shorter prime durations (80 and 40 ms). In fact, previous failures to find masked priming, particularly when the prime is always masked at or near recognition thresholds and is separated from the target by several hundreds of

milliseconds, may reflect a failure of attention rather than a true failure of sensitivity to masked primes [13]. Supporting this view, Nobre [19,23] has shown that temporal attention effects can have potent effects on other late ERP components (especially the P300).

One question that dogs all subliminal priming studies is the issue of whether the obtained effects may be due to residual conscious processing of the primes on some percentage of the trials (a phenomena we will call “conscious leakage”) [4]. In other words, could the obtained effects that we want to attribute to an automatic unconscious mechanism instead be due to a mixture of real supraliminal priming on trials where participants actually did consciously process the prime and null priming on trials where the prime was effectively masked? We acknowledge that our results in the 40 ms condition are undoubtedly contaminated to some degree by conscious leakage (18% of masked animal probes were correctly detected, suggesting that participants could sometimes consciously process primes at 40 ms). In fact, we believe it is impossible to completely eliminate this possibility, as to do so would most likely require the utilization of primes of such short

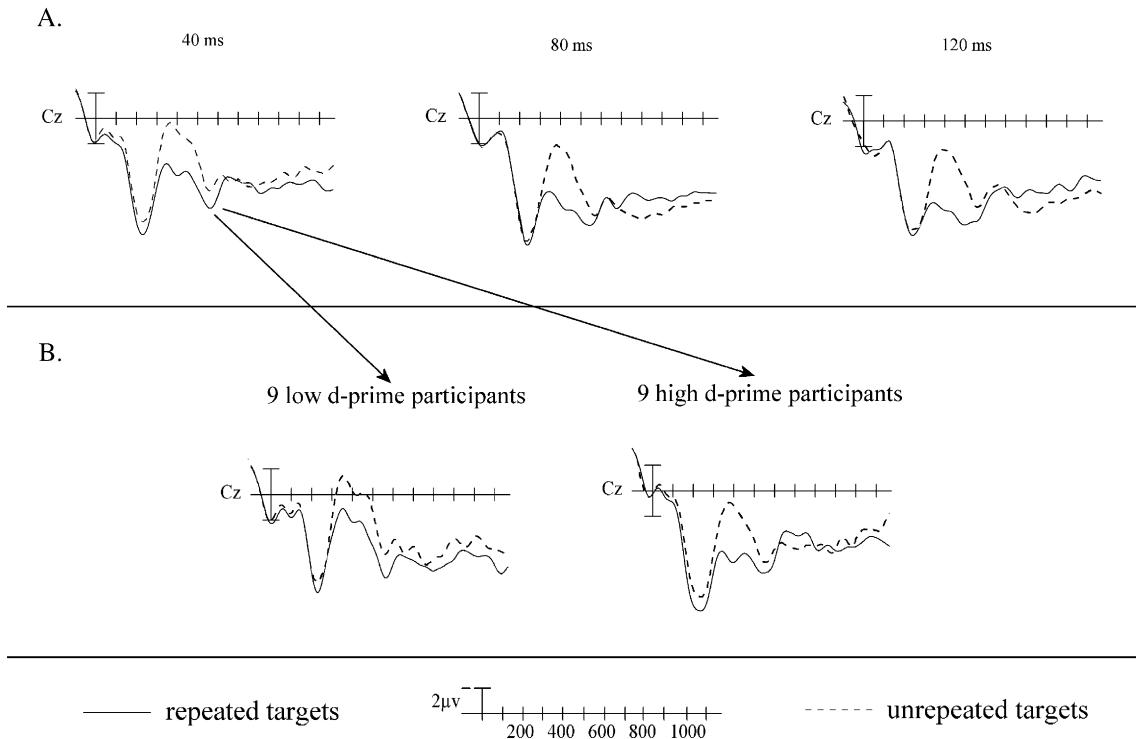


Fig. 6. (A) Target repetition effects for the three prime durations at the Cz electrode site for all 18 participants. (B) Target repetition effects from the 40 ms condition subdivided into the nine participants with the lowest 40 ms d-prime scores (left) and the nine participants with the highest 40 ms d-prime scores (right).

duration that all priming effects would likely be precluded (no one argues that there is a lower limit past which no perceptual processing can take place!). However, we believe that the more important question is whether or not there are priming effects beyond those that can be attributed to conscious leakage. Our approach to resolving this issue was two fold. First, we used masking parameters and manipulated prime durations in such a way that encouraged prime categorization, but made it relatively easy on some trials (120 ms duration), more difficult on others (80 ms) and nearly impossible on the remaining trials (40 ms). Second, we then used prime categorization responses to occasional probe items to determine if the size of the obtained ERP priming effect could be accounted for by an estimate of the size of conscious prime processing. We did this both across all subjects and also within subgroups of subjects sorted based on their categorization performance at short prime durations.

Using several approaches, we found a lack of any apparent relationship between prime visibility and the size of the N400 repetition effect at short prime durations which suggest that conscious leakage had a minimal impact on priming at 40 ms. Across all subjects and sites, the size of the 40 ms N400 priming effect was only marginally different from that at 120 ms. However, based on probe categorization performance, the priming effect at 40 ms should have been only 23% of that at 120 ms if conscious leakage was the only factor producing priming. Moreover,

when subjects were divided into groups based on their d-prime scores to probes in the 40 ms condition, there was no N400 amplitude difference between the high and low d-prime groups in the 40 ms condition and there was no overall relationship between 40 ms N400 amplitude and 40 ms d-prime values. Taken together, these findings provide strong evidence that the N400 repetition effects at 40 ms in this experiment were due in large part to automatic unconscious processes and were not strictly the result of conscious leakage from consciously perceived primes.

Unlike Misra and Holcomb [21] and a number of other previous unmasked ERP repetition priming studies (e.g., [24,27–30]), there was no clear evidence of an effect on the post-N400 late positivity. This is somewhat surprising in the case of the 80 and 120 ms primes given that they were clearly visible in almost all cases and presumably would have resulted in the formation of an episodic memory trace sufficient in magnitude to produce an ERP memory effect. However, one difference between this and most previous repetition priming studies is the relatively short prime-target SOA employed in this study (500 ms). This may not have been a sufficient duration for the formation of an episodic trace or, alternatively the almost immediate repetition may have made episodic retrieval unnecessary. Consistent with this interpretation is a study by Olichney et al. [24] that also failed to find late positive repetition effects when an episodic trace was arguably not available due to their participants being amnesic [8].

