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An electrophysiological study of cross-modal repetition priming

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Abstract

Few studies have focused on language processing across modalities. Two experiments examined between-modality interactions across three prime–target intervals (0, 200, and 800 ms) in a cross-modal repetition priming paradigm. Event-related potentials were recorded to auditory targets following visual primes (Experiment 1) or visual targets following auditory primes (Experiment 2). In Experiment 1 robust repetition effects were found for auditory targets as early as 100 ms, and continued through the N400 epoch. Moreover, these visual–auditory repetition effects were large across all three prime–target intervals although they onset 200 ms later at the shortest interval. In Experiment 2 repetition effects to visual targets started later (at 200 ms), but also offset relatively later (~1000 ms). These auditory–visual repetition effects were both smaller overall and absent for the two shortest prime–target intervals during the typical N400 window.

Descriptors: ERPs, N400, Repetition priming, Word recognition

Although substantial efforts have been focused on understanding mechanisms of word processing during reading and listening, comparatively little emphasis has been placed on determining the degree of interactivity between the modalities (but see Bradley & Forster, 1987; Grainger, Diependaele, Spinelli, Ferrand, & Farioli, 2003; Kouider & Dupoux, 2001). This is somewhat understandable given that most language contexts involve a single input modality and that reading and listening utilize at least some "modality specific" perceptual and neural processes. However, at another level this lack of interest is curious given the obvious importance of between-modality interactions during the acquisition of reading skills or the performance of tasks such as reading aloud. That these situations exist suggests that at some point after initial encoding a shared or "common" set of processes/representations is engaged during written and spoken word comprehension.

One model of word recognition makes specific claims about the types of between-modality interactions that occur during word recognition. That is the bimodal interactive-activation model of Grainger and Ferrand (1994) and its recent extensions (e.g., Grainger et al., 2003). In this theoretical framework there are strong reciprocal connections between orthographic and phonological representations of words at the sublexical (e.g., letters and phonemes) and lexical levels (whole-word orthographic and phonological representations). Word recognition is initially driven by representations directly tied to the modality of stimulus presentation (orthographic for visual words, phonological for auditory words). However, the strong bidirectional connections across these representations implies that the word recognition process is rapidly constrained by representations that are not directly associated with the input modality. Behavioral research has shown this to be particularly true for phonological influences on visual word recognition (e.g., Ferrand & Grainger, 1994; Lukatela & Turvey, 1994; Perfetti & Bell, 1991; Van Orden, 1987), and there is growing evidence that spoken word recognition is affected by the orthographic characteristics of words (e.g., Ziegler & Ferrand, 1998; Ziegler, Muneaux, & Grainger, 2003).

The current study examined the time course of between-modality interactivity by recording event-related brain potentials (ERPs) in a cross-modal *immediate repetition priming*[1] paradigm. This study builds on our earlier work (Anderson & Holcomb, 1995; Holcomb and Anderson, 1993) in which the semantic relationship between words was manipulated (i.e., semantic priming). Robust N400 effects were found across three prime–target intervals, including one condition where the prime and target items onset simultaneously, *within* both the visual and auditory modalities (Anderson and Holcomb, 1995). In a second study

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[1]Here we use *immediate* to refer to the type of repetition priming paradigm used by researchers in the word recognition literature to study issues at the level of lexical processing. In this literature words are typically repeated immediately, as opposed to after varying numbers of intervening unrelated words. This latter form of repetition, which is referred to as *lagged repetition priming*, is more often used to study aspects of episodic memory.

(Holcomb and Anderson, 1993) there were large *between*-modality N400 effects across prime–target intervals when the prime was a visual word and the target a spoken word. These N400 effects were obtained even when primes and targets onset simultaneously, suggesting that the two modalities interact relatively early during the processing of the meaning of words. However, this conclusion was tempered by the effects obtained when the prime was auditory and the target visual (Holcomb & Anderson, 1993, Experiment 2). In this case, between-modality N400 priming effects were robust when the interval between prime and target was relatively long (800 ms), but unlike the first experiment, there was no ERP evidence of cross-modal priming in the simultaneous onset condition. Holcomb and Anderson interpreted this difference in the time course of semantic priming effects as possibly reflecting the different temporal dynamics of word processing in the two modalities In other words, because spoken words unfold over time, there may not have been sufficient acoustic information available from the auditory primes (which averaged >500 ms in duration), especially in the shortest interval condition, to activate and establish a semantic context in time for the visual targets to benefit from the overlap in semantics. Alternatively, Holcomb and Anderson suggested that the stronger influence of visual processing might also explain the asymmetry in N400 priming effects between the modalities, as previous studies had suggested that when the modalities compete, visual stimuli tend to dominate (e.g., Colavita, 1974; Posner, Nissen, & Klein, 1976).

ERP effects of semantic priming, such as those reviewed above, are typically restricted to the N400 component. The N400 is thought to reflect, at least in part, the postlexical access process of semantic integration (e.g., Holcomb, 1993; Rugg, 1990—but see Deacon, Hewitt, Yang, & Nagata, 2000, for an alternative account of the N400 that attributes a substantial influence to automatic spreading activation). One possibility for Holcomb and Anderson's failure to find cross-modal effects in their auditory–visual simultaneous onset condition might reflect the relative insensitivity of semantic processes to the early overlap of auditory primes and visual targets. Most important, semantically related primes and targets will generally not share the kind of orthographic and phonological representation thought to be at the center of cross-modal interactions according to the bimodal model discussed above. For this reason, the present study examines repetition priming. According to the bimodal model, a word that is repeated in different modalities should benefit from rapid cross-modal transfer between sublexical and lexical representations. We therefore expect to see repetition effects that arise much earlier than in the Holcomb and Anderson (1993) study. This possibility is buttressed by findings from several sources. Unlike semantic priming, immediate repetition priming, in which the prime is immediately followed by the relevant target word, has been shown to be sensitive to word-based processes prior to semantic activation (e.g., Forster & Davis, 1984). In the case of ERPs, there is evidence that negativities in the time range of the N400 component as well as earlier and later components are sensitive to repetition.

The N400 repetition effect is thought to reflect the same postlexical integrative process found in semantic priming studies (Rugg, 1990). In other words when the target word is not a repetition of the prime, the N400 is large because it is relatively more difficult to integrate the meaning of the target into the context formed by the prime (this is the same account used to explain N400 semantic priming). When the target is a repeat of the prime, the N400 is much smaller either because semantic integration is not necessary (e.g., when the subject realizes that it is the same word) or is substantially easier (e.g., when the prime has already partially activated the meaning of the target word). This latter case might occur when prime and target temporally overlap (as in the current experiments) and there is not enough time for the prime to fully activate meaning.

In addition to repetition N400 effects, there is now evidence that an earlier N250 component reflects a process(es) directly associated with lexical or prelexical operations (Kiyonaga, Midgley, Grainger, & Holcomb, 2004; Geyer, Grainger, Holcomb, 2004; Pickering & Schweinberger, 2003), whereas a later late positive component (LPC) effect is sensitive to episodic memory processing (e.g., Olichney et al., 2000).

Thus, the primary purpose of the present study was to extend the findings of Holcomb and Anderson (1993) with semantic priming to the presumably more sensitive manipulation of immediate repetition priming. Below we report the results of two experiments that examined the time course of between-modality priming using the immediate repetition paradigm. In the first experiment, the prime word was presented in the visual modality and the target item was presented auditorily (visual/auditory). In Experiment 2, the conditions were reversed and the primes were spoken words and the targets visual (auditory/visual). A lexical decision task in which one-third of the target items were pseudowords (e.g., doctor/teble) was used in both experiments. Among the word targets, half were repetitions of the prior prime word (doctor/DOCTOR) and half were unrelated (shoe/DOCTOR). In such tasks, repetition priming effects are usually manifested by quicker and more accurate button presses to related target words compared to unrelated target words, and by smaller N250s and N400s, but larger LPCs for repeated compared to unrelated target words. As in Holcomb and Anderson (1993) the interval between prime and target was varied across three stimulus-onset asynchronies (SOAs): long (800 ms), short (200 ms), and simultaneous onset (0 ms). The rationale for this latter manipulation is that by systematically changing the temporal interval between prime and target it is possible to determine the time range of overlap in prime–target processing and therefore the time course of between-modality interactivity.

EXPERIMENT 1

The purpose of the first experiment was to explore the time course of between-modality repetition priming when the prime was visual and the target auditory. As in the previous Holcomb and Anderson (1993) study using semantic priming we predicted that there would be robust N400 priming effects across prime–target SOAs. However, because repetition priming with printed words has also been shown to modulate an earlier ERP negativity that has been proposed to reflect prelexical access processes, we predicted that a priming effect earlier than the N400 might also be obtained (Kiyonaga et al., 2004). The presence of such early effects would be consistent with between-modality interactivity occurring at the level of sublexical and lexical processing, as in the bimodal interactive activation model (Grainger & Ferrand 1994; Grainger et al., 2003). Given that repetition priming also produces differences in a post-N400 late positive component (e.g., Rugg, 1990), we also predicted that repeated auditory targets might also produce a larger late positive component than unrelated words.

Method

Participants

Sixteen right-handed Tufts University undergraduates (9 women) with a mean age of 19 years received partial course credit or \$10.00 for their participation. All of them were native speakers of English with normal visual and auditory acuity.

Stimuli and Procedure

Visual stimuli were presented on a 20-in. monitor (NEC model 5D) and auditory stimuli were presented binaurally through headphones (Sony MDR S30) both under the control of a PC computer. The participant sat in a comfortable chair in a sound-attenuating chamber. On each trial, the participant was presented with two stimuli. One (the prime) was a legal English word presented visually; the other (the target) was either a legal word or a pronounceable pseudoword that was presented auditorily through headphones. Each participant was presented with a total of 360 visual–auditory pairs, comprised of equal proportions of repeated words (e.g., pepper/PEPPER), unrelated words (e.g., window/PEPPER), and word/pseudoword (e.g., window/PAPPER) pairs. Unrelated pairs were formed by rearranging the repeated pairs so that the primes and targets did not have a semantic relationship. Pseudowords were constructed from legal words by altering one letter (phoneme) in such a way that it did not violate the orthographical or phonological rules of English. None of the pseudowords were pseudohomophones. All visual stimuli were two to seven letters in length and all auditory stimuli were of one or two syllables.

