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An electrophysiological analysis of modality-specific aspects of word repetition

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Abstract

Priming effects to words are reduced when modality changes from study to test. This change was examined here using behavioral and electrophysiological measures of priming. During the study, half of the words were presented visually and half auditorally; during a subsequent lexical decision test, all words were presented visually. Lexical decisions were faster for within- than cross-modality repetitions. In contrast, modality influenced recognition only for low-frequency words. During lexical decision, event-related brain potentials were more positive to studied than unstudied words (200–500 ms). A larger and shorter duration effect was observed for within- than cross-modality repetitions (300–400 ms). This latter effect is viewed as an electrophysiological index of modality-specific processing associated with priming. Results suggest that multiple events—both modality-specific and modality-nonspecific—underlie perceptual priming phenomena.

Descriptors: Memory, Cross-modality, ERP, Repetition priming, Perceptual priming, Lexical decision test

Considerable research has gone into investigating the differences between performance on implicit and explicit tests of memory. Explicit tests assess memory by making reference to prior encounters with items, whereas implicit tests allow inferences about memory from changes in various other performance measures (Schacter, 1992; Tulving & Schacter, 1990). Performance on implicit and explicit tests appear to be subserved by nonidentical neural systems with different functions; the differential sensitivities of implicit and explicit test performance to particular experimental manipulations provide support for this hypothesis. Specifically, on the whole, explicit memory varies with factors such as level of processing, study duration, and attention at study, whereas implicit memory is affected by changes in stimulus features like font and modality (Graf & Ryan, 1990; Jacoby & Dallas, 1981; Jacoby & Hayman, 1987; Jacoby, Toth, & Yonelinas, 1993; Marsolek, Kosslyn, & Squire, 1992; Roediger & Blaxton, 1987; Smith & Oscar-Berman, 1990). In addition, whereas patients with damage to certain parts of the brain show impaired explicit memory but spared implicit memory (e.g. Squire, 1992), in other patients with damage to different brain areas, at least some types of implicit memory are impaired whereas explicit memory is spared (e.g., Gabrieli, Fleischman, Keane, Reminger, & Morrell, 1995).

Several research groups have used event-related brain potentials (ERPs) to investigate the processes underlying performance on implicit and explicit memory tests. The main finding has been an enhanced posterior positivity between 250 and 700 ms in the ERPs to repeated versus new items (Rugg & Doyle, 1992; Smith & Halgren, 1989). This ERP repetition effect subsumes at least three, and possibly more, ERP components including the N2, the N400, and the late positive component (LPC) (Swick & Knight, 1997; Van Petten & Senkfor, 1996): repetition generally reduces N2/N400 amplitude and enhances LPC amplitude (Domalski, Smith, & Halgren, 1991; Smith, Stapleton, & Halgren, 1986; see Johnson, 1995, and Rugg, 1995, for review). To date, there are no consistent perceptual priming effects on early sensory-evoked potentials.

Some modulations in earlier portions (~300–500 ms) of the ERP repetition effect appear to be related to priming, whereas later portions (~500–800 ms) index recognition processes (Swick & Knight, 1997). In particular, manipulations that affect perceptual priming yield small, short duration, focal effects that occur moderately early (~200–400 ms) in the time course of the ERP repetition effect (Paller & Gross, 1998; Paller, Kutas, & McIsaac, 1998). By contrast, manipulations that affect recognition, as well as differences between various measures of recognition (recollection vs. familiarity), are reflected in larger, longer duration effects in later (~500–900 ms) portions of the ERP repetition effect (Paller & Kutas, 1992; Paller, Kutas, & McIsaac, 1995; Rugg & Doyle, 1992; Smith, 1993; Swick & Knight, 1997; Van Petten et al., 1991; Wilding, Doyle, & Rugg, 1995; Wilding & Rugg, 1996). It has been suggested that this modulation of the LPC reflects contributions from the P300 (related to target detection and decision making) and other potentials related to repetition and retrieval (e.g., Swick & Knight, 1997; Van Petten & Senkfor, 1996).

Priming has also been studied using changes in stimulus modality from one presentation to the next. These generally lead to a

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significant reduction (Bassili, Smith, & MacLeod, 1989; Ellis, 1982; Graf, Shimamura, & Squire, 1985; Jacoby & Dallas, 1981; Kirsner, Milech, & Standen, 1983; McClelland & Pring, 1991; Roediger & Blaxton, 1987), if not abolition of behavioral priming effects (Jackson & Morton, 1984; Jacoby & Hayman, 1987). Cross-modality manipulations have also been reported to affect the scalp distribution, onset latency, and/or duration of ERP repetition effects in some studies, although the most consistent effects are on ERP amplitude (Domalski et al., 1991; Rugg, Doyle, & Melan, 1993; Rugg, Doyle, & Wells, 1995). Typically, within-modality repetitions are associated with larger positivities between 300 and 600 ms than cross-modality repetitions (Rugg et al., 1993, 1995); this result is more robust for visual–visual versus auditory–visual repetition. For auditory–auditory versus visual–auditory repetition, there are either no priming differences (Rugg et al., 1993) or they are later with a more parietal distribution (Rugg et al., 1995).

In the present study, cross-modal perceptual priming was examined using a lexical decision test (LDT) paradigm that has been successfully used to investigate the relationship between implicit and explicit memory processes. In this paradigm, the later portions of the repetition effect (LPC) are (1) influenced by levels of processing manipulations, being larger for "deeper" or more semantic processing than for "shallow" or nonsemantic processing (Paller & Kutas, 1992); (2) enhanced in magnitude when a recognition judgment immediately follows each lexical decision as compared with when only lexical decisions are made (Paller et al., 1995); (3) bilaterally symmetric for nonsemantically studied words across age groups, but larger over the left hemisphere for semantically encoded words in younger individuals only (Joyce, Paller, McIsaac & Kutas, 1998); and (4) sensitive to repetition in the auditory modality (Gonsalves & Paller, in press). Also in this particular paradigm, altering visual word-form from its initial exposure at study to a second exposure during a lexical decision task results in a small modulation in earlier portions of the ERP repetition effect locally over occipital sites (Paller et al., 1998; see also Paller & Gross, 1998). Although these ERP effects are earlier than those reflecting recollective processes, they seem to bypass the early sensory components such as the N1, P1, or P2. However, the manipulations of visual word-form used in these studies have been relatively mild compared with other stimulus manipulations known to affect priming. In particular, a modality manipulation could potentially reveal more robust and/or earlier ERP correlates of repetition priming, assuming that such affects could be dissociated from the correlates of explicit memory.

