

Research report

# Event-related brain potentials during auditory and visual word recognition memory tasks

Jürgen Kayser\*, Regan Fong, Craig E. Tenke, Gerard E. Bruder

*New York State Psychiatric Institute, Department of Biopsychology, Box 50, 1051 Riverside Drive, New York, NY 10032, USA*

Accepted 31 July 2002

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## Abstract

Event-related brain potentials (ERPs) recorded during presentation of a series of words or pictures show enhanced positivity between 300 and 800 ms after presentation of repeated items. However, little attention has been directed to the characterization of this ERP recognition memory effect using auditory stimuli. The present study directly compared the ERP ‘old/new effect’ for words presented in the visual and auditory modalities. Nose-referenced ERPs were recorded from 30 electrode sites while participants ( $N=16$ ) were engaged in visual and auditory continuous word recognition memory tasks. Spatially and temporally overlapping ERP components were identified and measured by covariance-based principal components analysis. The expected old/new effect was observed in both modalities, with a comparable time course peaking at 560 ms, but having a more anterior scalp topography for visual items. This suggests a common cognitive process (i.e. successful retrieval of information from memory) associated with separable neural generators in each modality. Despite this temporal synchronization, the old/new effect overlapped ERP components having distinct scalp topographies (N2) or peak latencies (P3) for each modality. The positive-going old/new effect was preceded by an earlier negativity peaking at 370 ms that was greater across modalities for old than new words, likely reflecting semantic processing aspects of word recognition memory. A late (beyond 900 ms), broadly-distributed negativity was also greater for old than new words, prolonged for auditory items, and may represent activity of a post-retrieval process.

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*Theme:* Neural basis of behaviour

*Topic:* Learning and memory: systems and functions

*Keywords:* Event-related potentials (ERPs); Recognition memory; Visual and auditory modality; Principal components analysis (PCA)

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## 1. Introduction

Event-related potentials (ERPs) represent time-locked electrical brain activity associated with successive stages of information processing [21]. This methodology allows for the recording of discrete changes in brain activity with a high degree of temporal resolution, making it an unique method for studying real time aspects of cognitive processes that contribute to recognition memory [25]. Electrophysiological correlates of memory-retrieval processes have been examined by measuring ERPs during explicit memory tasks, in which subjects make ‘old’ or ‘new’

judgments for a series of stimuli, some of which are repeated once. ERPs elicited by correctly identified old items are typically found to be more positive when compared to correctly identified new items [23,24,65,68]. This finding has been labeled the ERP ‘old/new effect’ [25]. This old/new effect begins around 400 ms post-stimulus, continues for 300–400 ms, is prominent over posterior regions, and has been observed with either words [23,68], pictures [24,96], faces [29,74], or other visual stimuli [9,48]. The old/new effect has been interpreted as a representation of retrieval processes involved in the subject’s ability to consciously discriminate old from new items [55,68]. This conclusion is supported by experiments that varied contextual or source information for studied items (e.g. visual–auditory, male–female voice) [76,89–91], indicating that the posterior old/new effect reflects episodic memory processes associated with recollection.

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\*Corresponding author. Tel.: +1-212-543-5169; fax: +1-212-543-6540.

E-mail addresses: [kayserj@pi.cpmc.columbia.edu](mailto:kayserj@pi.cpmc.columbia.edu) (J. Kayser), URL address: <http://psychophysiology.cpmc.columbia.edu>

A similar increase of positivity to repeated items can be observed during implicit or indirect memory tasks, in which subjects make a decision that is unrelated to recognition memory (e.g. whether items are ‘natural’ or ‘man-made’ [43]). Although some evidence has been presented that this so-called ERP ‘repetition effect’ or repetition priming effect can be dissociated temporally and topographically (earlier occurrence between 300 and 500 ms with little frontal contribution) from the conscious old/new effect [35,67], it is unclear whether the ERP repetition effect represents an electrophysiologic correlate of non-conscious memory retrieval processes [25], and to what extent repetition priming effects contribute to the old/new effect. The difficulty determining precisely what or how many processes are actually reflected by the old/new effect is further aggravated by the effect’s relatively long time span (i.e. about 300–400 ms or even longer), which encompasses at least two distinct ERP components in visual recognition memory tasks: a negativity peaking at approximately 400 ms (N400, N2) and a positivity peaking around 600 ms (P600, P3). Although conceptualizations of N400 and P3 have included semantic and decision processes (e.g. see review by Friedman [25]), among various others, the cognitive correlates associated with any ERP component depend heavily on the context of the experimental paradigm, making across-paradigm ERP interpretations tentative, at best. Furthermore, the scalp distribution of the old/new effect differs from those of N400 and P3 [34,43], which implies a different contribution of neural generators and probably altogether different cognitive processes as well [25].