The 360 words used to make the repeated and unrelated pairs or words were arranged into six similarly constructed sublists of 40 pairs each. The 120 auditory pseudowords and their unrelated visual word primes were selected from three similarly constructed lists of 40 word–pseudoword pairs. The word pairs were counterbalanced so that, across subjects, all words appeared in both the repeated and unrelated conditions (in the latter as both a prime and target) and in each of the three SOA conditions (see below). However, within subjects, each list and therefore each stimulus was presented only once (with the exception of repeated targets). Note that this Latin Square procedure assures that all items occur in all conditions an equal number of times and that the resulting ERPs are formed from the same items across conditions and participants. In forming unrelated pairs target words were randomly paired with another item from the list to serve as the prime. These pairs were carefully checked by two experimenters to make sure there was no obvious semantic relationships between the primes and targets.

A second within-subject variable was the SOA between items in each pair. Forty stimulus pairs in each of the three target type conditions (repeated, unrelated, and pseudoword) were presented with an SOA of 0 ms (i.e., simultaneous prime and target onset), 40 others were presented with an SOA of 200 ms, and the remaining 40 were presented with an SOA of 800 ms. To summarize, each participant was presented with a total of 360 pairs of items (in a pseudorandom order) that were either repeated, unrelated, or word/pseudoword pairs, and had an SOA of either 0, 200, or 800 ms, resulting in a total of 40 stimulus pairs in each of nine conditions (three SOAs $\times$ three target types).

The visual stimuli were displayed as white lowercase letters on a black background. The auditory stimuli were spoken by a female member of our research team and were digitized at 16 kHz. Each spoken stimulus was edited so as to align word onset with ERP recording. The average duration of auditory targets was 568 ms (range 300–862 ms).

Each trial began with a warning stimulus (a red "X") in the middle of the screen. Then, 500 ms later, the visual prime word replaced the warning stimulus and remained on the screen for 200 ms. For the 0 ms SOA condition, the auditory target onset was simultaneous with the onset of the prime; for the other two SOAs, the target onset was either 200 or 800 ms after the onset of the prime. The end of the trial was indicated by the appearance of a green "X" 1500 ms after the onset of the target. This stimulus alerted the participant that it was permissible to blink. After a 1250-ms intertrial interval, the green "X" changed to a red "X" and the next trial began.

Participants were instructed to respond as quickly and accurately as possible by pressing a button labeled "YES" with one thumb if the target was a real word or a button labeled "NO" with their other thumb if it was not a real word. They were told to try to pay attention to the visual prime but not to make an overt response. The hand used for each response was counterbalanced across participants. Participants were told not to blink or move their eyes while the stimuli were being presented. The experiment lasted about 35 min, including short breaks about every 60 trials. A practice block of eight trials preceded the experiment.

EEG Procedure

Thirteen tin electrodes were held in place on the scalp with an elastic cap (Electrode-Cap International). The scalp locations included standard International 10–20 system locations over the left and right hemispheres at the frontal (F7 and F8) and occipital sites (O1 and 02) and three locations on the midline: frontal (Fz), central (Cz), and parietal (Pz). In addition, six electrodes were placed at the following nonstandard locations: left and right temporal-parietal (Wernicke's area and its right hemisphere homolog, WL and WR: 30% of the interaural distance lateral to a point 13% of the nasion–inion distance posterior to Cz); left and right temporal (TL and TR: 33% of the interaural distance lateral to Cz); and left and right anterior-temporal (ATL and ATR: 50% of the distance between T3/4 and F7/8). To monitor for eyeblinks, one electrode was placed below the left eye, and to monitor for horizontal eye movement, an electrode was placed lateral to the right eye. All the electrodes were referenced to the left mastoid, and the right mastoid was recorded from actively.

The electroencephalogram (EEG) was amplified by a Grass Model 12 amplifier system using a bandpass of 0.01 to 30 Hz (3 dB cutoff). The EEG was sampled continuously throughout the experiment (200 Hz), and off-line, separate ERPs were averaged (using a pretarget baseline of 100 ms) for each participant at each electrode site for the three target types (related, unrelated, and pseudoword) at each of the three SOAs. Only correct response trials that were free of eye and muscle artifact were included. In addition, difference waves were formed by subtracting the ERPs of the related condition from the ERPs of the unrelated condition.

Data Analysis

To carefully evaluate the time course of priming effects, ERPs to target words were quantified by measuring mean amplitudes relative to the 100-ms pretarget onset period in four successive 100-ms temporal windows from 100 ms after target onset until the end of the window typically used to measure the N400 (i.e., 500 ms). Two final "late" windows encompassing activity after the N400 were also measured (500 to 700 ms and 700 to 1000 ms).

These latter two windows were included because of obvious late activity in some of the conditions. We did not analyze the ERPs to pseudoword targets because these items did not include the repetition factor and because although they were formed from words that were of similar characteristics to the target words, they were not matched precisely for visual/acoustic similarity with the word targets. In analyzing the behavioral data (RTs and percent correct responses) we did include the pseudoword data. We deemed the "lexicality" factor to be an important one in demonstrating the basic behavioral effect of slower RTs to pseudowords in the lexical decision task.

Repeated-measures analyses of variance (ANOVAs) were performed on the above dependent measures with Repetition (repeated vs. unrepeated) and SOA (0 vs. 200 vs. 800 ms) as the primary factors in the ERP analyses. In the RT and percent correct analyses we also analyzed target Lexicality (word vs. pseudoword). In ERP analyses midline and lateral sites were analyzed separately. In midline analyses, in addition to Repetition and SOA, there was an anterior–posterior factor of Electrode Site (Fz vs. Cz vs. Pz). For lateral analyses the anterior–posterior factor of Electrode Site spanned five successive sites (F7/8 vs. ATL/R vs. TL/R vs. vs. PL/R vs. O1/2) and there was also a factor of Hemisphere (left vs. right). Significant Repetition × SOA interactions were followed up with simple effects tests to help elucidate the source of the interaction. This involved analyzing the effects of Repetition separately for each SOA. The Geisser–Greenhouse (1959) correction was applied to all analyses with more than one degree of freedom in the numerator.

Results

Behavioral Findings

As is typical in lexical decision experiments using wordlike pseudowords, participants were significantly faster and more accurate responding to auditory target words than pseudowords (main effect of target Lexicality, RT: $F[1,15] = 131.03$, $p < .001$; percent correct: $F[1,15] = 44.02$, $p < .001$). In addition, repeated words were responded to significantly faster and more accurately than unrelated words (main effect of Repetition, RT: $F[1,15] = 186.90$, $p < .001$; percent correct: $F[1,15] = 14.14$, $p < .002$; see Table 1). The RT (but not percent correct) repetition effect varied somewhat as a function of SOA (SOA × Repetition interaction: $F[2,30] = 4.86$, $p < .029$, epsilon = .68). Follow-up analyses revealed that there were significant RT effects of repetition at all three SOAs (main effect of Repetition, 0 SOA, $F[1,15] = 150.16$, $p < .001$; 200 SOA, $F[1,15] = 172.48$, $p < .001$; 800 SOA, $F[1,15] = 107.24$, $p < .001$), but that repeated targets differed across the SOAs (repeated: $F[2,30] = 10.22$, $p < .001$, epsilon = .79; unrelated: $F < 1.4$).

Table 1. *Mean Reaction Time and Percent Correct Target Performance in Experiment 1*

SOA	Trial type	Mean RT	Std. error	Mean % correct	Std. error
0-ms SOA	Repeated	740	23.8	98.1	0.8
	Unrelated	907	16.7	95.8	0.9
	Pseudoword	986	22.2	89.5	1.6
200-ms SOA	Repeated	698	24.3	97.5	0.9
	Unrelated	902	16.6	95.3	0.9
	Pseudoword	958	19.3	89.1	2.1
800-ms SOA	Repeated	679	25.2	98.9	0.6
	Unrelated	892	15.4	95.6	0.9
	Pseudoword	960	19.3	92.7	1.4

Visual Inspection of ERPs

As can be seen in Figures 1 to 3 the target ERPs in this experiment consisted of an early widely distributed negativity (N1) that peaked at about 100 ms and was followed by a positivity (P2) that peaked at about 200 ms. Note, however, that the P2 was markedly smaller in the 200-ms and 800-ms conditions than the 0 ms condition. This was likely due to the former two ERPs being primarily the exogenous response to the auditory target word and the latter being a compound ERP resulting from the simultaneous onset of the visual prime and auditory target. Note also that in the 200-ms SOA condition (Figure 2) there is residual activity in the early part of the waveform due to the overlap of the visual P2 from the prime (visible primarily as a large positivity at time 0).

Following the P2 component the waves in all three SOA conditions diverged markedly as a function of repetition, with repeated words producing a more positive-going ERP than that produced by unrepeated words. Depending on the site, this difference persisted until between 700 ms and the end of the recording epoch.

Analyses of ERP Data

100–200-ms epoch. Unrelated auditory targets produced more negative-going ERPs than auditory words that were a repetition of the visual prime (main effect of Repetition, midline, $F[1,15] = 7.70$, $p < .014$). Over the lateral electrode sites this repetition effect was larger over the right than the left hemisphere (Repetition × Hemisphere interaction, $F[1,15] = 9.46$, $p < .008$). Also at midline sites there was a repetition × SOA interaction, $F(2,30) = 3.44$, $p < .048$, epsilon = .96. Follow-up analyses revealed that the effects of repetition were significant in the 200-ms, $F(1,15) = 9.13$, $p < .009$, and 800-ms SOA conditions, $F(1,15) = 8.07$, $p < .012$, but not in 0-ms SOA condition, all Fs involving Repetition < .6.