## 7. Experiment 2—masked semantic priming

As noted in the Introduction, priming effects can be obtained in cases other than direct repetition of the prime. In particular, when the target word is *semantically* related to the prime, there is a decrease in RT as well as a decline in the amplitude of the N400 component compared to when the prime and target are semantically unrelated (e.g., [1,2,11,20]). Such semantic priming effects are usually explained, at least in part, in the same way as repetition effects<sup>1</sup>. In the case of ERPs, semantically related target words produce smaller N400s because they are relatively easier to integrate with the context established by the prime word than are targets words that are unrelated to the prime [12].

The above account of N400 effects has usually been interpreted as a post-lexical explanation of priming. In other words, the integration process(es) reflected by the N400 occurs after the reader has accessed and recognized the word in question. Supporting this view is a seminal study by Brown and Hagoort [3] who found no evidence of an N400 effect when related and unrelated prime words were pattern masked below the level of participant awareness, and robust N400 effects when primes were clearly visible (i.e., not masked). Importantly, Brown and Hagoort obtained their null effect on the N400 in the presence of significant RT masked semantic priming effects, albeit in separate experiments and participants. They persuasively argued that their pattern of ERP and RT data suggested that RT is sensitive to both lexical (automatic) and effortful (conscious) priming effects, while the N400 is sensitive only to the latter.

Several more recent studies have challenged the Brown and Hagoort findings and interpretation. Deacon and colleagues [6] and Kiefer and colleagues [14,15] examined masked and unmasked semantic priming within the same subjects using experimental designs similar to those of Brown and Hagoort. However, unlike Brown and Hagoort, both of these more recent reports found evidence of significant N400 masked semantic priming. Moreover, in the Deacon et al. study, there were no statistically reliable N400 differences between masked and unmasked semantic priming. This latter finding is consistent with the results from Experiment 1, which found only small differences between visible and effectively masked N400 repetition priming, and argues that similar mechanisms underlie masked and unmasked N400 effects. Following the logic of Brown and Hagoort [3], Deacon et al. concluded that the presence of masked priming effects on the N400 argues that this component reflects an automatic pre-lexical priming mechanism. We believe the premise this conclusion is based on is questionable and will return to this topic in the General discussion.

<sup>1</sup> Repetition effects are usually larger and can last for much longer periods of time than semantic effects. Some authors have argued that this is because repetition priming reflects additional perceptual and memorial processes over and beyond those responsible for semantic priming.

The current experiment was designed to follow up on the findings from Experiment 1 where significant N400 masked repetition priming effects were found across prime durations that made prime recognition easy, difficult or nearly impossible, while simultaneously controlling for level of attention to the prime epoch. As pointed out in Experiment 1, controlling attention to the prime epoch is important because when all primes are difficult to detect and are also not task relevant, participants may not pay sufficient attention to the prime epoch to extract the appropriate information critical for priming. Neither the Deacon et al. nor the Kiefer studies controlled prime processing and therefore it is not clear whether their participants allocated similar attentional resources to primes in their various conditions.

Experiment 2 used the same design and task as Experiment 1, but instead of repeating primes in the target position (e.g., fork-FORK), 50% of critical trials contained targets that were semantically related to the preceding prime word (e.g., knife-FORK) while the remaining 50% of trials contained semantically unrelated primes and targets (e.g., desk-FORK). The same three prime durations used in Experiment 1 were again used in Experiment 2. Prime durations of 40 ms (short) were assumed to be not visible, while primes at 80 ms (medium) were expected to be seen on some occasions, and primes displayed at 120 ms (long) were expected to be seen most of the time. Prime-target SOAs were kept constant at 500 ms across conditions. It was predicted that, as in Experiment 1, all three prime durations would result in significant N400 effects when comparing ERPs to related and unrelated target words. It was also predicted that, because repetition priming reflects a more complete overlap between prime and target, the N400 effects in Experiment 2 might be smaller than those in Experiment 1 [21].

## 8. Methods

### 8.1. Participants

Eighteen right-handed, native English speaking Tufts University students (10 male, mean age = 18.9) received partial course credit for participation in this experiment. The data from five of the participants were blink-corrected. Two additional participants completed this study, but their data were not used, in one case due to an equipment failure and in another case because of excessive movement during the experiment.

### 8.2. Stimuli and procedure

The *critical* stimuli for this experiment were formed from 240 pairs of highly semantically related items that were either associatively (e.g., glove-hand) and/or categorically related (e.g., eye-ear) nouns, verbs and adjectives from 2 to 7 letters in length (adapted from Anderson and Holcomb

[1]). An additional set of non-critical stimulus pairs was formed by combining 120 animal names with 120 unrelated non-animal words (these included items used in Experiment 1). Stimulus lists consisted of 360 trials each containing a prime–target pair of words. There were two critical stimulus conditions in each list: semantically related, which contained 120 related pairs (e.g., *table-chair*), and semantically unrelated, which contained 120 unrelated pairs (e.g., *car-uncle*). The latter were created by randomly recombining primes and targets from the 180 unused related pairs. For the 120 non-critical pairs, 60 contained animal names in the prime position and an unrelated word in the target position, while the other 60 trials contained an unrelated word in the prime position and an animal name in the target position. As in Experiment 1, the animal names served as *probe* items in a go/no-go semantic categorization task and response hand was counterbalanced.

As in Experiment 1, there were two experimental variables: relatedness (related/unrelated) and prime duration (40 ms, 80 ms and 120 ms), which resulted in six types of critical trials of 40 pairs/condition (see Table 3). Six different lists were formed so that each related pair appeared once per list, but across lists, each pair appeared in each of the six critical trial types. All else was as in Experiment 1.

### 8.3. Data analysis

Separate waveforms were calculated by averaging compound ERPs to prime and target words based on the three prime durations and the two target relatedness conditions. Using relatedness (instead of repetition) and prime duration as critical factors, data were analyzed as in Experiment 1.

## 9. Results

### 9.1. Behavioral data

Participants detected 91% of animal probes in the target position within a window of 200 to 1200 ms post-probe

Table 4  
Prime detectability measures, Experiment 2

Prime duration	Probability of a hit	Probability of a false alarm	d-prime
40 ms prime	0.15	0.01	0.9
80 ms prime	0.54	0.02	2.2
120 ms prime	0.76	0.02	3.1

onset. As in Experiment 1, participants detected significantly different numbers of prime position animal probes across the three prime durations ( $F(2,32) = 60.46, P < 0.001$ , see Table 4) which translated into a significant difference in the d-prime values ( $F(2,32) = 39.96, P < 0.001$ ). The correlation between target probe hits and 40 ms prime probe hits was not significant ( $r = 0.26, P > 0.33$ ), suggesting that the tendency to detect probes in the prime position was not predictive of performance in the overall task of semantic categorization.