Data from human lesion studies [69,80,88], functional imaging [20,95], and intracranial ERP recordings [30,31,81] strongly indicate that medial temporal lobe (MTL) structures, which are well-known to participate in memory processes [71,83], contribute to the scalp-recorded ERP old/new effect, presumably by indirect modulation of cortical activity via efferent projections. Studies using depth electrodes targeting MTL structures in patients undergoing treatment for temporal lobe epilepsy have described components with a morphology and latency similar to the scalp N400 and P600 components, which were more positive when items were repeated [30,31,69,80,81]. However, while the old/new effect may be reduced or eliminated in cases of extensive MTL damage (either surgical or pathological), it is not generally disrupted by seizure foci in the temporal lobes [62,69,80,81,88].

Although some ERP recognition memory studies have addressed cross-modal (e.g. auditory/visual) priming effects in a study-test paradigm [66,90], the main focus of research in this area has been on visually presented stimuli, with few ERP studies examining recognition memory in the auditory modality. Gonzalez and Paller [28] manipulated level of processing while subjects remembered spoken words during a study phase (visualize the word

versus detect letters), and observed a dissociation of ERP priming and recognition effects during the test phase, with more positive ERPs between 600 and 900 ms for more thoroughly studied items. Using environmental sounds, Chao et al. [11] observed an ERP old/new effect for correctly recognized items, however, its topography varied with the delay between initial and second presentations, being largest over Pz for a short delay (2 s), but over Oz for a longer delay (4–12 s). This suggests variations in stimulus presentation that affect retrieval processes also affect the topography of the old/new effect, even within a single modality.

Behavioral studies in normal volunteers and brain lesioned patients suggest that visual and auditory short-term memory processes are distinct and involve separate neural paths and representations [26,50,56,57,77,87]. Dual-task studies evidenced less interference between two concurrent tasks when cross-modality stimuli were employed, for instance, presented in the auditory modality in one task but visually in the other, compared with presenting all stimuli to one modality [2,63,64], which implies the utilization of at least partially-independent resource systems. Penney [56,57] suggested that the short-term memory trace laid down when the subject silently articulates visually presented items does not hold the same information as the trace when a word is heard. Auditory items are automatically encoded and maintained in both an acoustic code, which holds information regarding the sensory properties of the stimulus, and a phonological code, which includes information regarding words, phonemes and articulation, similar to the one proposed in Baddeley’s model of working memory [3]. In contrast, visually presented items are retained in both the phonological code, which is also thought to represent their silent articulation, and a visual code, which includes grapheme and orthographic information. Whereas the phonological code is common to both auditory and visual information, acoustic and visual codes are unique to stimuli that are heard or read. ERPs should reflect the time course and anatomy of these separate streams of perceptual, linguistic, and mnemonic processes, beginning in primary and secondary modality-specific cortices, that is, dorsal-superior portions of the temporal lobe (Heschl’s gyrus, AII) for auditory information, and ventral-occipital regions (VI, VII) for visual information. These distinct pathways converge for higher-order conceptual processes (e.g. semantics), which in turn depend on structures (e.g. the extrasyllabic temporo-parietal region) subserving these functions (e.g. grapheme-to-phoneme conversion originally postulated to involve angular gyrus and Wernicke’s area [61]).