200–300-ms epoch. The effects of repetition continued at both midline and lateral sites in this time window (midline: $F[1,15] = 41.98$, $p < .001$; lateral: $F[1,15] = 29.06$, $p < .001$), again reflecting the fact that unrelated auditory target words produced more negative-going ERPs than repeated auditory targets. There was also a difference in the repetition effect as a function of SOA (Repetition × SOA midline: $F[2,30] = 9.74$, $p < .002$, epsilon = .77; lateral: $F[2,30] = 4.08$, $p < .033$, epsilon = .87). Follow-up analyses indicated that the repetition effect was significant in this epoch for both the 200-ms (midline: $F[1,15] = 26.86$, $p < .001$; lateral: $F[1,15] = 17.33$, $p < .001$) and 800-ms SOA conditions (midline: $F[1,15] = 25.10$, $p < .001$; lateral: $F[1,15] = 14.77$, $p < .002$), but not the 0-ms SOA condition, all Fs involving Repetition < 1.0.

300–400-ms epoch. The effects of repetition continued into this, the beginning of the traditional N400 epoch. Unrelated auditory target words produced more negative-going ERPs than repeated auditory target words (midline: $F[1,15] = 86.23$, $p < .001$; lateral: $F[1,15] = 77.84$, $p < .001$). There was again a Repetition × SOA interaction (midline: $F[2,30] = 8.58$, $p < .002$, epsilon = .85; lateral: $F[2,30] = 5.68$, $p < .011$, epsilon = .89), indicating that the repetition effect continued to be larger in the 200- and 800-ms SOA conditions than the 0-ms SOA condition.

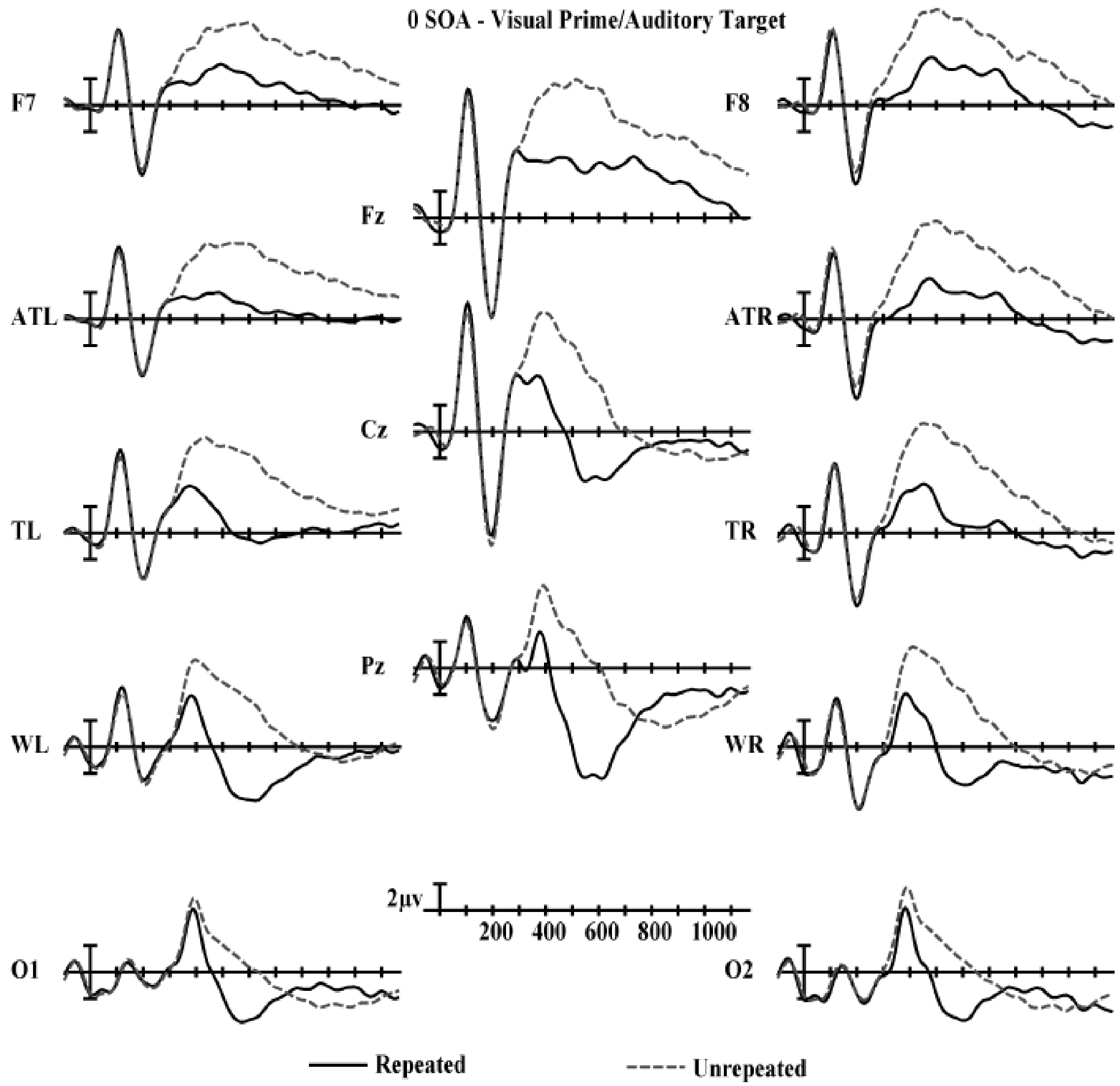

Figure 1. Compound ERPs to visual primes and auditory targets in the 0-ms SOA condition at 13 scalp sites. Note that primes and targets onset simultaneously in this figure and that negative is plotted up.

However, follow-up analyses revealed that for the first time the Repetition effect was significant at all three SOAs (0-ms SOA, midline: $F[1,15] = 11.31$, $p < .004$; lateral: $F[1,15] = 12.10$, $p < .003$; 200-ms SOA midline: $F[1,15] = 111.93$, $p < .001$; lateral: $F[1,15] = 87.5$, $p < .001$; 800-ms SOA, midline: $F[1,15] = 63.41$, $p < .001$; lateral $F[1,15] = 48.71$, $p < .001$). Interestingly, the pattern of repetition effects across the scalp differed as a function of SOA (Repetition × SOA × Electrode Site, midline: $F[4,60] = 3.22$, $p < .046$, epsilon = .57; lateral: $F[8,120] = 5.95$, $p < .007$, epsilon = .24). These analyses indicted that although the 200- and 800-ms SOAs tended to produce larger repetition effects over more central and posterior sites, the 0-ms SOA condition produced larger effects at more anterior sites (see Figures 1 to 3).

400–500-ms epoch. The effects of repetition continued into this epoch (midline: $F[1,15] = 133.43$, $p < .001$; lateral: $F[1,15] = 156.59$, $p < .001$) although there was not a significant difference in the size of this effect across SOAs (Repetition × SOA interactions, $F\text{s} < 3.0$). However, there was a difference in the distribution of repetition effects across the SOAs (Repetition × SOA × Electrode Site, lateral: $F[8,120] = 4.01$, $p < .013$, epsilon = .37). As indicated in Figures 1 to 3, although the 200- and 800-ms SOA repetition effects continued to be largest at temporal-parietal sites and smallest at frontal sites, the 0-ms SOA condition produced a somewhat more anterior pattern, with the smallest effects over occipital sites.

500–700-ms epoch. Unrelated auditory targets continued to produce more negative-going ERPs then repeated auditory targets (midline: $F[1,15] = 111.83$, $p < .001$; lateral: $F[1,15] = 154.12$, $p < .001$). There was also a Repetition × SOA × Electrode Site interaction (midline: $F[4,60] = 5.46$, $p < .004$, epsilon = .69; lateral: $F[4,120] = 7.11$, $p < .001$, epsilon = .41). Examination of Figures 1 to 3 suggests that for the first time the 0-ms SOA condition produced a more temporal-parietal pattern of repetition effects, whereas the 200-ms and especially the 800-ms SOAs produced a somewhat more frontal repetition effect.

700–1000-ms epoch. In this final epoch there was again a main effect of Repetition but only at lateral sites (lateral, $F[1,15] = 14.58$, $p = .002$; midline $F < 1.3$). There were also Repetition × Electrode Site interactions (midline: $F[2,30] = 114.07$, $p < .001$,