As in Experiment 1, participants were subdivided into two groups based on a median split of d-prime scores in the 40 ms prime duration condition. The mean of the low group's d-prime at 40 ms was  $-0.01$  and did not significantly differ from 0 ( $P > 0.95$ ). The mean of the high group's d-prime at 40 ms was  $1.8$  which did significantly differ from 0 ( $t = 13.84, P < 0.001$ ).

### 9.2. Event-related potentials

Plotted in Figs. 7–9 are the compound prime–target ERPs contrasting the related and unrelated conditions at each of the three prime durations. Plotted in Fig. 10 are side-by-side comparisons of the relatedness effect in the three duration conditions (top) and the relatedness effect for the eight lowest and eight highest d-prime participants (bottom). As can be seen by comparing these figures to Figs. 3–6, target ERPs were strikingly similar across the two experiments. As in Experiment 1, the P2 component to targets was followed by a slow negative-going component which peaked near 400 ms (N400) and a large widely distributed slow positivity that, at all but the most posterior

Table 3  
Experiment 2 trial types

	Description	Prime duration	Mask	Prime	Mask	Target
1	Related	Short (40 ms)	CBLRF	Table	CBLRF	CHAIR
2	Related	Medium (80 ms)	CRWFL	Yes	CRWFL	NO
3	Related	Long (120 ms)	FBCRL	Uncle	FBCRL	AUNT
4	Unrelated	Short (40 ms)	DGTQF	Beach	DGTQF	KNIFE
5	Unrelated	Medium (80 ms)	HKRTM	Boy	HKRTM	DESK
6	Unrelated	Long (120 ms)	MJFDR	Pencil	MJFDR	COAT
7	Animal prime	Short (40 ms)	BWKRK	Moose	BWKRK	SACK
8	Animal prime	Medium (80 ms)	TBVXS	Flea	TBVXS	CLOUD
9	Animal prime	Long (120 ms)	FBCRL	Tiger	FBCRL	PROP
10	Animal target	Short (40 ms)	TBVXS	Cork	TBVXS	LEECH
11	Animal target	Medium (80 ms)	CBLRF	Movie	CBLRF	HIPPO
12	Animal target	Long (120 ms)	MJFDR	liter	MJFDR	PANDA

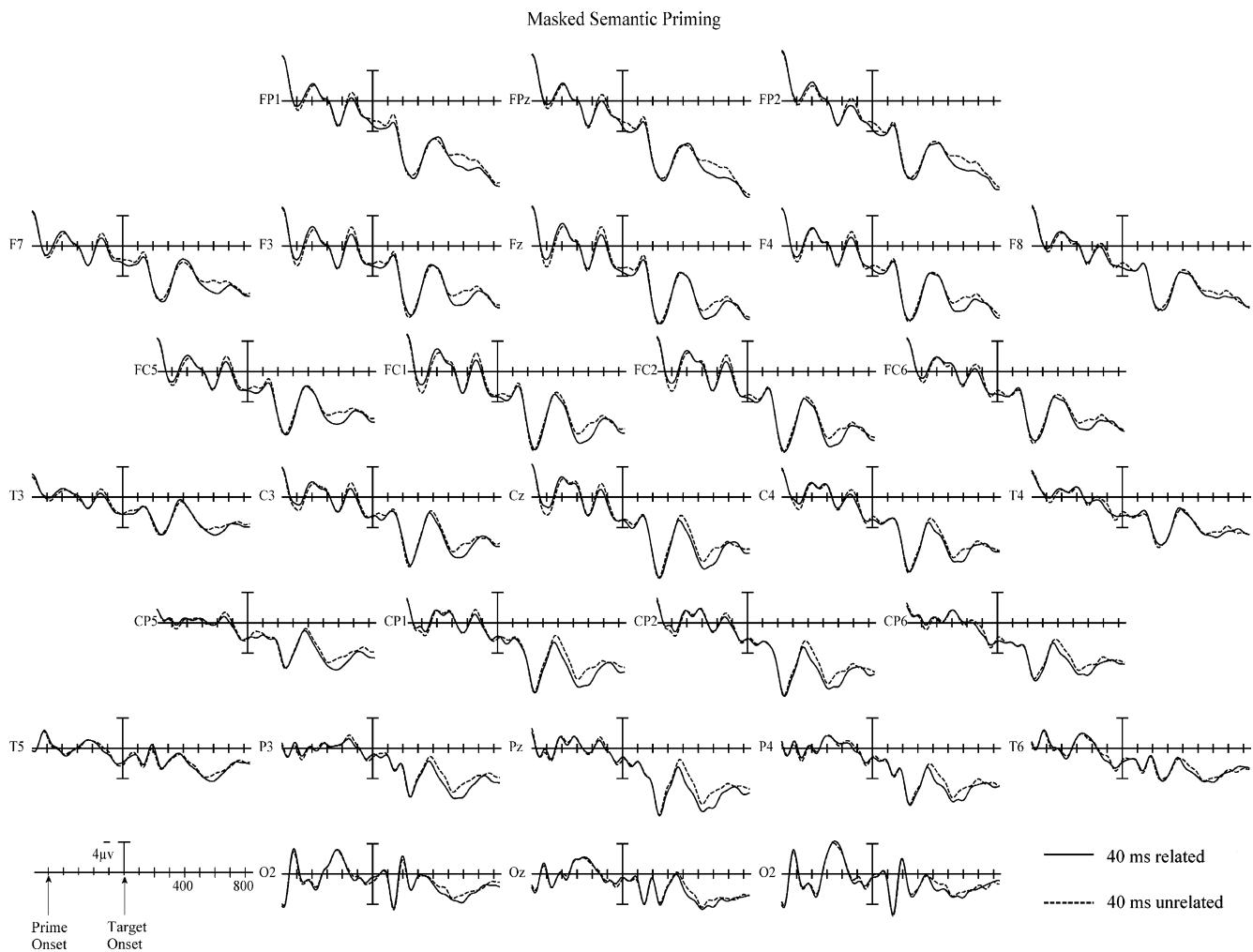


Fig. 7. Compound ERPs time locked to prime onset in the related and unrelated target conditions (Experiment 2) following primes of 40 ms duration. Note that in this and subsequent figures the target onset is the vertical calibration bar and negative voltages are plotted in the upward direction.

sites, remained positive-going through the end of the recording epoch.