Little is currently known about the ERP correlates of auditory word recognition memory processes. In light of the behavioral evidence suggesting separate auditory and visual processing streams, a direct comparison of auditory and visual ERP old/new effects should provide elec-

trophysiologic evidence of the separability of those processing streams and the different neural pathways involved. To our knowledge, such a direct comparison has not been reported. Thus, this initial study examined the properties of the ERP old/new effect across modalities in a within-subjects design, using the same visual and auditory stimuli in the same continuous word recognition memory paradigm.

## 2. Materials and methods

### 2.1. Participants

ERPs were recorded from 22 volunteers (12 men) who were paid \$15/h for their participation. Subjects were recruited through newspaper and informal personal advertisements. The experiment was undertaken with the understanding and written consent of each subject. All participants were screened to exclude those with current or past neurologic or psychiatric disorders. Hearing acuity was also assessed using standard audiometric procedures, which required all participants to have a difference of less than 10 dB between ears at threshold and a hearing loss no greater than 25 dB at 500, 1000, or 2000 Hz. Two subjects (one male) were excluded after confusing old and new response buttons. Four additional subjects were excluded because of excessive artifact in the EEG data caused by large, frequent, and incorrectable eye blinks (one male, one female), and noise from faulty electrode connections (two males).

The ages of the remaining 16 participants (eight male), whose data were analyzed and appear in this report, ranged from 24 to 40 years (mean=31.7, S.D.=6.2). Mean education level was 17.4 years (S.D.=1.4). All participants were right-handed as assessed by the Edinburgh Handedness Inventory [53], with a mean Laterality Quotient (LQ) of +80.4 (S.D.=21.4; range +30.0 to +100.0). Handedness LQ can vary between -100.0 (completely left-handed) and +100.0 (completely right-handed).

### 2.2. Word recognition memory task

A continuous word recognition memory paradigm was used [78], in which a series of words is presented and participants indicate for each word whether it was new (never presented in the series) or old (presented previously) by pressing one of two buttons on a response pad. Words were arranged in four separate blocks composed of 114 trials, two blocks in the auditory and two in the visual modality. Participants were informed that there would be no overlap between blocks for word repetitions and that they should try to respond to every stimulus as quickly and accurately as possible. Response hand assignment (i.e. left/right button press for old/new responses) was balanced within participants across modalities. Responses

were accepted from 200 ms post-stimulus onset until the next stimulus onset.

In the visual condition, graphic files showing word items in black on a light gray background were presented in foveal vision on a computer monitor (400 ms duration), subtending a vertical angle of 0.95°, and horizontal angles ranging from 3.3 to 8.7°. In the auditory condition, sound files of word items (median duration=411 ms; range=229–718 ms) were recorded in a male voice at a sampling rate of 16 kHz using a commercially available text-to-speech computer program (Dragon Systems, Inc.) to control for the variability in emotionality and intonation that occurs in a human voice, and were presented binaurally through headphones at a comfortable listening level of about 72 dB SPL. For both modalities, a constant 2-s stimulus onset asynchrony was used. A fixation cross in the center of the screen was visible throughout the auditory task to minimize eye movements, and between stimulus exposures in the visual task to also indicate stimulus location.

Applying previously established norms for word frequency [44] and concreteness [54], a total of 320 nouns (word frequency range of 50–375 per million; concreteness rating ranged between 247 and 670) were selected from the MRC Psycholinguistic database [14], and arranged in four lists of 80 words at the beginning of the study. Word assignment to the lists was random, with the constraint that values for word frequency and concreteness were balanced across lists. For each list, an item sequence was constructed so that an equal number of words ( $n=17$ ) was repeated once following either a short lag (eight intervening items) or a long lag (24 intervening items). Thus, each sequence had 34 words that repeated once, 17 at each lag, and 46 filler words that did not repeat, yielding a total of 114 items per sequence. Items that were repeated were considered *new* items at the first presentation, and *old* items at the second presentation, and these repeated items formed the basis for the subsequent data analysis to compare 'true' memory effects that are largely independent of the physical and connotational differences between stimuli. In contrast, never-repeated words were considered *filler* items and not included in the data analysis. Word presentation order was pseudo-randomized within each sequence to yield an equal distribution of short and long lags.