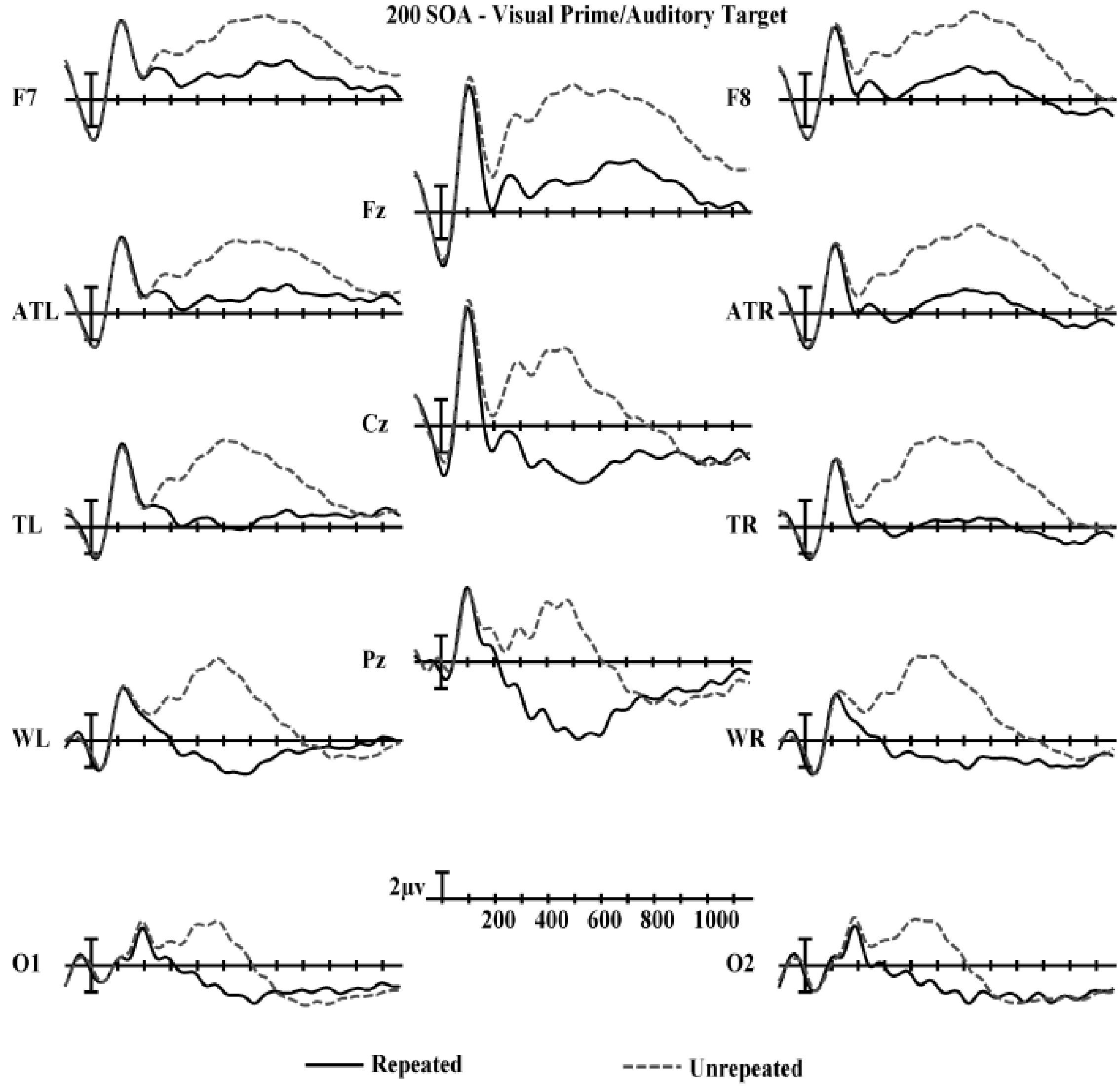

Figure 2. Compound ERPs to visual primes and auditory targets in the 200-ms SOA condition. Note that in this figure auditory targets onset at the vertical calibration bar and visual primes onset 200 ms earlier. Negative is up.

epsilon = .92; lateral: $F[4,60] = 78.31$, $p < .001$, epsilon = .58). This latter effect was due to an attenuation and eventually a reversal of the Repetition effect going toward the back of the head (main effect of Repetition at F7/8 unrelated targets more negative-going than repeated targets, $F[1,15] = 55.01$, $p < .001$; at O1/O2 unrelated targets marginally more positive-going than repeated targets, $F[1,15] = 4.10$, $p = .061$; see Figures 1 to 3).

Summary. Auditory target words following unrelated visual prime words produced more negative-going ERPs than auditory target words following the same (repeated) visual word primes. In the 200- and 800-ms SOA conditions these repetition effects began as early as the 100–200 ms epoch and continued as late as 1000 ms. In the 0-ms SOA condition the effects of repetition started later in the 300–400-ms epoch and had a more anterior scalp distribution until the 500–700-ms epoch, when they became more posterior.

Discussion

Experiment 1 examined cross-modal immediate repetition priming while varying the interval between the onset of a visual prime word and auditory targets. There were large and long-lasting repetition effects starting as early as the 100- to 200-ms window and lasting at least until 1000 ms post-target onset. Within both the N400 region ($\sim$300 to 500 ms) and the late positive component (500 to 700 ms) the effects of repetition were present at all three SOAs.

Interestingly, the scalp distribution of repetition effects changed as a function of the measurement window, suggesting that more than one ERP component was influenced by repetition. In the two earliest windows to show repetition effects (100 to 200 ms and 200 to 300 ms) both the 200-ms SOA and the 800-ms SOA conditions showed their largest repetition effects at anterior sites and over the right hemisphere. In subsequent windows (300 to 400 ms and 400 to 500 ms) this distribution shifted to more posterior sites consistent with the typical N400 effect. For the 0-ms SOA condition a similar pattern was obtained (i.e., early anterior and later posterior); however, in this case the pattern was delayed by about 200 ms, with the frontal pattern starting in the 300–400-ms window and the posterior pattern in the 500–700-ms window. The early similarity of priming effects in

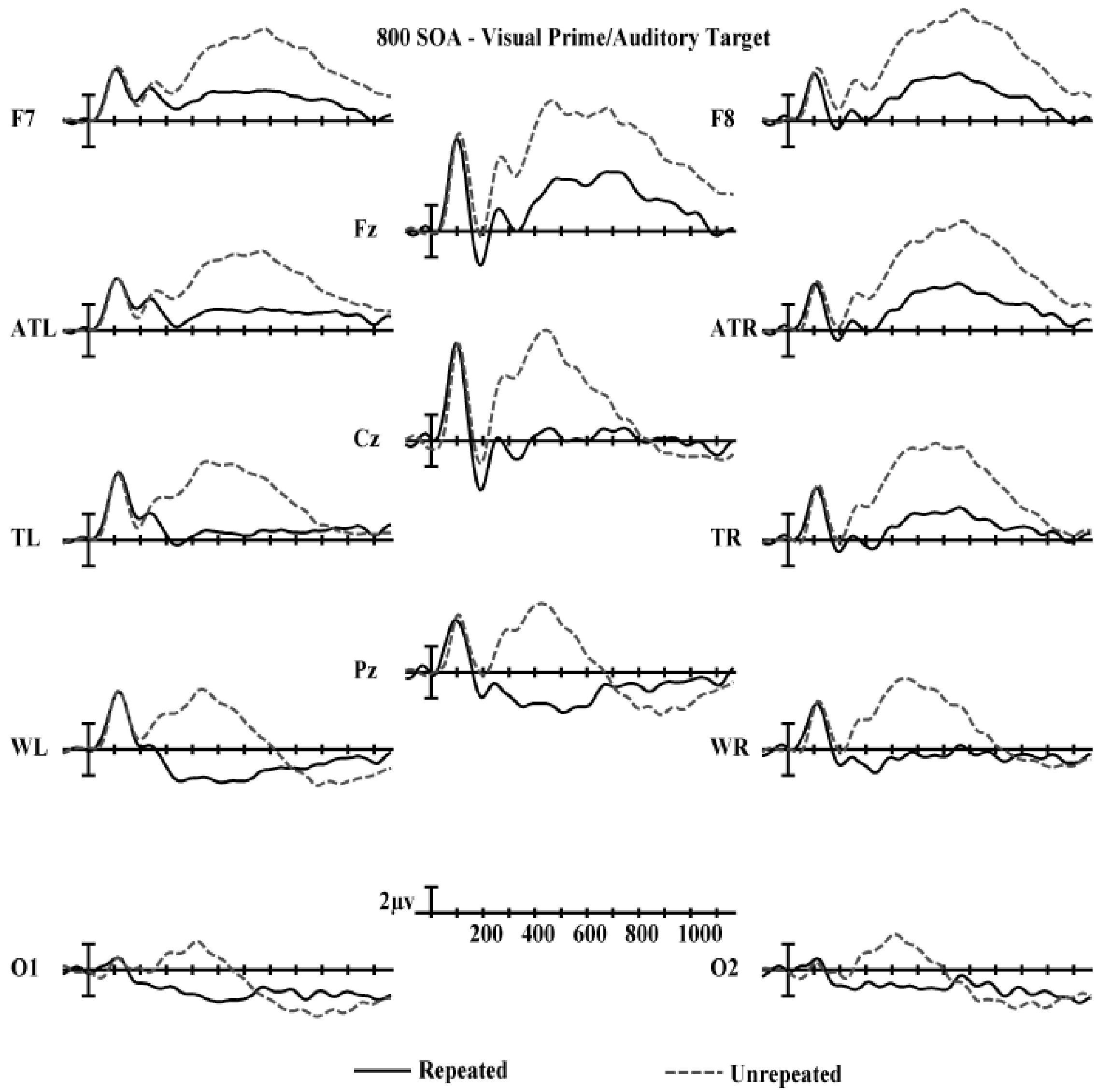

Figure 3. ERPs to visual primes and auditory targets in the 800-ms SOA condition. Note that in this figure auditory targets onset at the vertical calibration bar and visual primes onset 800 ms earlier.

the 200- and 800-ms SOA conditions along with the approximately 200-ms delay in the simultaneous onset condition suggests that 200 ms is a good estimate of the amount of time needed to process a visual word to a level sufficient to support full repetition priming of words presented auditorily.

The overall pattern of cross-modal N400 effects seen in this experiment are quite similar to those reported by Holcomb and Anderson (1993) for between-modality visual–auditory priming using an identical SOA manipulation but with semantic rather than repetition priming. The biggest differences between the studies is that the current effects started earlier (in the 100–200-ms window vs. the 200–300-ms windows for Holcomb & Anderson) and Holcomb and Anderson did not find such a large difference in the onset of priming effects between the SOAs. In fact, for semantic priming the 0-ms SOA condition produced a slightly earlier priming effect than either the 200- or 800-ms SOA conditions. The earlier effects of cross-modal repetition priming found in Experiment 1 are in line with the predictions of the bimodal interactive activation model (Grainger & Ferrand, 1994; Grainger et al., 2003). According to this model, a visually presented prime word will rapidly generate activation in appropriate orthographic and phonological representations. Thus, when the target is the same word as the prime, then processing of this target word is very quickly affected by the fact that appropriate phonological representations are already activated (in the 200-ms and 800-ms SOA conditions).