#### 9.3. 150–300 ms target epoch

There were no relatedness (all  $P$  values  $>0.22$ ) or prime duration (all  $P$  values  $>0.06$ ) effects on the target ERPs during this epoch.

#### 9.4. 300–500 ms target epoch

Targets following unrelated primes were more negative-going than targets following related primes (main effect of relatedness; midline:  $F(1,14) = 18.45, P = 0.001$ ; COL1:  $F(1,14) = 27.17, P < 0.001$ ; COL2:  $F(1,14) = 17.06, P = 0.001$ ; COL3:  $F(1,14) = 8.53, P = 0.01$ ). Unlike Experiment 1, the overall difference between targets as a function of prime duration was not significant (all  $P$  values  $>0.26$ ) nor did it interact with the relatedness variable. However, also unlike Experiment 1, there was a difference in the relatedness effect across prime durations as a function of

prime visibility group (relatedness by prime duration by 40 ms prime visibility group, midline:  $F(2, 28) = 7.50, P = 0.005$ ; COL1:  $F(2, 28) = 6.31, P = 0.01$ ; COL2:  $F(2, 28) = 7.81, P = 0.003$ ; COL3:  $F(2, 28) = 5.79, P = 0.009$ ).

Follow-up analyses contrasting each prime duration condition separately revealed significant relatedness effects at all three prime durations, with target words following unrelated prime words producing larger N400s than target words following related primes (40 ms midline:  $F(1,14) = 4.58, P = 0.05$ ; COL1:  $F(1,14) = 5.84, P = 0.03$ ; COL2:  $P > 0.19$ ; COL3:  $P > 0.58$ ; 80 ms midline:  $F(1,14) = 4.27, P = 0.058$ ; COL1:  $F(1,14) = 6.18, P = 0.026$ ; COL2:  $F(1,14) = 5.17, P = 0.039$ ; COL3:  $F(1,14) = 4.16, P > 0.061$ ; 120 ms midline:  $F(1,14) = 12.18, P = 0.004$ ; COL1:  $F(1,14) = 8.88, P = 0.01$ ; COL2:  $F(1,14) = 9.79, P = 0.007$ ; COL3:  $F(1,14) = 7.63, P = 0.015$ ). However, in the 40 ms condition (but not the 80 or 120 ms conditions), the relatedness effect varied as a function of the prime visibility grouping factor (relatedness by prime visibility interaction at 40 ms, midline:  $F(1, 14) = 18.05, P = 0.001$ ; COL1:  $F(1, 14) = 14.95, P = 0.001$ ; COL2:  $F(1, 14) = 14.62, P = 0.002$ ; COL3:  $F(1, 14) = 7.66, P =$

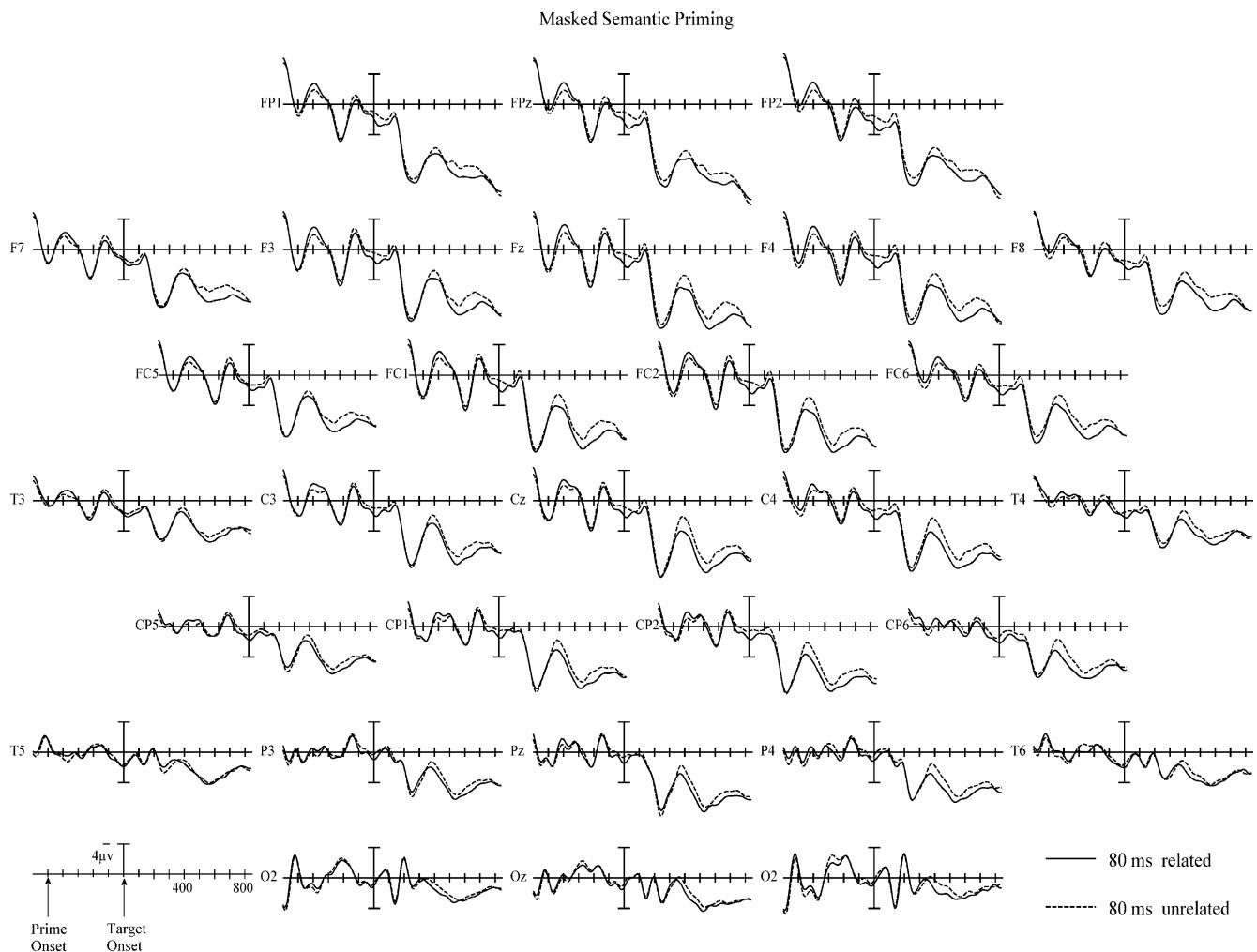


Fig. 8. Compound ERPs time locked to prime onset in the related and unrelated target conditions following primes of 80 ms duration.