In the present report, the focus was on processes contributing to that part of the ERP repetition effect thought to be involved in perceptual priming. Because a modality shift is a particularly effective way of disrupting processes that depend on perceptual overlap between two occurrences of an item, modality of presentation was altered from the first to the second presentation for half of the studied words. Upon initial exposure, words were presented either in the visual or auditory modality, whereas during the LDT all letter strings (words and pseudowords) were presented visually. In part, the aim was to find ERP markers of perceptual priming in this paradigm, which could then be harnessed for a variety of studies of implicit memory. For example, with priming markers in hand, it would be easier to test alternative conceptions of perceptual and conceptual priming, or effects of processing perceptual form versus meaning (e.g., Roediger & McDermott, 1993). In the current experiment, within-modality priming (visual study–visual test) was considered to have a larger contribution from perceptual mechanisms than cross-modality priming (auditory study–visual test). In contrast, savings with respect to stimulus meaning (conceptual priming) was thought to be essentially similar for within- and cross-modality conditions.

Repeated words were expected to show priming (decreased lexical decision times and an early ERP repetition effect) compared with words seen for the first time during the LDT. Moreover, both behavioral priming and early ERP repetition effects were expected to be larger for words that reappeared in the visual modality than those that had originally been heard. On the other hand, recognition was expected to be determined largely by elaborative processing at study and thus to be relatively independent of study modality. Such results would provide further evidence for functional dissociation between implicit and explicit memory, which is often taken as evidence for the existence of distinct memory systems. The extant literature on this issue across various tests of explicit memory are mixed: whereas several studies indicate that performance on explicit memory tests are unaffected by a shift in modality from study to test, there are also reports of better performance for within- than cross-modality *and* for the reverse (Carlesimo, Marfia, Loasses, & Caltagirone, 1996; Challis & Sidhu, 1993; Craik, Moscovitch, & McDowd, 1994; Habib & Nyberg, 1997; Jacoby & Dallas, 1981; Rajaram & Roediger, 1993; Richardson-Klavehn & Gardiner, 1996; Wilding et al., 1995). The ERP data could also prove useful for models of memory processes that take the time courses of the processes into account. Given the divergence between various conceptualizations of the mechanisms of perceptual priming in the existing literature (e.g., Bowers, 1996; Ratcliff & McKoon, 1996; Tulving & Schacter, 1990), the ability to monitor mechanisms of perceptual priming empirically would likely induce theoretical progress in this area. This study, by itself, however was not designed to adjudicate among these various alternatives, but to find ERP markers of priming. Our juxtaposition of between- and cross-modality repetition in the present experiment did in fact yield an electrophysiological measure of a modality-specific component of visual word priming.

Methods

Participants

Twenty-six right-handed native English-speaking adults (13 women), aged 18–30 years (mean = 23.8 years) of whom 11 had left-handed family members were paid or received course credit for participating in a single, 3-hr experimental session. The data of one male participant were excluded from the analyses due to excessive muscle artifact in the electrophysiological recordings, so all analyses were based on 25 participants.

Stimuli

Three word lists consisting of 150 words each were used. For a given participant, two of the lists were study items and the third consisted of new items in the lexical decision phase, with list-to-condition assignments counterbalanced across subjects. Each list was balanced for word frequency (Kucera & Francis, 1967) and word length. Overall there were 165 low frequency words (fewer than 7 occurrences/million), 141 medium frequency words (7–24 occurrences/million), and 144 high frequency words (more than 24 occurrences/million). One hundred pseudowords were also used; 50 were presented only once and 50 were repeated within their respective test blocks. All pseudowords were orthographically plausible. An additional 239 words of comparable length and frequency were used as distractors during the recognition test.

For each participant 300 words were presented in the study phase. The lexical decision phase contained those same 300 words, 150 new words, 50 single presentations of pseudowords, and 50 pseudowords presented twice. Finally, the recognition test consisted of the original 300 words plus 239 new words.

Stimulus Presentation

For the study and test phases, a white rectangle (4.2 inches by 1.2 inches) appeared in the center of the computer monitor. Visual words were presented inside the rectangle in upper case letters (vertical visual angle = 0.6°). Auditory words were presented via two speakers at an angle of ~45°, placed symmetrically at a distance of 80 inches in front of the participant.

During the study phase, the duration of visually presented words was 256 ms. The duration of auditory words varied from approximately 640 to 922 ms. Words were presented at a rate of one every 3,024 ms. During the lexical decision test phase letter strings were presented for 256 ms at a rate of one word every 1,278 ms. Instructions printed above the white rectangle reminded participants of which hand they were to use for which response (e.g., small/large size, nonword/word).

The final recognition test consisted of 539 words printed in 11 columns on a single sheet of paper.

General Procedure

Following electrode application, the participants were taken into a sound-attenuating chamber and seated in a chair approximately 65 cm from the video monitor. Participants were taught each experimental task separately and given several practice trials. They were instructed to minimize body movements and blinks because corresponding artifacts interfere with recording of the electroencephalogram (EEG).

Participants were given 10 experimental blocks, each consisting of a study phase and a lexical decision phase. During the study phase, participants were asked to perform an imagery task in which they visualized the objects represented by each word and indicated whether they were larger or smaller than the video monitor. All responses were given via a button press with one or the other hand. In each study block, 15 words were presented visually and 15 were presented auditorally. Presentation modality was alternated every word.

Each study phase was followed by a lexical decision phase in which the 30 studied words were intermixed with 15 new words and 15 pseudowords. Participants were asked to indicate as quickly as possible via button press whether the presented letter string was a word or a nonword. For the LDT, all words and nonwords were presented visually. The experiment concluded with a paper and pencil recognition test in which participants were asked to circle the words they remembered seeing or hearing during the earlier study/test portions of the experiment.