A final difference between studies is that with semantic priming (Holcomb & Anderson, 1993) all of the later effects of priming seemed to center on the N400, whereas in the current study there were clear repetition effects occurring on a separate late positive component (see Figures 1 to 3). Repeated words had a notable positive component peaking around 600 ms and unrelated words produced little positive-going activity at all until very late ($\sim$ 900 ms). These differences between studies are likely due in part to the current repetition manipulation being sensitive to both semantic influences on the N400 as well as earlier lexical influences on pre-N400 negativities and later episodic influences on the late positive component. The semantic priming manipulation in Holcomb and Anderson was most likely sensitive only to the semantic influences on the N400.

EXPERIMENT 2

The bimodal interactive activation model predicts that cross-modal interactions should occur in both directions, from auditory to visual as well as from visual to auditory. However, there is evidence that the strength of across-modality interactions might not be equivalent for these two directions. This could be due to possible differences in the speed with which phonological information can be derived from a printed word on the one hand and with which orthographic information can be derived from a spoken word on the other. Although both behavioral and electrophysiological evidence concur in favor of an early availability of phonological information during visual word recognition, there is not yet clear evidence as to just how early orthographic information is available during auditory word recognition.

A clear asymmetry in across-modality priming was reported by Holcomb and Anderson (1993). Recall that Holcomb and Anderson reported N400 effects across SOAs in their visual–auditory semantic priming experiment whereas in the auditory–visual experiment N400 effects were notable only at the longest SOA (800 ms). They attributed these prime–target order differences to the different time courses of information availability for written and spoken word processing. Although spoken words revealed early sensitivity to semantic influences when they were the target, they nevertheless did not reciprocally constrain the semantic processing of a simultaneously presented visual or other auditory targets when they were the prime (Anderson & Holcomb, 1995; Holcomb & Anderson, 1993). Visual words on the other hand revealed relatively later effects of priming when they were the targets, but influenced the semantic processing of other visual or auditory targets very quickly when they served as primes. However, as pointed out in the introduction, semantic priming produces differences almost exclusively on the N400. Immediate repetition priming in the visual modality on the other hand has been shown to produce semantic (N400) as well as other earlier prelexical effects (Geyer et al., 2004; Kiyonaga et al., 2004), although there are no published reports of what effects immediate repetition have in the case of auditory primes. If the lack of significant priming effects at short SOAs in Holcomb and Anderson (1993) was due to insufficient time for auditory–visual semantic overlap, then it is still possible that evidence for prelexically based priming effects resulting from the interaction of written and spoken word sublexical codes could nevertheless be found. The rationale for this prediction is based on the assumption from the bimodal interactive activation model that sublexical information should on average be active sooner than semantic information. In other words, the initial acoustic information in an auditory prime could rapidly cross-activate the word initial orthographic representation of the visual target. This would presumably show up in one of the early repetition sensitive ERPs components such as the N250.

Thus, the goal of Experiment 2 was to extend the repetition manipulation to the auditory–visual case. Like Holcomb and Anderson (1993) we predicted that N400 (semantic) effects would be robust only at longer prime–target intervals due to differences in the time course of written and spoken word processing. However, because repetition priming has been shown to produce differences in earlier lexically sensitive ERP components, we also predicted that earlier repetition effects might be seen at shorter prime–target intervals as well. A comparison of Experiments 1 and 2 will provide more critical information on possible asymmetries in cross-modal interactions during word recognition. Procedurally, Experiment 2 was identical to Experiment 1 with one exception: In Experiment 2 the primes were auditory and the targets visual. Otherwise the stimuli, task, and presentation parameters were the same as those used in Experiment 1.

Method

Participants

Sixteen right-handed Tufts University undergraduates (9 women) with a mean age of 20 years received partial course credit or $10.00 for their participation. All were native speakers of English with normal visual and auditory acuity.

Stimuli and Procedure

The stimuli and procedure were identical to Experiment 1 with the exception that primes were all spoken words and targets were visually presented words and pseudowords. Participants were instructed to respond as quickly and accurately as possible by pressing a button labeled "YES" with one thumb if the visual target was a real word or a button labeled "NO" with their other thumb if it was not a real word. They were told to try to pay attention to the spoken prime but not to make an overt response. Participants were told not to blink or move their eyes while the stimuli were being presented.

Results

Behavioral Findings

As in Experiment 1, subjects were significantly faster and more accurate responding to visual target words than pseudowords (RT: $F[1,15] = 102.26$, $p < .001$; percent correct: $F[1,15] = 17.31$, $p < .001$; see Table 2) and repeated words were responded to significantly faster and more accurately than unrelated words (main effect of Repetition, RT: $F[1,15] = 59.76$, $p < .001$; percent correct: $F[1,15] = 17.64$, $p < .001$; see Table 2). The RT (but not percent correct) repetition effect varied as a function of SOA (SOA $\times$ Repetition interaction: $F[2,30] = 15.91$, $p < .001$, epsilon = .94). Follow-up analyses indicated that the Repetition effect was significantly larger in the 800-ms SOA than either the 200- or 0-ms SOA conditions (200-ms vs. 800-ms: $F[1,15] = 20.17$, $p < .001$; 0-ms vs. 800-ms: $F[1,15] = 22.15$, $p < .001$).

Table 2. *Mean Reaction Time and Percent Correct Target Performance in Experiment 2*

SOA	Trial type	Mean RT	Std. error	Mean % correct	Std. error
0-ms SOA	Repeated	644	22.9	97.2	1.2
	Unrelated	685	27.5	97.2	1.3
	Pseudoword	790	22.8	94.7	1.1
200-ms SOA	Repeated	610	20.4	98.6	1.0
	Unrelated	657	25.4	96.9	1.1
	Pseudoword	749	26.0	94.7	1.3
800-ms SOA	Repeated	531	21.3	97.5	1.1
	Unrelated	645	21.8	95.9	1.2
	Pseudoword	733	26.7	93.7	1.3

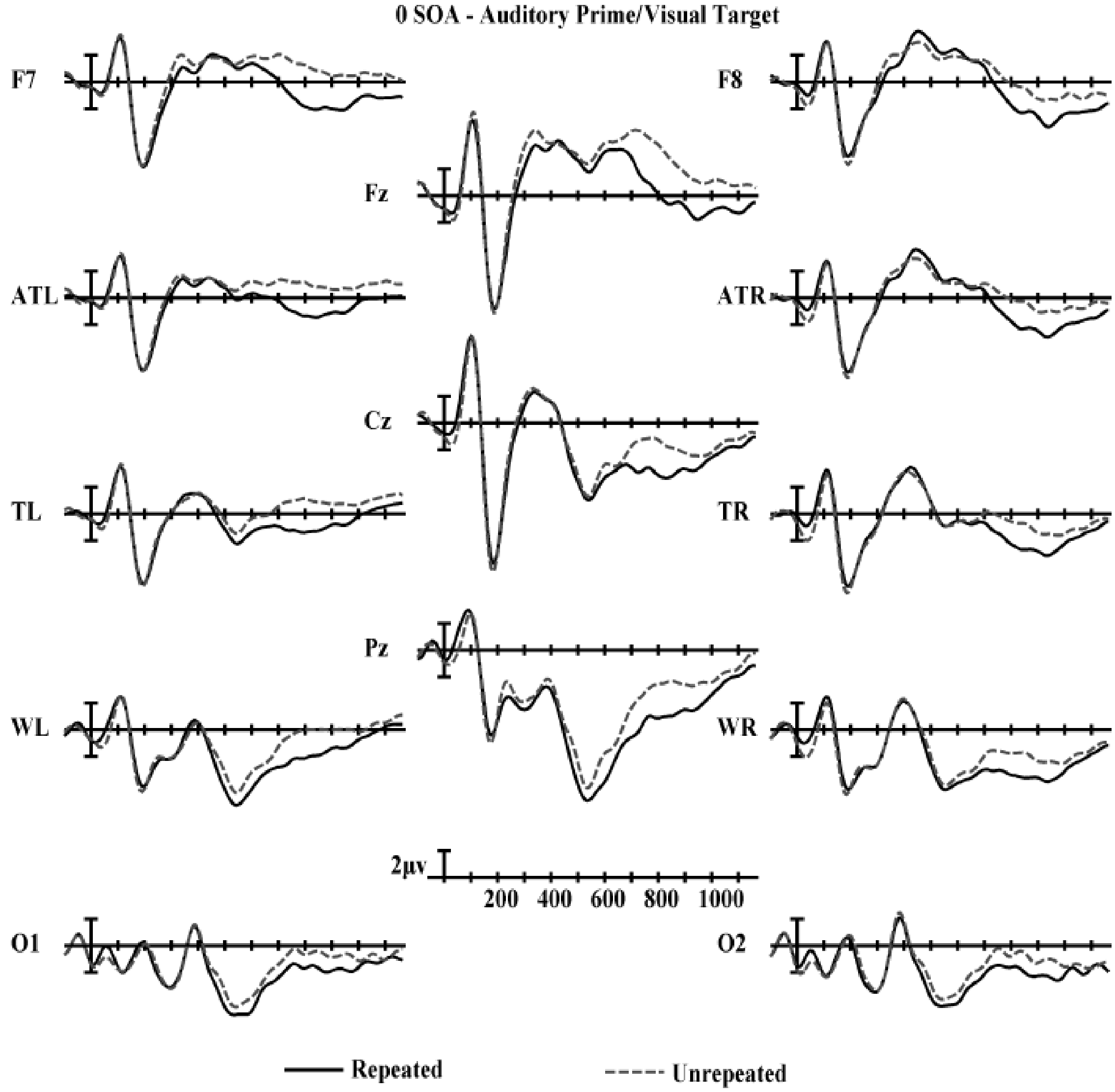

Figure 4. Compound ERPs to auditory primes and visual targets in the 0-ms SOA condition at 13 scalp sites in Experiment 2. Note that primes and targets onset simultaneously in this figure and that negative is plotted up.