0.015; at 80 and 120 ms all  $P$  values  $>0.11$ ). This interaction was explained by the fact that, in the high d-prime group, N400 amplitude was, as expected, larger for unrelated than related targets, but in the low d-prime group, the N400 effect was absent or slightly reversed. So, unlike repetition priming in Experiment 1, for semantic priming in Experiment 2, visibility of primes at 40 ms (as measured by button presses to probe items) predicted the N400 effect for targets following very briefly presented primes. This possibility was supported by the existence of a significant relationship between 40 ms d-prime values and the N400 relatedness effect at Cz ( $r^2 = 0.434, P = 0.006$ ). Across all 16 subjects, the size of the N400 priming effect in the 40 ms condition was 42% of the effect in the 120 ms condition across the midline sites, but based on probe categorization performance the priming effect at 40 ms should have been 25% of that at 120 ms. As in Experiment 1, to quantify this difference, we compared the actual 40 ms N400 priming effect to the estimated effect if priming had only occurred on 25% of 40 ms trials. We derived this estimate by taking 25% of the 120 ms N400 effect. Using this procedure at the midline sites, the actual 40 ms effect was not significantly larger than the estimated effect ( $P > 0.17$ ).

#### 9.5. 500–800 ms target epoch

Following the pattern seen for the 300–500 ms epoch, targets following unrelated primes continued to be more negative-going than targets following related primes (main effect of relatedness; midline:  $F(1,14) = 5.41, P < 0.035$ ; COL1:  $F(1,14) = 7.34, P = 0.017$ ; COL2:  $F(1,14) = 6.66, P = 0.022$ ; COL3:  $F(1,14) = 4.22, P = 0.059$ ). However, unlike the previous epoch, the relatedness effect did not significantly differ as a function of prime duration (all  $P$  values  $>0.8$ ).

Analyses comparing the two 40 ms d-prime groups found no evidence of a difference in relatedness effects across the three prime duration conditions (group by relatedness by prime duration, all  $P$  values  $>0.35$ ).

#### 9.6. Between experiment comparisons

The N400 epoch was also directly compared for Experiments 1 and 2 at the midline sites. A mixed design ANOVA including a single grouping factor of Experiment (Experiment 1 vs. Experiment 2) and within-subjects factors as in the previous analyses revealed that, while there were no

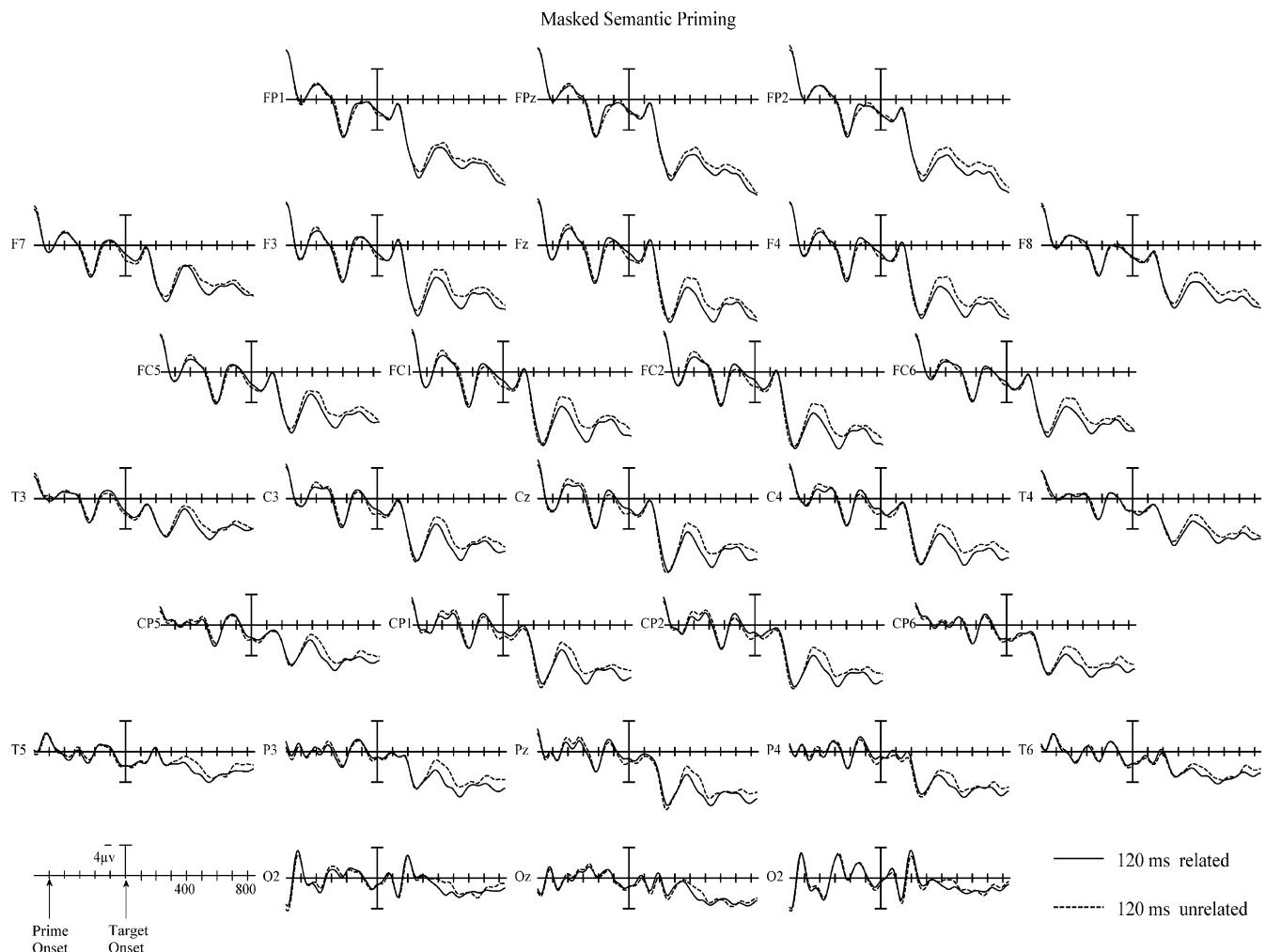


Fig. 9. Compound ERPs time locked to prime onset in the related and unrelated target conditions following primes of 120 ms duration.

overall effects of experiment ( $P$  values  $>0.5$ ), there was a significant difference in the size of the priming effect between the experiments (experiment  $\times$  priming interaction: midline  $F(1,32) = 6.26, P = 0.018$ ; Col1  $F(1,32) = 8.39, P = 0.007$ ; Col2  $(1,32) = 7.43, P = 0.01$ ; Col3  $F(1,32) = 4.47, P = 0.042$ ). Specifically, repetition priming (Experiment 1) produced a larger overall priming effect than semantic priming (Experiment 2).