All four word sequences were presented to each participant in four blocks of 114 items (456 trials total), with two sequences (blocks) presented in the auditory modality, and the other two sequences in the visual modality. Two different modality presentation orders, auditory–visual–visual–auditory (AVVA) or visual–auditory–auditory–visual (VA AV), were counterbalanced across participants. To avoid confounding response hand assignment and modality, each participant responded in the first two blocks with either the left (L) or the right (R) hand to old items, and vice versa in the other two blocks. These two response

hand orders (i.e. LLRR or RRLL) were systematically combined across participants with the modality orders (i.e. AVVA or VAAV), yielding four different modality/response hand presentation orders (e.g. AL–VL–VR–AR). A random order was chosen for the four word sequences and converted to a 4×4 latin square, so that each word sequence is placed at each of the four possible positions within a presentation order, with similar relative position to the other three word sequences across the rows of the latin square. The four modality/response hand presentation orders were systematically assigned to the four rows of the latin square, yielding four stimulus permutations, which were yoked across gender. This system guaranteed a fully balanced assignment of presentation order with respect to modality, response hand, and word sequence across participants for each gender.

### 2.3. Data acquisition and recording procedures

Scalp EEG was recorded from four midline (Fz, Cz, Pz, Oz) and 13 lateral pairs of tin electrodes (FP1/2, F3/4, F7/8, FC5/6, FT9/10, C3/4, T7/8, CP5/6, TP9/10, P3/4, P7/8, P9/10, O1/2) using an electrode cap (Electro Cap International, Inc.) with a nose electrode as reference and an Fpz ground. Standard tin drop electrodes at supra- and infra-orbital sites surrounding the right eye were used to monitor eye blinks and vertical eye movement (bipolar), and electrodes at right and left outer canthi monitored horizontal eye movements (bipolar). All electrode impedances were maintained at 5 k $\Omega$  or less and were recorded through a Grass Neurodata acquisition system at a gain of 10k (5k and 2k for horizontal and vertical eye channels, respectively), with a bandpass of 0.01–30 Hz. A PC-based EEG acquisition system (Neuroscan) was used to continuously sample the data at 200 Hz during the task. Responses and response latencies were recorded online along with the EEG data for later analyses. Recording epochs of 2000 ms (300 ms pre-stimulus) were extracted off-line, tagged for A/D saturation, and low pass filtered at 20 Hz (–24 dB/octave). Blinks were corrected on a trial-by-trial basis using a linear regression routine [75]. Epochs contaminated by amplifier block or drift, residual blinks, lateral eye movements, muscle activity or movement-related artifacts were excluded from analysis by means of a rejection criterion of  $\pm 100$   $\mu$ V on any channel and direct visual inspection of the raw data. ERP averages were computed for each condition (old/new), lag (short/long), and modality (visual/auditory) for artifact-free trials (correct responses only). ERP waveforms were screened for electrolyte bridges [84], spline-interpolated to 256 sample points (128 Hz) to facilitate cross-study comparisons [37], and digitally low pass filtered at 12.5 Hz (–24 dB/octave). ERPs were separately normalized for each modality by vector scaling across time, electrodes, condition and lag following the procedure suggested by McCarthy and Wood [47]. This approach effectively normalized modality-spe-

cific variance within subjects. However, the original and normalized grand mean waveforms were highly comparable. Finally, a 100-ms baseline correction was applied to the normalized ERP waveforms.

### 2.4. Data reduction and analysis

Excluding filler items (i.e. unrepeated words), correctly identified new and old words were included in the ERP averages, resulting across lags in a mean number of 57.0 (S.D.=7.8, range 43–67) and 49.1 (S.D.=7.5, range 34–63) trials for new and old items in the visual condition, and 49.7 (S.D.=11.2, range 31–65) and 42.8 (S.D.=10.8, range 24–60) trials for the corresponding items within the auditory condition. Despite the smaller number of trials for the auditory task,  $F_{1,14}=9.68$ ,  $P=0.008$ , and for repeated items,  $F_{1,14}=12.0$ ,  $P=0.004$ , a visual inspection of the ERP waveforms plotted for each participant and each condition revealed an acceptable signal-to-noise ratio in all instances.