Visual Inspection of ERPs

As can be seen in Figures 4 to 6 the target ERPs in this experiment consisted of an early widely distributed negativity (N1) that peaked at about 100 ms and was followed by a positivity (P2) that peaked at about 200 ms. Note that as in Experiment 1 in the 200-ms SOA condition (Figure 5) there is residual activity in the early part of the waveform due to the overlap of the auditory P2 from the prime (visible as a large positivity at time 0). After these early components the waves differed substantially from those in Experiment 1 (cf. Figures 1–3 and 4–6).

Analyses of ERP Data

100–200-ms epoch. Unlike Experiment 1, there were no effects of repetition in this epoch (all *F*s involving the repetition factor <1.3).

200–300-ms epoch. As can be seen in Figures 4 to 6, the first effects of repetition started in this epoch. Visual target words paired with unrelated auditory primes produced significantly more negative-going ERPs than visual target words that were repetitions of their auditory primes (Repetition, midline: $F[1,15] = 17.40$, $p < .001$; lateral: $F[1,15] = 12.86$, $p < .003$). These effects of repetition at lateral sites were larger over the right than left hemisphere (Repetition $\times$ Hemisphere interaction: $F[1,15] = 8.90$, $p < .009$). Although statistical evidence of a difference in repetition effects for the different SOAs did not reach conventional levels of significance (Repetition $\times$ SOA, midline, $F[2,30] = 2.70$, $p = .087$, epsilon = .95; lateral $p > .15$), examination of Figures 4 to 6 suggests that the 0-ms SOA condition produced smaller and more spatially restricted repetition effects than the 200- and 800-ms conditions. Follow-up analyses examining the three SOAs separately revealed clear Repetition effects for the 200-ms (midline: $F[1,15] = 7.86$, $p < .013$) and 800-ms SOA conditions (midline: $F[1,15] = 18.51$, $p < .001$) but in the 0-ms SOA condition, although there was not an overall effect of Repetition ($F < 1.5$), there was a small but significant effect at the midline parietal site (Pz: $F[1,15] = 4.65$, $p < .048$; see Figure 4).

300–400-ms epoch. Unrelated visual targets continued to produce more negative-going ERPs than repeated visual targets

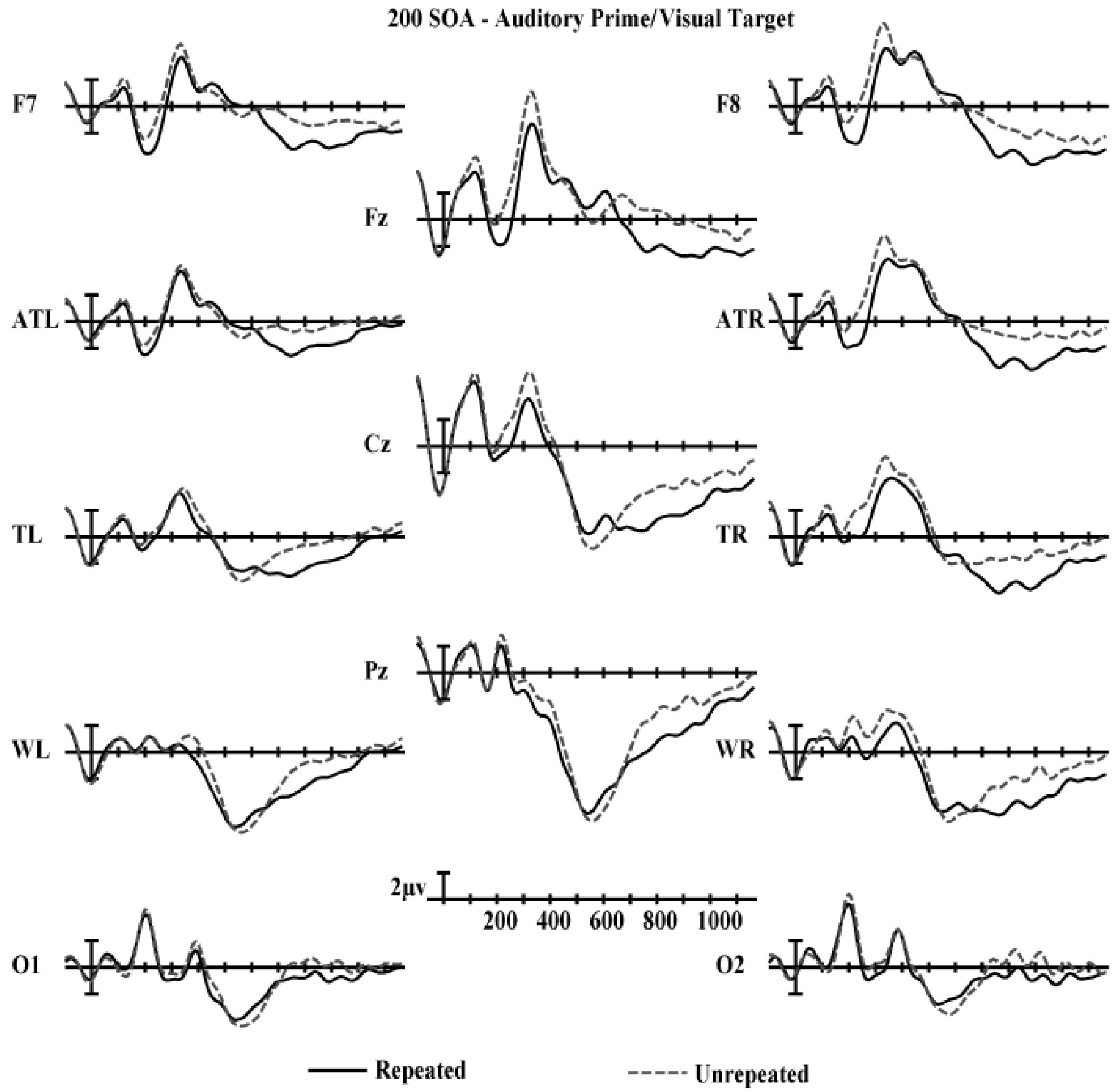

Figure 5. Compound ERPs to auditory primes and visual targets in the 200-ms SOA condition at 13 scalp sites in Experiment 2. Note that targets onset at the vertical calibration bar and primes 200 ms earlier.

(Repetition, midline: $F[1,15] = 10.24$, $p < .006$; lateral: $F[1,15] = 6.09$, $p < .026$). There was also a significant difference in the size of the priming effect as a function of SOA (Repetition $\times$ SOA interaction, midline $F[2,30] = 4.40$, $p < .024$, epsilon = .93; Repetition $\times$ SOA $\times$ Electrode Site interaction, lateral $F[8,120] = 7.01$, $p = .001$). Follow-up analyses indicated that only the 800-ms SOA condition produced robust Repetition effects (midline: 800-ms SOA, $F[1,15] = 13.37$, $p < .002$; Repetition $\times$ Electrode Site interaction, lateral: 800-ms SOA, $F[4,60] = 10.66$, $p < .001$, epsilon = .50; all 0- and 200-ms SOA Repetition effects, $Fs < 1.8$).

400–500-ms epoch. Although there was not a main effect of Repetition there were differences in Repetition across the three SOAs as a function of Electrode Site (Repetition $\times$ SOA $\times$ Electrode Site interaction, midline: $F[4,60] = 5.17$, $p < .006$, epsilon = .64; Repetition $\times$ SOA $\times$ Electrode Site, lateral: $F[8,120] = 3.42$, $p < .022$, epsilon = .40). Follow-up analyses indicated that these effects were due to the beginning of what eventually becomes a reversal in the polarity of the Repetition effect in the 800-ms SOA condition (800-ms SOA, Repetition $\times$ Electrode Site interaction, midline: $F[2,30] = 11.34$, $p < .002$, epsilon = .63; lateral: $F[4,60] = 10.63$, $p < .001$, epsilon = .47). Neither the 0- or 200-ms SOA conditions produced Repetition effects in this epoch (both $Fs < 1.0$).

500–700-ms epoch. As in the previous epoch there were no main effects of Repetition ($Fs < 2.1$), but there were Repetition $\times$ SOA interactions (midline: $F[2,30] = 8.10$, $p < .002$, epsilon = .94; lateral: $F[2,30] = 8.21$, $p < .002$, epsilon = .91). Follow-up analyses indicated that the 800-ms SOA condition continued its trend of producing larger positive-going ERPs in the unrelated condition (800-ms SOA Repetition effect, midline, $F[1,15] = 10.49$, $p = .006$; lateral, $F[1,15] = 10.45$, $p = .006$). Neither the 0- or 200-ms SOA conditions produced significant Repetition effects ($Fs < 1.9$).