Electrophysiological Recordings

Tin electrodes embedded in an elastic cap were used to make recordings from 13 scalp locations of the International 10-20 System (Jasper, 1958): midline frontal (Fz), central (Cz), and parietal (Pz) sites, and lateral pairs at frontal (F3/F4), central (C3/C4), parietal (P3/P4), posterior temporal (T5/T6), and occipital (O1/O2) sites. The online reference was an electrode placed on the left mastoid; recordings were rereferenced offline to averaged activity at the left and right mastoids. Vertical eye movements and blinks were monitored via an electrode placed beneath the right eye, referenced to the mastoid. Horizontal eye movements were monitored by a pair of electrodes placed near the outer canthi of each eye, referred to each other. Trials contaminated by artifacts were eliminated prior to averaging: these accounted for approximately 10% of the trials. Blinks were identified on a subject by subject basis by an algorithm that checked for amplitude of the potential from an electrode below the eye together with polarity inversion between this electrode and a site on the forehead. The electrical activity was amplified with a bandpass of 0.01–100 Hz and digitized at a rate of 250 Hz. ERPs were computed for epochs extending from 100 ms prior to word onset to 924 ms after word onset. Only ERPs recorded during the LDT are reported.

Statistical Analyses

For reaction time and recognition data, analyses of variance (ANOVAs) were conducted using three levels of study condition (words studied visually, words studied auditorally, or new words), and three levels of word frequency (low, medium, high). A further analysis was conducted after discarding reaction times of trials that exceeded 2.5 *SD* above or below each individual participants' mean within each condition. As the pattern of results following this procedure was identical to that in the raw, untrimmed data, only the values based on the raw data are reported.

ERP data were quantified as mean amplitudes to capture early (200–500 ms) and late (500–800 ms) repetition effects (e.g., Joyce et al, 1998; Swick & Knight, 1997). In addition, because early portions of the repetition effect are thought to be sensitive to perceptual manipulations, additional analyses of 100-ms intervals within the 200–500-ms time period were conducted to look for more focal effects due to study modality. Mean amplitudes were calculated relative to activity during the 100 ms prior to word onset. These data were submitted to ANOVAs with three levels of study condition (visually studied vs. new, or auditorally studied vs. new), five levels of anterior to posterior electrode sites (frontal, central, parietal, temporal, occipital), and two levels of laterality (left, right). Simplified ANOVAs were used to test a priori hypotheses concerning relations among the three study tasks.

Post hoc analyses were performed using the Tukey test. Reported values are based upon degrees of freedom determined by applying the Huynh–Feldt correction procedure for controlling Type I errors in repeated measures designs.

Results

Lexical Decision Performance

Lexical decision times demonstrated priming (shorter reaction times to studied than new words) and modality-related effects (shorter reaction times to visually than auditorally studied words), as shown in Figure 1A. There were significant main effects of study condition, $F(2,50) = 18.24$, $p = .0001$, $\epsilon = 0.75$, and word frequency, $F(2,50) = 42.15$, $p < .0001$, $\epsilon = 0.96$, and a significant Study condition × Word frequency interaction, $F(4,100) = 3.79$, $p < .015$, $\epsilon = 0.84$.[1]

[1] A post hoc Tukey test revealed that the main effect of word frequency was due to slower reaction times for low as compared with both medium and high frequency words. For all three study conditions, lexical decision times to low frequency words were significantly longer than those to medium frequency words, visual: $F(1,25) = 12.97$, $p < .002$; auditory: $F(1,25) = 23.63$, $p = .0001$; new: $F(1,25) = 42.61$, $p < .0001$). For auditory and new word conditions, lexical decision times to low frequency words were also significantly longer than those to high frequency words, auditory: $F(1,25) = 19.04$, $p = .0002$; new: $F(1,25) = 22.78$, $p = .0001$. For the visual condition, lexical decision times to medium frequency words significantly shorter than those to high frequency words, $F(1,25) = 4.67$, $p < .05$.