To determine common variance sources in the ERP data, particularly with respect to the ERP old/new effect across modalities, the averaged waveforms were submitted to a temporal principal components analysis (PCA) derived from the covariance matrix, followed by unscaled Varimax rotation (see Refs. [12,60]). This approach results in the generation of distinctive PCA components (i.e. the factor loadings) and corresponding weighting coefficients (i.e. the factor scores), which more efficiently describe the variance contributions of temporally and spatially overlapping ERP components than conventional ERP measures (e.g. yielding larger effect sizes [37,38,40,42] or higher reliabilities [7]). The factor scores can be interpreted as weighted time window amplitudes if the associated factor loadings span a narrow and cohesive time interval and lack inverse or secondary loadings at different latencies [38,39,41]. The correspondence between the time course and topography of PCA factors and ERP components (e.g. N1, N2, P3) allows identification of physiologically relevant factors for further analysis, which is analogous to the identification of relevant deflections or time intervals from visually inspecting grand mean ERPs (i.e. this approach also uses common ERP knowledge and reasoning), but the latter lacks the ‘data-driven’ objectivity and orthogonality of variance contributions [41,60]. Although several limitations of PCA techniques (e.g. misallocation of variance resulting from latency jitter or component overlap) are well-known and demand cautious attention, it is important to recognize that peak- or time window-based ERP measures are subject to the very same limitations, but, unlike PCA, these constraints are rarely made explicit (e.g. Refs. [1,6,12,16,49,93]). Using BMDP statistical software (program 4M [18]), the temporal PCA was computed for 218 sample points (–100 to 1600 ms) as data matrix variables (columns), and 3840 cases (rows) resulting from the combination of participants (16), modality (2), conditions

(2), lag (2) and electrode sites (30). The number of orthogonal factors extracted and rotated by the PCA was not limited to maximize the removal of ‘noise’ from meaningful components [41].

Fig. 1 shows the time courses of the factor loadings for the first seven PCA factors, which together accounted for 86.5% of the variance after Varimax rotation, and the corresponding factor score topographies for each modality. PCA factors were identified by linking their temporal characteristics (i.e. the peak latencies of the noninverting, triangular factor loadings) and their spatial configurations (i.e. using the factor score topographies for each condition and modality; see Refs. [38,39]) to the original ERPs.

Factor *F130* (peak latency 130 ms, 3.8% explained variance) corresponded to a left-lateralized inferior-parietal negativity (N1) in the visual task, and a central negativity (N1) in the auditory task (Fig. 1). Factor *F220* (220 ms, 6.3%) corresponded to a prominent central positivity (P2), particularly in the auditory task, and a lateral-parietal negativity, particularly in the visual task. Factor *F370* (370 ms, 7.5%) had a midline negativity, being maximum at

sites Cz (auditory task) and Oz (visual task). Factors *F520* (520 ms, 17.6%) and *F750* (750 ms, 19.3%) revealed posterior P3-like topographies having mid-parietal (*F520*) and left posterior (*F750*) maxima in visual and auditory tasks, respectively. Factors *F1000* (1000 ms, 13.9%) and *F1350* (1350 ms, 19.3%) corresponded to a broadly distributed late negativity for old items, which had a longer duration in the auditory task (e.g. see site Pz in Figs. 2 and 3). Factors *F130* and *F220* closely corresponded to early ERP components (N1, P2) and had distinct, modality-specific topographies. However, as there were no a priori predictions of condition-related effects for these components, and there was no clear evidence of early old/new effects (see Fig. 4), statistical analyses were confined to the first five principal components extracted (*F370*, *F520*, *F750*, *F1000*, *F1350*).