700–1000-ms epoch. There were main effects of Repetition (midline: $F[1,15] = 16.11$, $p < .001$; lateral: $F[1,15] = 20.63$, $p < .001$) with unrelated visual targets producing more negative-going ERPs than repeated visual targets. And at lateral sites the effects of Repetition interacted with SOA (lateral:

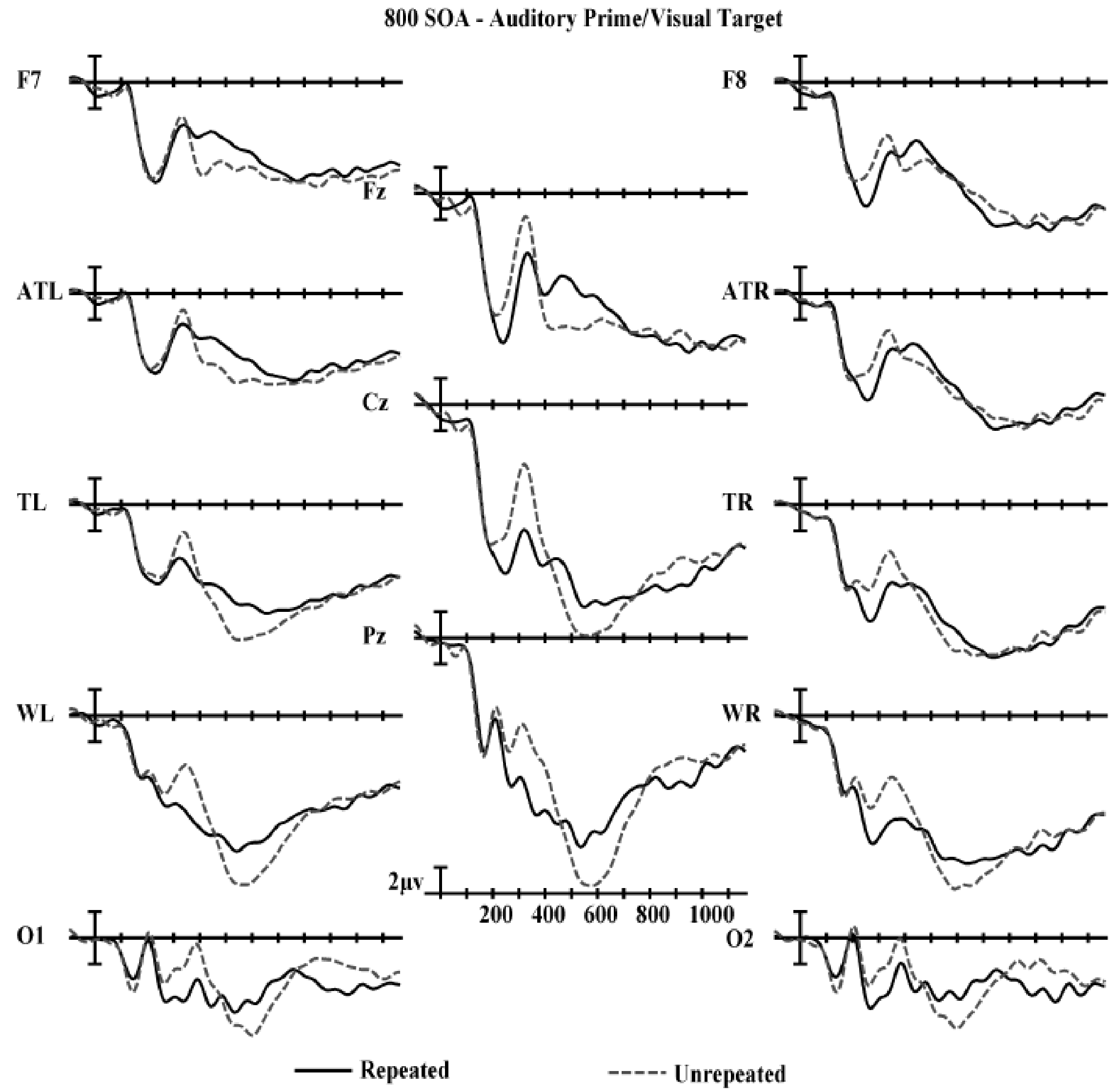

Figure 6. ERPs to auditory primes and visual targets in the 800-ms SOA condition at 13 scalp sites in Experiment 2. Note that targets onset at the vertical calibration bar and primes 800 ms earlier.

$F[2,30] = 7.62$, $p = .002$, epsilon = .98; midline $p > .09$). Follow-up analyses indicated that only the 0- and 200-ms conditions produced significant repetition effects in this epoch (0-ms SOA, $F[1,15] = 42.51$, $p < .001$; 200-ms SOA $F[1,15] = 19.61$, $p < .001$; 800-ms SOA $p > .65$).

Summary. The effects of Repetition began in the 200–300-ms epoch, but were significant only for the 200- and 800-ms SOAs. In the next three epochs (300–400, 400–500, and 500–700 ms) only the 800-ms SOA condition produced significant Repetition effects and in the latter two epochs (500–700 and 700–1000 ms) the 800-ms SOA repetition effect reversed in polarity, with repeated visual targets producing larger negativities than unrelated targets. Only in the final epoch did the 0- and 200-ms SOA conditions produce significant repetition effects.

Discussion

Experiment 2 examined cross-modal immediate repetition priming with auditory primes and visual targets with varying intervals between prime and target onset. In this experiment the effects of immediate repetition priming in the traditional N400 epoch (300–500 ms) were relatively small, especially in the 0- and 200-ms SOA conditions. At these two shortest SOAs the largest effects of repetition occurred relatively late in the target epoch (700–1000 ms). Only at the longest SOA, when the auditory prime onset 800 ms before presentation of the visual target, were there clear repetition effects in the traditional N400 epoch (i.e., 300–500 ms). However, even in the 800-ms condition, the N400-like effects of repetition were short-lived and by 500 ms actually reversed in polarity, with unrelated visual targets producing more positive-going ERPs than repeated targets.

The overall pattern of N400-like effects found in Experiment 2 are similar to those reported by Holcomb and Anderson (1993) with semantic rather than repetition priming. They reported small but significant N400 effects for visual targets preceded by auditory primes at 800 ms, but no priming effects at 200 and 0 ms. However, unlike Holcomb and Anderson, the current experiment did find evidence for earlier ‘‘pre-N400’’ priming effects between 200 and 300 ms. Moreover, evidence for pre-N400 effects was found even in the two shortest SOAs conditions (albeit rather weak

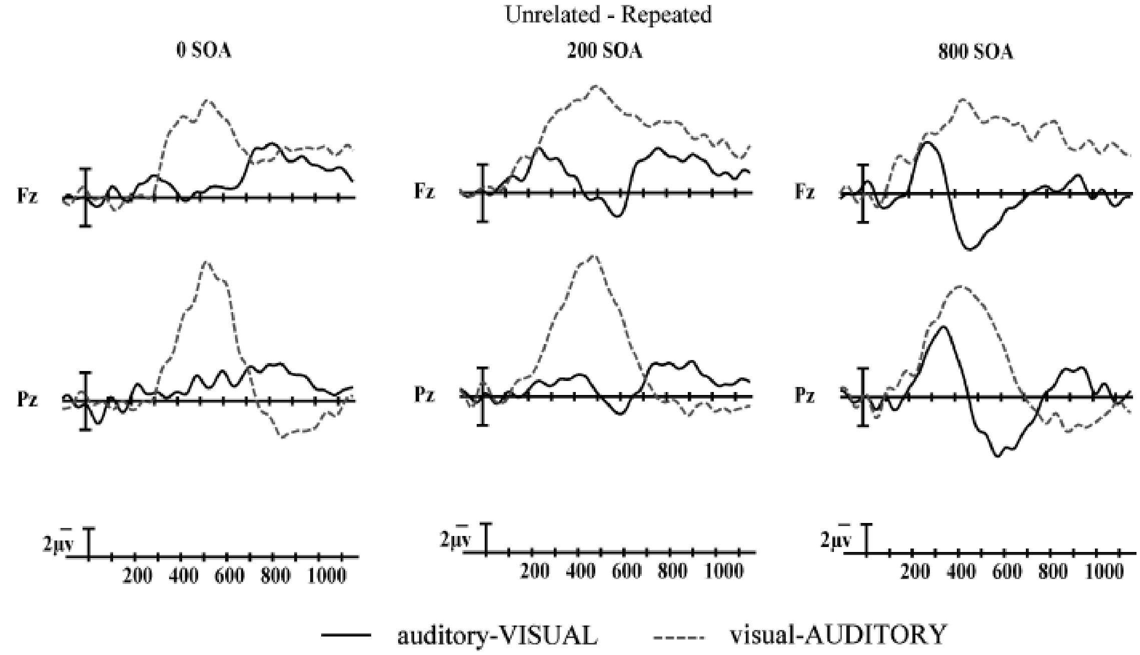

Figure 7. Difference waves computed by subtracting repeated target ERPs from unrelated target ERPs for each of the three SOAs and the two target modalities/experiments (dashed line = visual–AUDITORY Experiment 1, solid line = auditory–VISUAL Experiment 2) at the midline frontal (Fz) and parietal (Pz) sites.

evidence in the case of the 0-ms SOA condition, with effects being limited to a single site). This discrepancy in findings across studies is consistent with the predictions of the bimodal interactive activation model, made in the introduction. According to this model, repetition priming affects early prelexical processes that are not revealed in semantic priming paradigms when primes and targets do not share orthographic and phonological representations.

Evidence that the pre-N400 priming effects (200–300 ms) were on a different component than the N400 itself comes from the difference in scalp distribution for the early repetition effects compared to the effects that occurred in the N400 and later windows. In the early window, repetition effects had a clearly more anterior distribution and were larger over the right than left hemisphere for the 200- and 800-ms SOAs. The later effects of repetition tended to be more equally distributed across the scalp as is typical for the N400. Although in the 0-ms SOA condition frontal effects of repetition started somewhat later (300–400 as opposed to 200–300 ms), they were nevertheless more anterior in their distribution.

The failure to find the typical late positive repetition effect was unexpected. In fact, the unrelated target ERPs produced the larger late positivity in this experiment, at least in the 800-ms SOA condition. Why only the unrelated targets at this SOA produced such an effect is not clear. However, one possibility is that similar effects were masked in the simultaneous and 200-ms SOA conditions. Examination of Figures 5 and 6 suggests that the late positivity peaking near 600 ms may have been attenuated by a late negative wave that peaked around 800 ms. We will return to this finding in the General Discussion.

Between-Experiment Comparisons

To quantify the obvious qualitative differences in repetition effects between Experiments 1 and 2 as can bee seen in Figures 1 to 6, we used the same measurement epochs, but contrasted mean amplitudes in *difference waves* computed by subtracting repeated target ERPs from unrelated target ERPs. This approach avoids inherent differences in modality-specific waveform morphology (which make direct comparisons of auditory and visual ERPs problematic) because such differences are removed as part of the subtraction process. The resulting waveforms reflect the pure effects of repetition, which can then be compared across modalities.