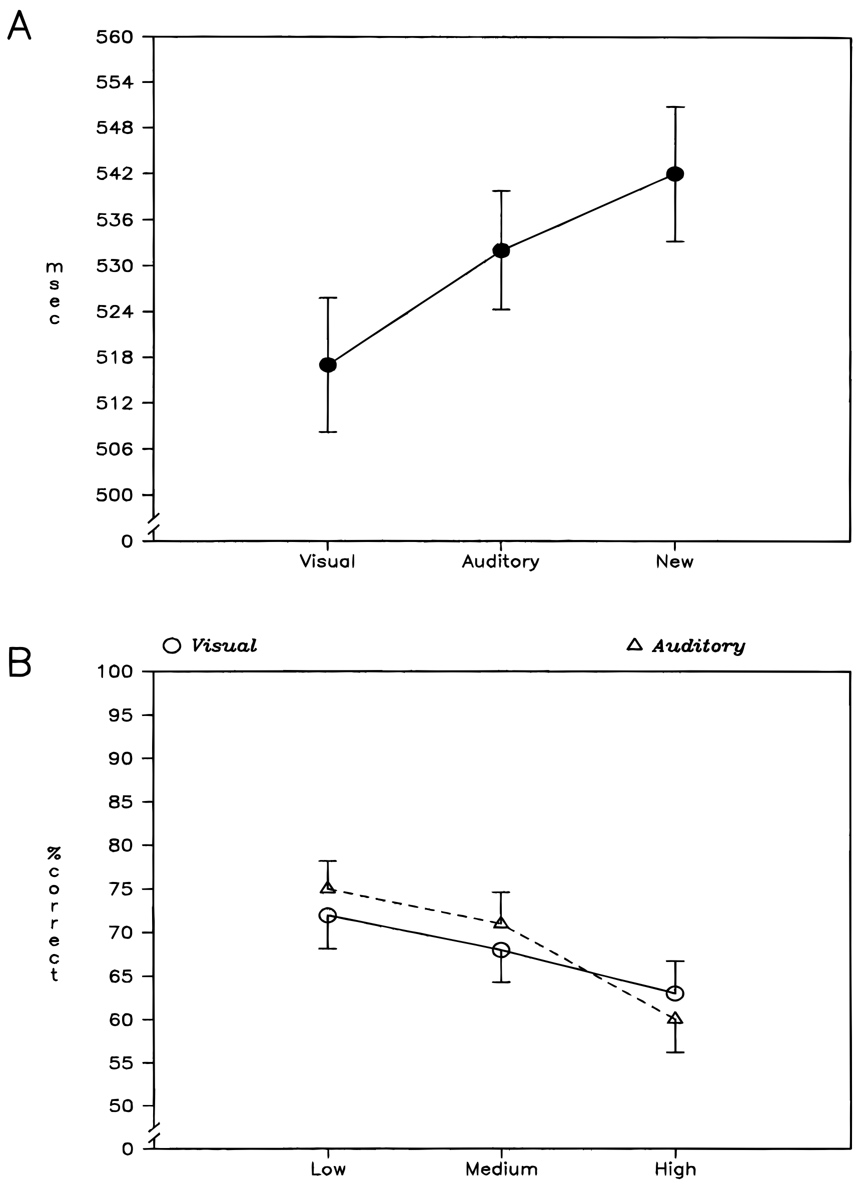

Figure 1. (A) Mean reaction times for lexical decisions to words studied visually and auditorally studied and unstudied words. Error bars indicate standard error of the mean. (B) Mean percentage correct during the recognition test for visually (circle/solid line) and auditorally (triangle/dashed line) studied low, medium, and high frequency words. Error bars = *SEM*.

Planned comparisons showed a significant priming effect after visual study (visual 25 ms faster than new, $F[1,25] = 25.22$, $p < .0001$) and a marginally significant priming effect after auditory study (auditory 10 ms faster than new, $F[1,25] = 3.92$, $p < .06$). A significant effect of study condition showed that visually studied words were responded to approximately 15 ms faster than auditorally studied words, $F(1,25) = 41.22$, $p < .0001$. Lexical decision times to repeated pseudowords were significantly faster than those on their initial presentations, 637 versus 646 ms, respectively, $F(1,25) = 4.40$, $p < .05$.

Recognition Performance

As shown in Figure 1B, the main effect of study condition was nonsignificant, $F(1,25) = 1.15$, $p > .2$, although the expected recognition advantage for low-frequency words was present, $F(2,50) = 31.50$, $p < .0001$, $\epsilon = 0.93$; Guttentag & Carroll, 1997].[2] Significant interaction of study condition with word frequency, $F(2,50) = 3.90$, $p < .03$, $\epsilon = 1.00$, reflected a tendency for better recognition of auditorally than visually studied low-frequency, $F(1,25) = 4.50$, $p < .05$, and medium-frequency words, $F(1,25) = 3.19$, $p < .09$. The tendency for better recognition for auditorally studied low-frequency words, with an opposite, nonsignificant tendency for high-frequency words, may be due, in part, to the fact that word-frequency estimates were based on written data. At least for some words, a different frequency categorization would result from norms derived from spoken data. New words were correctly identified 97% of the time (3% false-alarm rate).

[2] A post hoc Tukey test revealed this to be due to significantly lower recognition for high as compared with both medium and low frequency words.

Electrophysiological Results

The ERPs during the LDT, as shown in Figure 2, were characterized by a series of deflections: a small N1 (~50–100 ms), a pronounced P2 (~100–300 ms), a small N200 (~150–250 ms), a large N400 (~250–450 ms), and a large P300 (~400–900 ms). Preliminary analyses showed no significant interactions of study task with word frequency in any of the time intervals, so this variable was excluded from further analyses.

In the early analysis window (200–500 ms), there was a main effect of study condition, $F(2,48) = 11.56$, $p < .001$, $\epsilon = 1.00$, reflecting the more positive ERPs to previously studied as compared with new words, visual, $F(1,24) = 18.64$, $p < .0005$; auditory, $F(1,24) = 17.72$, $p < .0005$. These effects interacted with anterior/posterior distribution and laterality in both two- and three-way interactions. As shown in Figure 3A, there was an overall interaction of condition with laterality, $F(2,48) = 5.68$, $p < .007$, $\epsilon = 1.00$. This was driven by larger positivities over left than right hemisphere for old as compared with new words, visual, $F(1,24) = 8.42$, $p < .008$; auditory, $F(1,24) = 7.22$, $p < .02$). Further, old words showed larger frontal positivities at right hemisphere electrodes and larger posterior positivities at left hemisphere electrodes than new words, visual, $F(4,96) = 6.05$, $p < .001$, $\epsilon = 0.82$; auditory, $F(4,96) = 4.11$, $p < .01$, $\epsilon = 0.85$.

As expected, the ERP repetition effect was larger for within-modality than cross-modality repetitions, as shown in Figures 4 and 5. Specifically, between 300 and 400 ms, ERPs to visually studied words were significantly more positive than those to auditorally studied words across all recording sites, $F(1,24) = 7.30$, $p < .02$. The amplitude of this difference did not differ across hemisphere, $F(1,24) = 0.26$, $p > .1$, anterior-to-posterior direction, $F(4,96) = 1.74$, $p > .1$, $\epsilon = 0.48$, or both factors together, $F(4,96) = 0.69$ $p > .1$, $\epsilon = 0.85$.

In the later analysis window (500–800 ms), the only significant effect was an interaction of study condition with laterality,