### 2.5. Statistical analysis

For analyses of the behavioral data, response latency

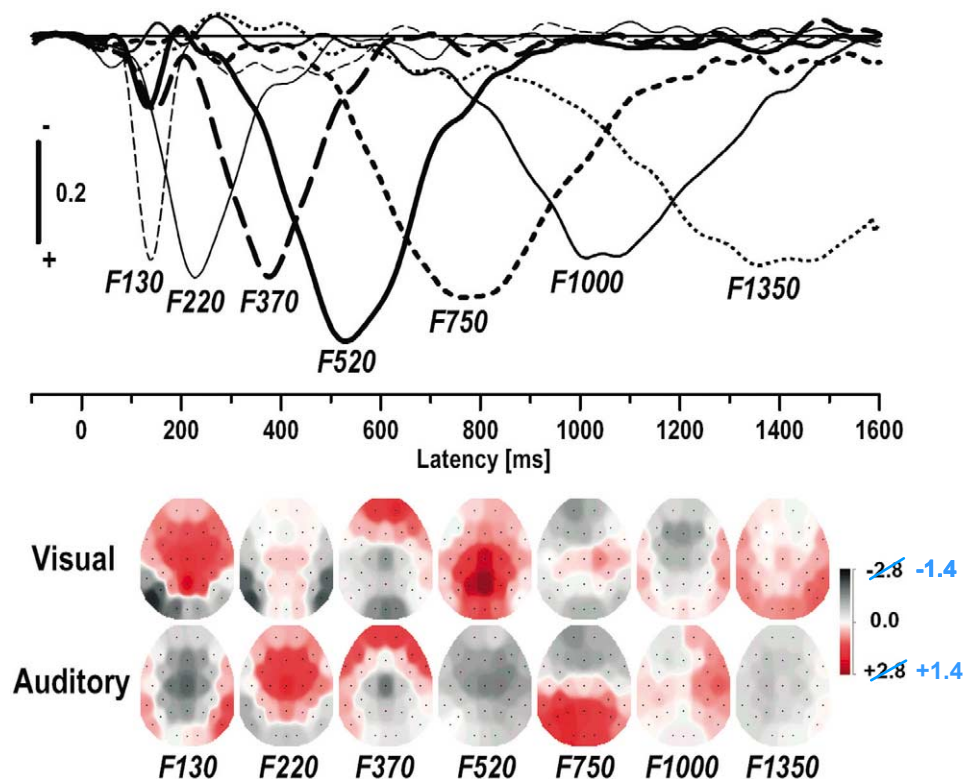


Fig. 1. Varimax rotated (unscaled) factor loadings plotted over time (top) and topographies of associated factor scores (bottom) for seven orthogonal factors extracted by principal components analysis (PCA). Factor labels (in italics) were chosen to reflect the time course of the factor loadings (i.e. their peak latencies). Because factor loadings were characterized by low secondary loadings (maximum loadings centered in a narrow time range), PCA factors may be interpreted as a measure of weighted time window amplitude (see Refs. [38,39]). Factor score topographies, which are shown separately for each modality (averaged across condition and lag), represent the contribution of each scalp region. The sign of the factor scores reflects the polarity of the corresponding event-related potential (ERP) (red shades are associated with positive ERP components, black shades with negative ERP components). No units are given for factor loadings and factor scores (i.e. PCA component coefficients and weights), however, the original ERPs [ $\mu\text{V}$ ] can be reconstructed by adding the grand mean ERP waveform to the sum of the scores-by-loadings products for each factor, which is simply a result of using a covariance matrix for factor extraction (e.g. Ref. [1]).