## 10. Discussion

As in Experiment 1, there was an effect of priming on target word ERPs both when the prime was clearly visible and categorizable (120 ms prime duration) and when it was not (40 ms prime duration). This effect, although smaller than in Experiment 1, appeared to be almost exclusively on the same ERP component—the N400. This finding together with the data from Experiment 1 would appear to provide further support for the sensitivity of the N400 to masked priming.

One caveat to the above conclusion was that, unlike in Experiment 1 (repetition priming), in Experiment 2 (seman-

tic priming), at the shortest prime duration, there was a correlation between prime visibility (as measured by the number of probe words detected at the shortest prime duration) and N400 amplitude. In other words, participants who detected the fewest animal names in the 40 ms prime duration condition also produced the smallest N400 priming effects at this prime duration, and participants that detected the most animal names tended to produce the largest N400 priming effects at short prime durations. Moreover, when the obtained 40 ms priming effect was compared to the estimated size of the priming effect (determined by scaling the 120 ms priming effect by the percentage of prime animal probes detected was  $-25\%$ ), there was no significant difference, whereas there was in Experiment 1. This suggests that, unlike the repetition priming effects obtained in Experiment 1, prime visibility likely played a role in the semantic priming effects obtained at the shortest prime durations of Experiment 2. Moreover, these findings draw into question previous reports of masked semantic priming that have claimed that the effects are due to unconsciously processed primes [6,14,15]. A more likely explanation in light of the current findings is that these previous reports obtained their

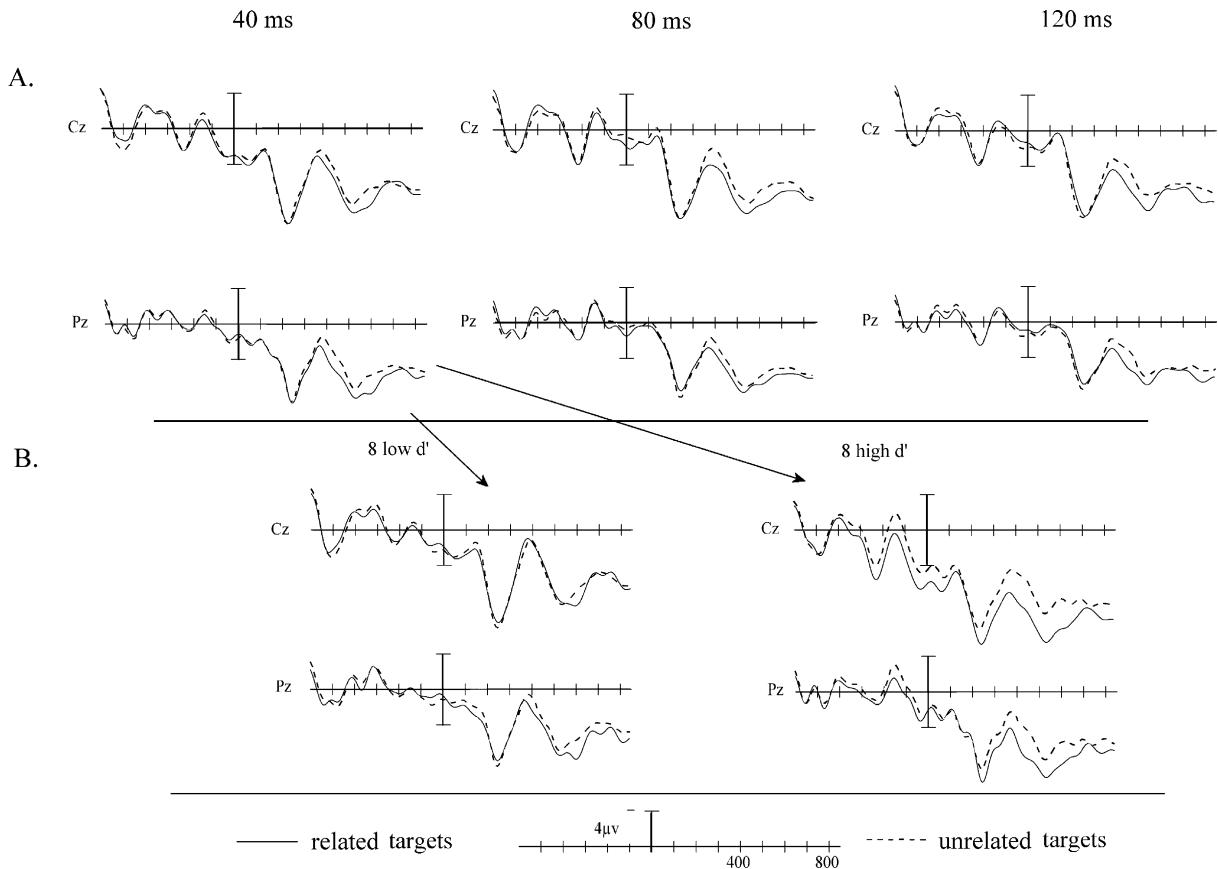


Fig. 10. (A) ERPs at the Cz and Pz sites for the related and unrelated conditions at each prime duration. (B) ERPs for the eight low d-prime participants (left) and the eight high d-prime participants in the 40 ms prime condition.

semantic priming at short masked prime durations because of conscious leakage on some percentage of trials.

## 11. General discussion

As just noted, one notable difference between the results of the two experiments was that, while 40 ms d-prime values did not predict N400 amplitude in Experiment 1, they did predict the size of the N400 effect in the 40 ms condition of Experiment 2. This suggests that prime visibility may play a bigger role in mediating masked semantic than masked repetition priming effects on the N400. There are several possibilities for such a pattern of effects.

One relatively simplistic explanation is that, because repetition priming tends, in general, to produce larger, more robust effects than semantic priming (e.g., due to semantic overlap being complete for repetition and partial for semantic priming), any manipulation, such as masking, that reduces the overall size of effects will have a relatively greater impact on the smaller (semantic) effect. Accordingly, as the limits of perception are approached, participants that extract more information from the masked prime will benefit relatively more from the semantic overlap showing larger priming effects than those that extract less information. Repetition priming would not, presumably, show a

similar result because it starts from a higher point on the priming function.