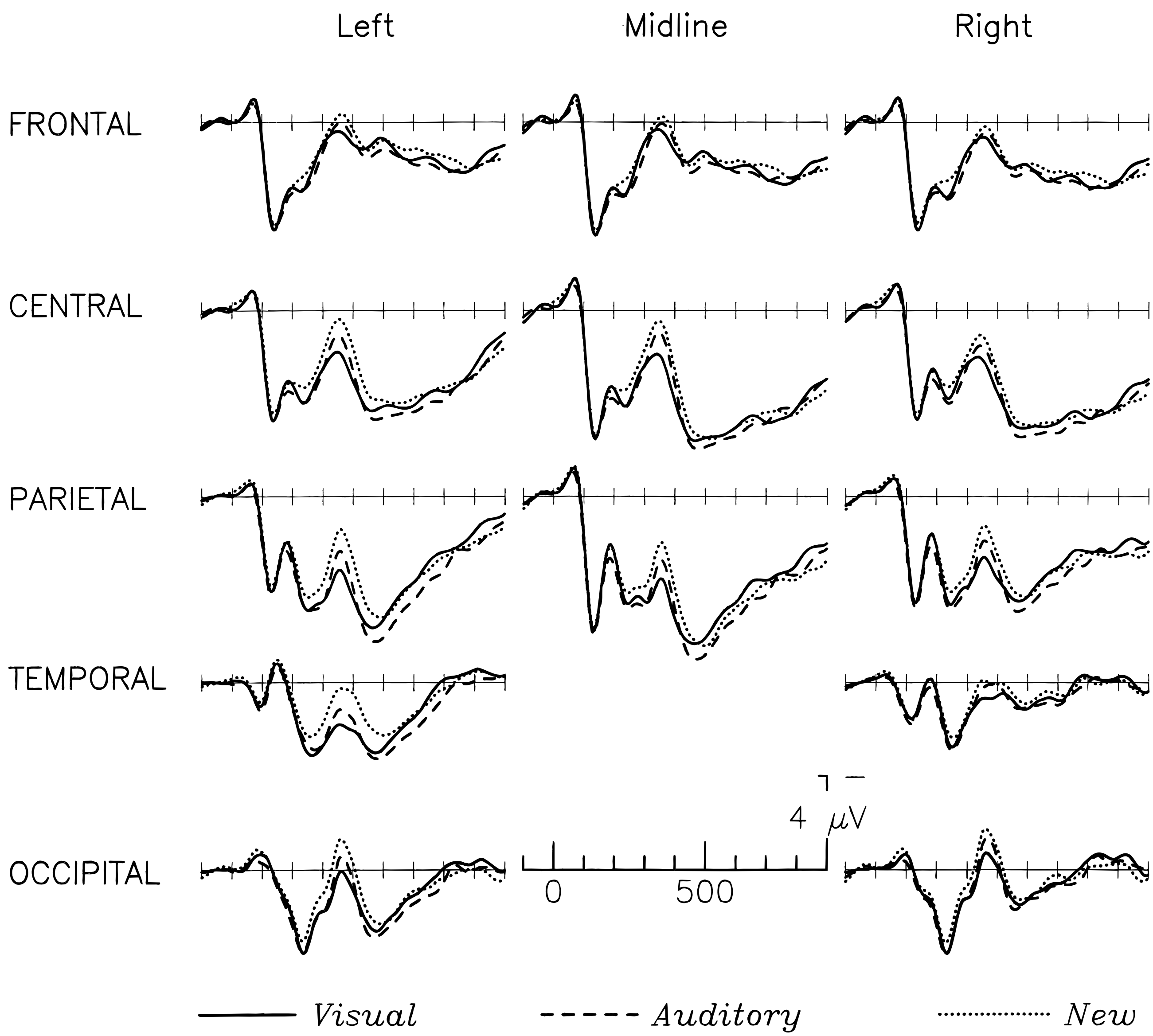

Figure 2. Grand-average event-related potentials ($N = 25$) recorded during the lexical decision test to visually (solid) and auditorally (dashed) studied words and unstudied (dotted) words at all electrode sites. Negative is plotted up on this and all subsequent figures.

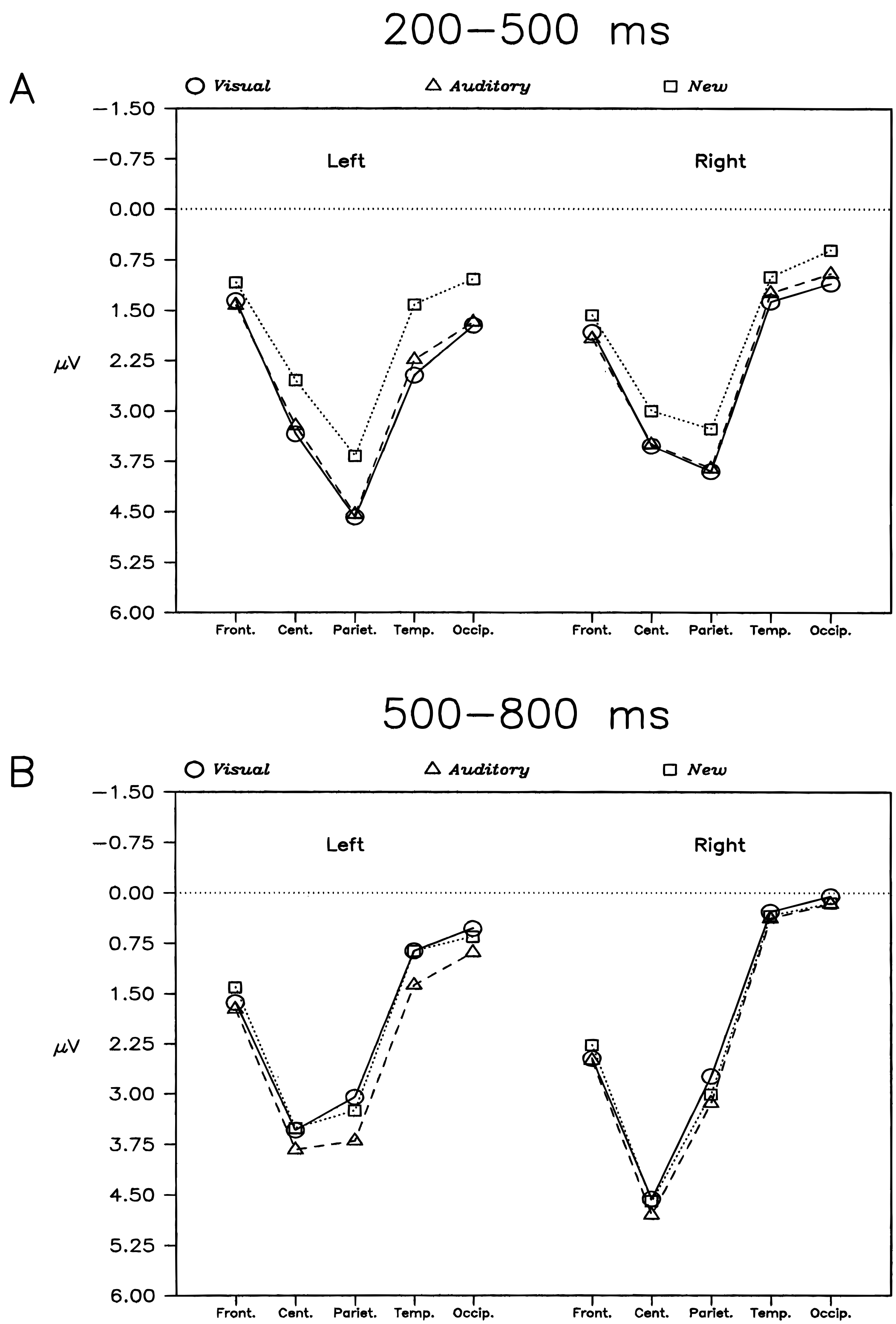

Figure 3. Comparison of the scalp distributions of the event-related potential mean amplitudes during lexical decisions for words studied visually (circle/solid line) and auditorally (triangle/dashed line) and unstudied words (square/dotted line). (A) Measurements made over the 200–500-ms interval. (B) Measurements made over the 500–800-ms interval.