As can be seen in Figure 7 there were large differences in Repetition effects between the experiments that extended across a wide range of latencies. Starting in the 200–300-ms window there were significant differences between the experiments with auditory targets following visual primes (Experiment 1) revealing larger repetition effects than visual targets following auditory primes (Experiment 2) especially over right hemisphere anterior sites (Experiment × Hemisphere × Electrode Site interaction: $F[1,30] = 6.18$, $p < .002$). Large differences in repetition effects between experiments were also apparent across the next three measurement epochs (300–400 ms, midline: $F[1,30] = 19.31$, $p < .001$; lateral: $F[1,30] = 17.25$, $p < .001$; 400–500 ms, midline: $F[1,30] = 87.74$, $p < .001$; lateral: $F[1,30] = 79.77$, $p < .001$; 500–700 ms, midline: $F[1,30] = 84.75$, $p < .001$; lateral: $F[1,30] = 116.37$, $p < .001$). Again it was auditory targets that produced substantially more negative effects than visual targets and these differences were apparent across SOAs (see Figure 7). In the final epoch the effects of Repetition between experiments were more complex, as indicated by significant Experiment × Electrode Site interactions (midline: $F[2,60] = 33.13$, $p < .001$, epsilon = .76; lateral: $F[4,120] = 33.63$, $p < .001$, epsilon = .49). Auditory targets (Experiment 1) tended to produce a strong anterior–posterior difference in repetition effects (anterior negative and posterior positive), whereas visual targets (Experiment 2) produced somewhat smaller negative effects across the scalp.

General Discussion

In two experiments we examined the time course of interactivity in word processing between the visual and auditory modalities using an immediate repetition priming paradigm. In Experiment 1, with visual primes and auditory targets, there was evidence in the ERPs of an interaction to repeated compared to unrelated target words across a wide temporal range. These effects of repetition started as early as 200 ms and ended as late as 1000 ms. In Experiment 2, with auditory primes and visual targets, there were also early ERP effects of repetition as well as later effects. However, these repetition effects were substantially smaller than in Experiment 1 and at the two shortest prime–target intervals there was little evidence of the typical N400 repetition effect at all. However, at the end of the target epoch Experiment 2 did produce significant priming effects at these two shortest SOAs. Taken together the results from these two experiments suggest that the two primary domains of language comprehension are highly interactive across a range of word-level processes, although the degree and time course of this interactivity differs as a function of prime and target modality.

The overall pattern of cross-modal N400 effects seen in this study are quite similar to those reported by Holcomb and Anderson (1993) for between-modality visual–auditory priming using an identical SOA manipulation but with semantic rather than repetition priming. Like the current study they found larger and more temporally extensive priming for visual primes and auditory targets than for auditory primes and visual targets. The biggest differences between the studies is that the current effects of priming started earlier in the 200- and 800-ms SOA conditions (in the 100–200-ms window vs. the 200–300-ms windows for Holcomb & Anderson) whereas Holcomb and Anderson found a marginally earlier onset in the 0-ms SOA condition. We interpret these differences between studies as likely being due to the current repetition manipulation being sensitive to both semantic influences on the N400 as well as earlier influences on pre-N400 negativities. The semantic priming manipulation in Holcomb and Anderson was most likely sensitive only to higher level semantic influences on the N400.

Evidence that these earlier effects are distinct from the later effects of repetition can be seen in the different scalp distributions of early and later effects. In the two earliest windows to show repetition effects (100–200 ms for Experiment 1 and 200–300 ms for both experiments) the 200-ms SOA and the 800-ms SOA conditions showed their largest repetition effects at anterior sites and over the right hemisphere. Later repetition effects, on the other hand, tended to have a more posterior distribution consistent with typical N400 effects such as those seen in Holcomb and Anderson (1993).

The earlier effects of across-modality repetition priming found in the present study were predicted by the bimodal interactive activation model, presented in the introduction. According to this account of lexical processing, orthographic and phonological processes interact during the early phases of word recognition such that recognizing a visual word is affected by its phonological properties and recognizing an auditory word is affected by its orthographic properties. Thus, a certain amount of prelexical and lexical-level processing occurs independently of modality of stimulus presentation, and these shared processes are thought to be the cause of the across-modality repetition effects reported here.

Recent work by our group has shown that an early ERP component with a peak latency between 200 and 300 ms (N250) is sensitive to immediate repetition priming when prime and target words are both visual and the prime is masked (Geyer et al., 2004; Kiyonaga et al., 2004). Although at first we thought this was just the early onset envelope of the N400, careful comparison of the scalp distribution of this component strongly suggests that it is a separate component generated by a nonidentical set of neural generators. Moreover, it appears to respond to a somewhat different set of experimental manipulations. For example, it has been shown to be sensitive to the orthographic overlap between prime and target, being larger when the overlap is greater (Geyer et al., 2004). From this finding we have argued that the N250, unlike the N400, is sensitive to lexical-level processes, and particularly the mapping from sublexical representations onto whole-word representations.[2]

Is the early negative effect seen especially in Experiment 1 an example of this lexical N250 component? It seems reasonable to propose that it is, as it has a similar time course and scalp distribution. It also seems plausible on the basis of the bimodal interactive-activation model in which orthographic as well as phonological processes feed into both auditory and visual lexical systems (e.g., Grainger et al., 2003). According to this model cross-modal repetition occurs because (in the case of auditory targets) rapidly processed orthographic cues from prime processing partially activate the appropriate auditory word representations, which are then further activated by the phonological input from the auditory target word itself (a comparable process could work for visual targets as well). Our data further suggest that when the visual prime word has at least a 200-ms head start on the auditory target that the cross-modal influence has enough time to produce maximal preactivation of the appropriate lexical entry. Interestingly, in another study (Kiyonaga et al., 2004) where the prime was visual (and masked) and the target auditory, we found no evidence of an N250 effect due to repetition. In fact, in this condition, which was similar to the 0-ms SOA condition in the current Experiment 1 (with the exception that the prime was masked and presented very briefly in the Kiyonaga et al. study), the effects of across-modality repetition were limited to the N400 window. In other words, masking plus the brief presentation of the visual prime appears to block the early cross-modal effects reported here. Indeed, increasing the prime exposure duration in the Kiyonaga et al. study from 50 ms to 67 ms led to a more rapid onset and increased amplitude of cross-modal repetition priming effects. The effects obtained with auditory targets in the present study demonstrate that further increases in prime exposure duration and SOA continue to generate cross-modal priming effects that onset more rapidly and have greater amplitudes.

As mentioned above one big difference between Experiments 1 and 2 was the presence of large N400 priming effects across SOAs in Experiment 1 (visual prime, auditory target) and very small or nonexistent effects in the traditional N400 epoch in Experiment 2 (auditory prime, visual target). Interestingly, the two SOAs that produced reduced priming effects on N400 amplitude (0- and 200-ms SOA) also produced a later negative-

[2]This conclusion is somewhat at odds with the work of Pickering and Schweinberger (2003), who have shown that a component with a similar time course (N250r) is *larger* for repeated than unrepeated familiar personal names. However, unlike our N250 effects, their N250r was very focal, being larger over the left than right hemisphere and largest at the P9 site. Our N250 has a much more central distribution. One possibility for this difference in distribution and direction of effects between studies is Pickering and Schweinberger's use of an average reference whereas we use a mastoid reference.

going effect of repetition. But what is this late negative effect? One very tentative possibility is that it reflects a delayed N400-like effect due either to the demands of visual word recognition temporarily blocking semantic processing of the overlapping auditory prime or the delayed buildup of semantic information from the slowly unfolding auditory primes. According to the first type of explanation, visual word recognition would generate a processing bottleneck relatively late, at about the time that attention-consuming, high-level semantic and/or decision-related processes are coming into play. The processing bottleneck generated by the visual target word would block (or at least severely hinder) simultaneous processing of the auditory prime word—especially in the 0-ms and 200-ms SOA conditions. Processing of the auditory prime could continue once the attention-consuming target-related processing is complete. Here we must assume that auditory word recognition does not block processing of visual primes to the same extent, either because of differences in the time course of visual and auditory word recognition or because of modality-specific attentional influences.

This blocking account of the pattern of priming effects obtained with visual targets would seem to fit with the fact that visual lexical decision RTs had a mean duration of 650 ms. Thus, participants might have been consumed with the decision component of this task at exactly the point in time when important semantic information from the auditory prime would normally be becoming available in the 0- and 200-ms conditions. We suggest that after the lexical decision was made, semantic processing of the temporally overlapping prime was able to commence/continue (possibly from a temporary sensory buffer). Accordingly we are suggesting that the late negative effect might reflect this delayed prime processing.

Alternatively, the lack of typical N400 effects, but the presence of a much later negativity effect, could be due to the relative slowness of auditory prime processing. However, if this is the case, then we would expect that there should have been a difference in the time course of the late negative effect as a function of prime–target temporal overlap. There was no evidence of such an effect with both the 0- and 200-ms SOA conditions producing comparable late negativities. Note that both of the above explanations assume that processing of the low level acoustic and even lexical attributes of the auditory prime continued unabated during visual target processing. This is supported by the presence of pre-N400 repetition effects across SOAs.[3]

Presumably one could decide between the above possibilities by further manipulations of task, SOA, and auditory prime duration or uniqueness points. If the relatively high demands of lexical decision blocked auditory prime processing, then by changing to a less demanding task we would predict that even at short SOAs (0 or 200 ms) that large cross-modal (auditory–visual) repetition would occur and the late repetition negative effect should dissipate. However, if the lack of 0- and 200-ms repetition was due to the availability of semantic information from the auditory primes, then shorter duration auditory primes or primes with earlier uniqueness points (Marslen-Wilson, 1987) should increase the effect.

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[3]There other possibilities including that it may be easier to ignore a task-irrelevant auditory than visual prime—especially when it is competing for resources with the visual target. This is similar to one possibility mentioned by Holcomb and Anderson (1993) in which it was pointed out that in other domains visual processing frequently dominates over auditory processing (e.g., Colavita, 1974; Posner et al., 1976).

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