Alternatively, as argued by Holcomb et al. [12], the N400 might reflect processing at a form-meaning interface that is sensitive to the compatibility of co-activated form (orthographic and phonological) and meaning representations. Thus, modulations of the N400 could reflect the influence of form and/or meaning information extracted from prime stimuli on processing of target stimuli at this form-meaning interface. Improving the processing of either form or meaning will help the lexical processor settle on a single form-meaning association via a resonance process involving the activation of similar form and similar meaning representations. Any prime stimulus that is related to the target stimulus in terms of form and/or meaning overlap will influence processing at this interface.

Critical for an account of the present findings is the following hypothesized distinction in the mechanisms underlying repetition and semantic priming. The complete pattern of priming effects obtained in the present study can be explained if one assumes that form information can be extracted automatically (i.e., without attention-demanding resources), while the extraction of semantic information is either not automatic at all and depends on the allocation of capacity-limited resources or relies to a greater extent on capacity-limited resources. If we further hypothesize that it is

precisely the allocation of attention-demanding resources that determines the level of visibility of prime stimuli, then we can explain why prime visibility correlated highly with semantic priming and not with repetition priming. However, to explain why the N400 effect was not modulated by prime visibility in Experiment 1, one has to assume that most of the effect in repetition priming is driven by shared form representations.

One way to avoid this relatively ad-hoc assumption would be to argue that the critical difference between repetition and semantic priming is that repetition priming is driven primarily by the pre-activation of representations that are shared by prime and target, while semantic priming involves, to a greater extent, establishing connections across related representations (e.g., as in theories such as compound-cue [26]). In this account, it is not the type of representation (form or meaning) that determines the automaticity of priming effects, but rather the type of mechanism utilized (pre-activation versus establishing connections). Thus, repetition priming is more automatic in that it relies relatively more on pre-activation of form and meaning representations, whereas semantic priming is less automatic because it relies relatively more on connecting up the representations of related concepts after the target has been at least partially processed. We hypothesize that it is the latter post-target connecting mechanism that requires allocation of attention-demanding resources and is therefore sensitive to the visibility of the prime. Future research could test this hypothesis using the same manipulation as in the present study but with translation equivalents in bilingual persons (e.g., arbre-TREE). Modulation of the N400 by priming with translation equivalents should not be sensitive to prime visibility since the same semantic representation would be pre-activated by the translation equivalent in the other language.

Another difference between the experiments was that semantic priming (Experiment 2) tended to last somewhat longer than repetition priming (Experiment 1). This later difference is not consistent with the literature on supraliminal repetition and semantic priming where repetition effects tend to extend into later ERP epochs more often than do semantic effects. However, if the extended masked semantic effects reflect a less precise time course for the N400 effect in the semantic case, this result might make sense. This could happen, for example, because of the almost certainly greater item-by-item variability in degree of semantic overlap between the various semantically related word pairs than between each word and its repetition. This increased semantic variability could, in theory, result in a jittered time course of semantic activation (especially when primes are masked) and thus a temporally extended N400 effect.

### 11.1. Implications for the functional significance of the N400

The pattern of results observed in these experiments would seem to call into question the interpretation of the functional

significance of the N400 offered by Brown and Hagoort [2] and others who have maintained that the N400 is exclusively sensitive to post-lexical semantic processes. If this was correct, then we should not have obtained significant masked priming at 40 ms durations in either Experiment 1 or 2 (nor should Deacon et al. [6] or Kiefer [14,15]).

It is important to note, however, that contrary to the claims of Deacon and others, neither we (nor they) have demonstrated that the process directly reflected by the N400 is exclusively automatic. What we have shown is that the N400 process is *sensitive* to the influence of automatic priming. To show that the N400 directly reflects an automatic process, one would have to find evidence of priming effects on the N400 when the evoking (target) stimulus itself is processed automatically. The evidence to date, which comes primarily from studies that have directed attention away from the semantic attributes of targets, suggests that when participants are encouraged to use exclusively automatic-like processes on the N400 eliciting stimuli themselves the N400 is relatively insensitive to priming [5,35].

In our view, the results of this and the earlier ERP masked priming studies converge on a somewhat modified version of the semantic integration hypothesis. Our working hypothesis is that the N400, while sensitive to the buildup of automatically established contexts such as those provided by a masked prime, nevertheless is a direct reflection of a later post-lexical process that requires attention to the semantic properties of the eliciting *target* stimulus. Of course, to *attend* to the semantic properties of a stimulus, one must be aware of the stimulus. Therefore, one prediction of this hypothesis is that there should be no N400 effect when participants are unaware of and unable to identify target words. One way to test this possibility would be to mask targets rather than primes. If the ERPs to masked targets following related/repeated and unrelated primes do not show N400 priming effects, then this would be strong evidence that the N400 does not directly reflect an automatic process. On the other hand, finding evidence of N400 priming effects on masked targets would strengthen the case for the N400 being a direct reflection of automatic processing and would force those of us who have assumed that it reflects a post-lexical stage of comprehension to rethink our position.<sup>2</sup>

<sup>2</sup> One study [32] has reported significant semantic priming effects on masked targets. However, the findings in this study are somewhat equivocal from our perspective because the authors used subjective measures of target identification to bin trials into unconsciously and consciously processed conditions rather than classifying trials based on more objective measures of target duration. The problem with the more subjective measures is that it is impossible to know which kind(s) of trials (long or short target durations) resulted in the obtained priming effect. If long duration targets made most or all of the contribution (something that was impossible to tell from their data), then one must be skeptical that the obtained effects were actually due to unconscious processing as the authors asserted.