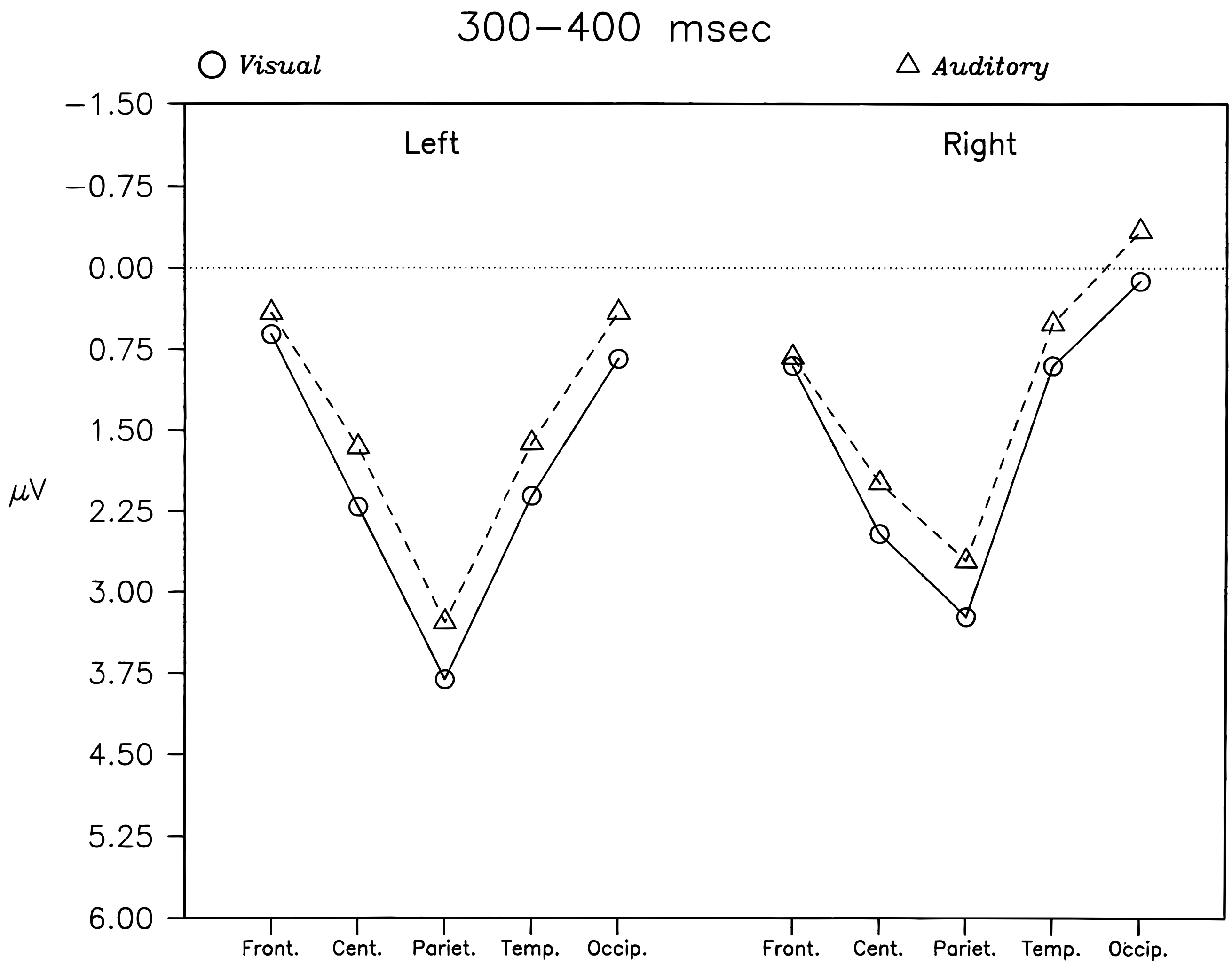

Figure 4. Comparison of the scalp distributions of the event-related potential mean amplitudes during lexical decisions for words studied visually (circle/solid line) and auditorally (triangle/dashed line) measured over the 300–400-ms interval.

$F(2,48) = 3.64$, $p < .04$, $\epsilon = 0.92$. Auditorally studied words exhibited larger positivities over left hemisphere sites than did either visually studied or new words, Auditory/new × Laterality, $F(1,24) = 4.59$, $p < .05$; Visual/auditory × Laterality, $F(1,24) = 6.60$, $p < .02$, see Figure 3B.

Discussion

The present results, together with prior ERP results, suggest that earlier portions of the ERP repetition effect are associated with perceptual priming whereas later portions are associated with conscious recollection and related factors. These findings thus add neurophysiological support for conceptualizations of multiple memory systems. Furthermore, our manipulation of study modality revealed an electrophysiological measure of modality-specific priming in this paradigm, or what can be taken as one component of perceptual priming effects in general. This work thus helps in the analysis of the processing components that ultimately sum to produce perceptual priming as measured behaviorally. Combined with other ERP priming effects in the literature, our findings indicate that behavioral priming is the outcome of multiple (and not a single) processes.

In several ways, our behavioral results are consistent with those in the literature: (1) word repetition yielded priming of lexical decision times, (2) greater priming was observed for words repeated within the same modality than across modalities, and (3) the change in stimulus modality from study-to-test had minimal effects on recognition accuracy. This pattern of results adds to the growing list of dissociations between repetition priming and recognition (e.g., Roediger & McDermott, 1993).

Words presented visually during the lexical decision phase, regardless of presentation modality at study, were characterized by greater positivity between 200 and 500 ms than were new words. Most likely, this ERP repetition effect included contributions from both implicit and explicit memory processes; a central challenge is to disentangle their distinct contributions. The early portion of the ERP repetition effect included a modality-sensitive phase (300–400 ms) with greater positivity to words repeated in the same modality. Because this effect occurred in the absence of a corresponding difference in recognition, it is linked to implicit rather

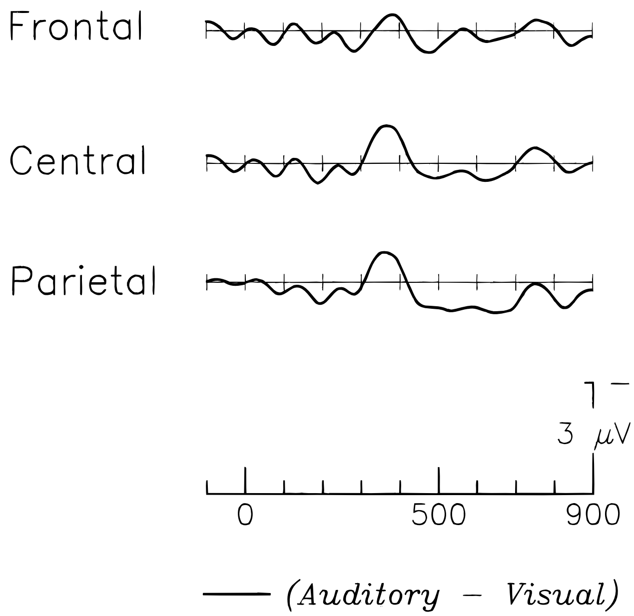

Figure 5. Difference event-related potentials for auditorally minus visually studied words at frontal, central, and parietal midline sites during the lexical decision task.

than explicit memory processes. Indeed, this modality-related ERP effect is viewed, at least in part, as a sign of perceptual priming of visually repeated words. This modality-related effect began later and was of shorter duration than the ERP repetition effect for old versus new words.

A key basis for our view that the ERPs for within- versus cross-modality repetitions reflect implicit rather than recollective processes is that equivalent recognition scores were obtained at the end of the experiment for these two conditions. However, one could argue that recollective factors did differ between conditions at the time of the LDT, but not at the end of the experiment because of the longer retention delay and/or the repetition of the studied words during the LDT. Indeed, recognition and priming were not tested at the same delay, nor could recognition have been tested earlier without significantly altering the subjects' strategies during the LDT (c.f., Paller et al., 1995). The pattern of recognition data in this experiment mitigates against this interpretation, however. As mentioned in the Introduction, the results of studies of within-modality repetitions versus cross-modality repetitions are mixed. On the whole, recognition scores were unaffected by the modality change in the present experiment. Moreover, when within-modality versus cross-modality recognition scores did differ (for low-frequency words only), they were more accurate for the cross-modality (acoustically) rather than within-modality (visually) studied words. Therefore, the enhanced ERP repetition effect at 300–400 ms for words studied visually cannot be ascribed reasonably to enhanced recollection for them. Furthermore, ERP correlates of recollection previously reported (e.g., Joyce et al., 1998; Paller et al., 1995) occurred over a longer duration and with a greater magnitude than the modality-related ERP repetition effect here. By contrast, the tendency toward differential recognition in the present experiment may be linked to the greater late positivity between 500 and 700 ms for acoustically studied words.

The ERP difference associated with within-modality versus cross-modality repetitions may be akin to ERP correlates of visual word-form priming in related paradigms (Paller & Gross, 1998; Paller et al., 1998). However, these ERP correlates of visual word-form priming showed a more focal scalp topography. One reason for this topographic discrepancy may be that the ERP repetition effects in the present experiment arose due to a multiplicity of factors that may have distinguished the conditions. Auditory versus visual study presentations could have given rise to differential processing in at least three ways. Unarguably, processing at study involved more visuoperceptual processing for visual presentations. Second, at least for some participants, visual presentations likely provoked some phonological processing following grapheme-to-phoneme conversion, whereas phonological input was provided for auditory presentations. Third, the extent of visual imagery also likely differed between conditions. There is reason to believe that visualizing each word's referent according to task requirements may have been more robust for auditory words than for visual words. Brooks (1967, 1970) reported that reading sentences describing spatial relationships interfered with the ability to visualize, whereas hearing the same descriptions did not. This difference was attributed to a greater potential for interference in perceptual processing (in working memory) for reading and imaging compared to listening and imaging. Likewise, in a study with auditory word presentations, ERPs appeared to reflect greater visual imagery than in prior studies in the visual modality (Gonsalves & Paller, in press).

Because of this set of processing differences at study, visually studied words in the LDT may have engaged (1) greater savings in visuoperceptual processing, (2) differential phonological processing, and (3) less savings in visual imagery, compared with auditorally studied words. Thus, the ERP difference associated with within-modality versus across-modality repetition in the present experiment was unlikely to be driven wholly by early sensory/perceptual mechanisms. In other words, ERP correlates of visual word-form priming induced by more subtle within-modality perceptual manipulations (Paller et al., 1998; Paller & Gross, 1998) may reflect a smaller subset of priming-related processes than the modality-related ERP difference in the present experiment.

Yet another factor that differs between auditory and visual word encoding is the temporal nature of stimulus processing. Presentation times for auditory words were overall longer and more variable than for visual words. Exactly how the different time courses of processing of written and spoken words might play out during the subsequent LDT in the visual modality is unclear. However, the reinstatement of phonological processing for auditorally studied words may give rise to ERPs that are different from ERP correlates of phonological processing for visually studied words, and such effects may be modulated due to the differential timing stemming from auditory versus visual study. At the simplest level, the visual presentation of an auditorally studied word may provoke auditory processing based on the participant's memory for the sound of the spoken word; no such auditory memory is available for a visually studied word.