## Acknowledgments

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## References

- [1] J.E. Anderson, P.J. Holcomb, Auditory and visual semantic priming using different stimulus onset asynchronies: an event-related brain potential study, *Psychophysiology* 32 (2) (1995) 177–190.
- [2] S. Bentin, G. McCarthy, C.C. Wood, Event-related potentials, lexical decision and semantic priming, *Electroencephalogr. Clin. Neurophysiol.* 60 (1985) 343–355.
- [3] C. Brown, P. Hagoort, The processing nature of the N400: evidence from masked priming, *J. Cogn. Neurosci.* 5 (1) (1993) 34–44.
- [4] J. Cheesman, P.M. Merikle, Word recognition and consciousness, in: D. Besner, T.G. Waller, G.E. MacKinnon (Eds.), *Read. Res.*, vol. 5, Academic Press Inc, Orlando, FL, 1985, pp. 311–352.
- [5] D.J. Chwilla, C.M. Brown, P. Hagoort, The N400 as a function of the level of processing, *Psychophysiology* 32 (3) (1995) 274–285.
- [6] D. Deacon, S. Hewitt, C.-M. Yang, M. Nagata, Event-related potential indices of semantic priming using masked and unmasked words: evidence that the N400 does not reflect a post-lexical process, *Cogn. Brain Res.* 9 (2) (2000) 137–146.
- [7] S. Dehaene, L. Naccache, L. Cohen, D. Le Bihan, J. Mangin, J. Poline, Riviere, Cerebral mechanisms of word masking and unconscious repetition priming, *Nat. Neurosci.* 4 (2001) 752–758.
- [8] E. Düzel, A.P. Yonelinas, G.R. Mangun, H.-J. Heinze, E. Tulving, Event-related brain potential correlates of two states of conscious awareness in memory, *Proc. Natl. Acad. Sci. U. S. A.* 94 (1997) 5973–5978.
- [9] K.I. Forster, C. Davis, Repetition priming and frequency attenuation in lexical access, *J. Exper. Psychol., Learn., Mem., Cogn.* 10 (4) (1984) 680–698.
- [10] P.J. Holcomb, Automatic and attentional processing: an event-related brain potential analysis of semantic priming, *Brain Lang.* 35 (1988) 66–85.
- [11] P.J. Holcomb, Semantic priming and stimulus degradation: implications for the role of the N400 in language processing, *Psychophysiology* 30 (1) (1993) 47–61.
- [12] P.J. Holcomb, J. Grainger, T. O'Rourke, An event-related brain potential study of orthographic similarity, *J. Cogn. Neurosci.* 14 (2002) 938–950.
- [13] T.A. Kahan, Negative priming from masked words: retrospective prime clarification of center-surround inhibition? *J. Exper. Psychol., Learn., Mem., Cogn.* 26 (6) (2000) 1392–1410.
- [14] M. Kiefer, The N400 is modulated by unconsciously perceived masked words: further evidence for an automatic spreading activation account of N400 priming effects, *Cognit. Brain Res.* 13 (1) (2002) 27–39.
- [15] M. Kiefer, M. Spitzer, Time course of conscious and unconscious semantic brain activation, *NeuroReport* 11 (11) (2000) 2401–2407.
- [16] H. Kučera, W.N. Francis, Computational analysis of present-day American English, Brown Univ. Press, Providence, RI, 1967.
- [17] A.J. Marcel, Conscious and unconscious perception: experiments on visual masking and word recognition, *Cogn. Psychol.* 15 (2) (1983) 197–237.
- [18] A.J. Marcel, Conscious and unconscious perception: an approach to the relations between phenomenal experience and perceptual processes, *Cogn. Psychol.* 15 (2) (1983) 238–300.
- [19] G. McCarthy, A.C. Nobre, Modulation of semantic processing by spatial selective attention, *Electroencephalogr. Clin. Neurophysiol., Evoked Potentials* 88 (3) (1993) 210–219.
- [20] D.E. Meyer, R.W. Schvaneveldt, Facilitation in recognizing pairs of words: evidence of a dependence between retrieval operations, *J. Exp. Psychol.* 90 (2) (1971) 227–234.
- [21] M. Misra, P.J. Holcomb, Event-related potential indices of masked repetition priming, *Psychophysiology* 40 (2003) 115–130.
- [22] J.H. Neely, Semantic priming effects in visual word recognition: a selective review of current findings and theories, in: D. Besner, G.W. Humphreys (Eds.), *Basic processes in reading: visual word recognition*, Lawrence Erlbaum Associates, Hillsdale, NJ, 1991, pp. 264–336.
- [23] A. Nobre, Orienting attention to instants in time, *Neuropsychologia* 39 (2001) 1317–1328.
- [24] J.M. Olichney, C. Van Petten, K.A. Paller, D.P. Salmon, J.I. Vicente, M. Kutas, Word repetition in amnesia: electrophysiological measures of impaired and spared memory, *Brain* 123 (2000) 1948–1963.
- [25] L. Osterhout, P.J. Holcomb, Event-related potentials elicited by syntactic anomaly, *J. Mem. Lang.* 31 (1992) 785–806.
- [26] R. Ratcliff, G. McKoon, A retrieval theory of priming in memory, *Psychol. Rev.* 95 (1988) 385–408.
- [27] M.D. Rugg, The effects of semantic priming and word repetition on event-related potentials, *Psychophysiology* 22 (1985) 642–647.
- [28] M.D. Rugg, Event-related brain potentials dissociate repetition effects of high- and low-frequency words, *Mem. Cogn.* 19 (1990) 367–379.
- [29] M.D. Rugg, M.E. Nagy, Event-related potentials and recognition memory for words, *Electroencephalogr. Clin. Neurophysiol.* 72 (1989) 395–406.
- [30] M.D. Rugg, M.C. Doyle, T. Wells, Word and nonword repetition within- and across-modality: an event-related potential study, *J. Cogn. Neurosci.* 7 (2) (1995) 209–227.
- [31] D.M. Schnyer, J.B. Allen, K.I. Forster, Event-related brain potential examination of implicit memory processes: masked and unmasked repetition priming, *Neuropsychology* 11 (2) (1997) 243–260.
- [32] G. Stenberg, M. Lindgren, M. Johansson, A. Olsson, I. Rosen, Semantic processing without conscious identification: Evidence from event-related potentials, *J. Exper. Psychol., Learn., Mem., Cogn.* 26 (2000) 973–1004.
- [33] J.J. van Berkum, P. Hagoort, C.M. Brown, Semantic integration in sentences and discourse: evidence from the N400, *J. Cogn. Neurosci.* 11 (6) (1999) 657–671.
- [34] C. Van Petten, M. Kutas, R. Kluender, M. Mitchiner, H. McIsaac, Fractionating the word repetition effect with event-related potentials, *J. Cogn. Neurosci.* 3 (2) (1991) 131–150.
- [35] W.C. West, P.J. Holcomb, Imaginal, semantic, and surface-level processing of concrete and abstract words: an electrophysiological investigation, *J. Cogn. Neurosci.* 12 (6) (2000) 1024–1037.
- [36] S. Yamagata, S. Yamaguchi, S. Kobayashi, Event-related evoked potential study of repetition priming to attended and unattended words, *Cognit. Brain Res.* 10 (1–2) (2000) 167–171.