It is important to note that ERPs associated with within-modality and cross-modality repetition (Figure 6) do not differ in a merely quantitative manner. An alternative possible outcome was that the two types of ERP repetition effects would be identical in all respects except amplitude. They could have had the same latency of onset, the same duration, and the same distribution across the scalp, while varying only in amplitude. In this event, the two types of priming effects could be linked to the same neural mechanisms, with stronger priming in one case than in the other. The possibility also exists that within-modality priming, being highly specific and perceptual in nature, would have preceded the more

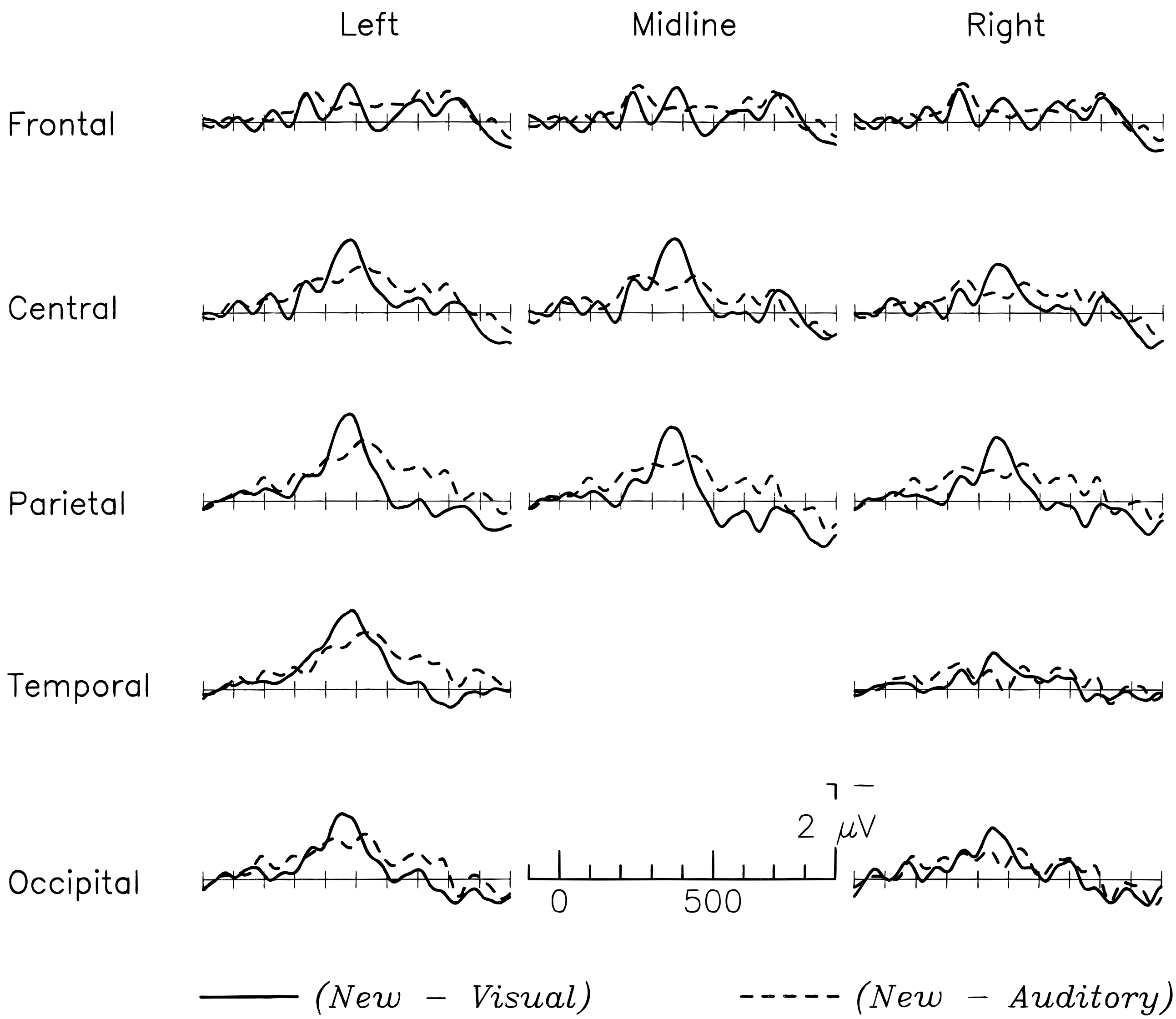

Figure 6. Difference event-related potentials during the lexical decision test for new minus visually studied (solid) and new minus auditorally studied (dashed) words at all electrode sites.

generic old–new ERP repetition effect and have been reflected in the modulation of early, sensory components (e.g., P1, N1, P2). Neither of these possibilities corresponds to what was observed, however. The experiment did not produce evidence of priming mechanisms due to altered early analysis of the sensory input, or to stimulus-induced changes in focal attention.

Behavioral data alone cannot explain the extent to which within-modality and cross-modality priming are related. Nor do they easily reveal the time course of either of these priming effects. The electrophysiological data thus go beyond the lexical decision times in showing that within-modality priming and cross-modality priming differ from each other in more than amplitude. The within-modality ERP effect appeared to be more short-lived than the cross-modality effect. Future studies are needed to determine whether the longer duration of the cross-modality effect is related to recollection of the auditory input per se, or whether the longer duration is a consequence of prolonged processing or greater latency variability related to the auditory input. Moreover, there was no indication that within-modality effects preceded cross-modal effects; in fact, at least in some participants, the cross-modality ERP repetition effect occurred before the within-modality ERP repetition effect. Future models of priming must attempt to take such temporal information into account.

In sum, our analysis of ERP differences as a function of study modality suggests that a host of processing differences come into play when these conditions are compared. ERP differences may reflect a combination of these factors, all of which potentially contribute to the behavioral priming effects observed in the subsequent overt response facilitation. Both of these ERP repetition effects were relatively broadly distributed and in many ways were similar to each other. Nevertheless, despite the simple pattern of priming revealed by lexical decision times, the priming for within-modality and cross-modality repetitions is not simply a comparison between strong priming and less-strong priming. Rather, the ERP data suggest that a set of qualitative differences between conditions is at work. Given that more focal, occipital visual

ERPs have been associated with perceptual priming effects related to processing visual word-form (Paller et al., 1998; Paller & Gross, 1998), it appears that perceptual priming results from altered processing in several brain regions, not just a single region. The activity of these different brain regions reflect several distinct cognitive operations, which can be monitored as they occur with ERP methods, even if the specifics of their functioning call for further analyses.

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