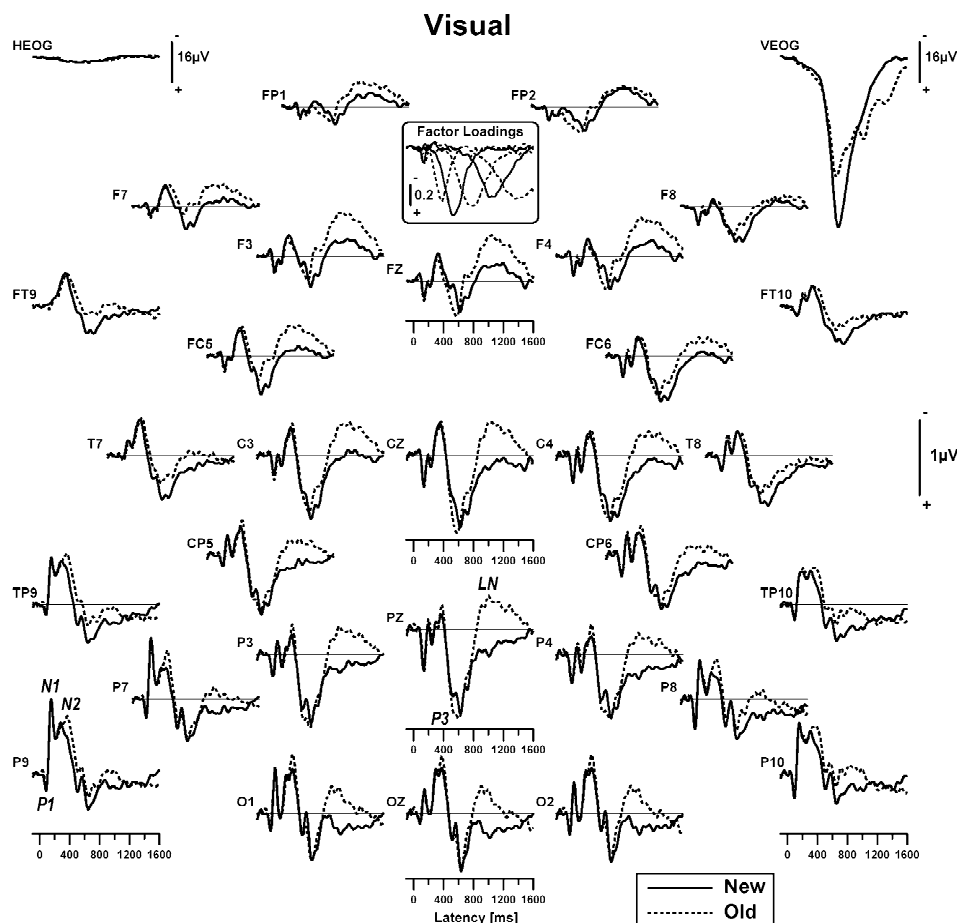


Fig. 2. Grand average event-related potentials ( $N=16$ ) for correctly identified new (solid) and old (dashed) words for the visual modality at all recording sites. Visual ERPs were normalized within this modality by vector scaling across time, electrodes, condition and lag following the procedure suggested by McCarthy and Wood [47]. Visual ERP components (in italics) are indicated at sites where they are prominent (i.e. P1, N1, and N2 at site P9, and P3 and LN at site Pz). The loadings of the first five PCA factors, four of which revealed old/new effects in the statistical analyses of the corresponding factor scores, are shown in the inset to facilitate their interpretation. Eye channels show averaged horizontal (HEOG) and vertical (VEOG) electrooculograms before artifact removal (blink correction).

(mean response time of correct responses) and percentages of correct responses were submitted to repeated measures analysis of variance (ANOVA) with condition (old/new), lag (short/long), and modality (visual/auditory) as within-subjects factors. As in our previous word recognition memory study [37], the  $d'$ -like sensitivity measure  $d_L$  was also calculated from the hit rate and false alarm rate [82] and submitted to an ANOVA with lag and modality as within-subjects factors.

As no significant effects of lag were observed for any of the behavioral measures (see below), and variations of lag were of secondary interest for the present objective, ERP measures were pooled across lag to reduce the complexity of the design for this report. For the same reason, statistical analyses focused on midline sites, because these analyses by and large captured the main findings of interest, that is, ERP old/new effects for each modality. Given this and the exploratory character of the study, modality-specific (e.g. N1 and P2 as represented by factors  $F130$  and  $F220$ )

and/or condition-related laterality effects were omitted from this report.<sup>1</sup> The factor scores of the first five PCA components extracted were submitted to repeated measures ANOVA with condition (old, new), modality (visual, auditory), and electrode site (Fz, Cz, Pz, Oz) as within-subjects factors. Greenhouse–Geisser epsilon ( $\epsilon$ ) correction was used to evaluate  $F$  ratios for within-subject effects where appropriate [86]. Significant interactions were followed-up by simple effects to explore the source of the interaction (BMDP-4V [18]). Gender (male/female) was entered as a control factor in all statistical analyses, but was not considered further as it accounted for little variance.

<sup>1</sup>An independent replication study based on a larger sample is currently under way and will more thoroughly address topographic effects of visual and auditory continuous word recognition memory.

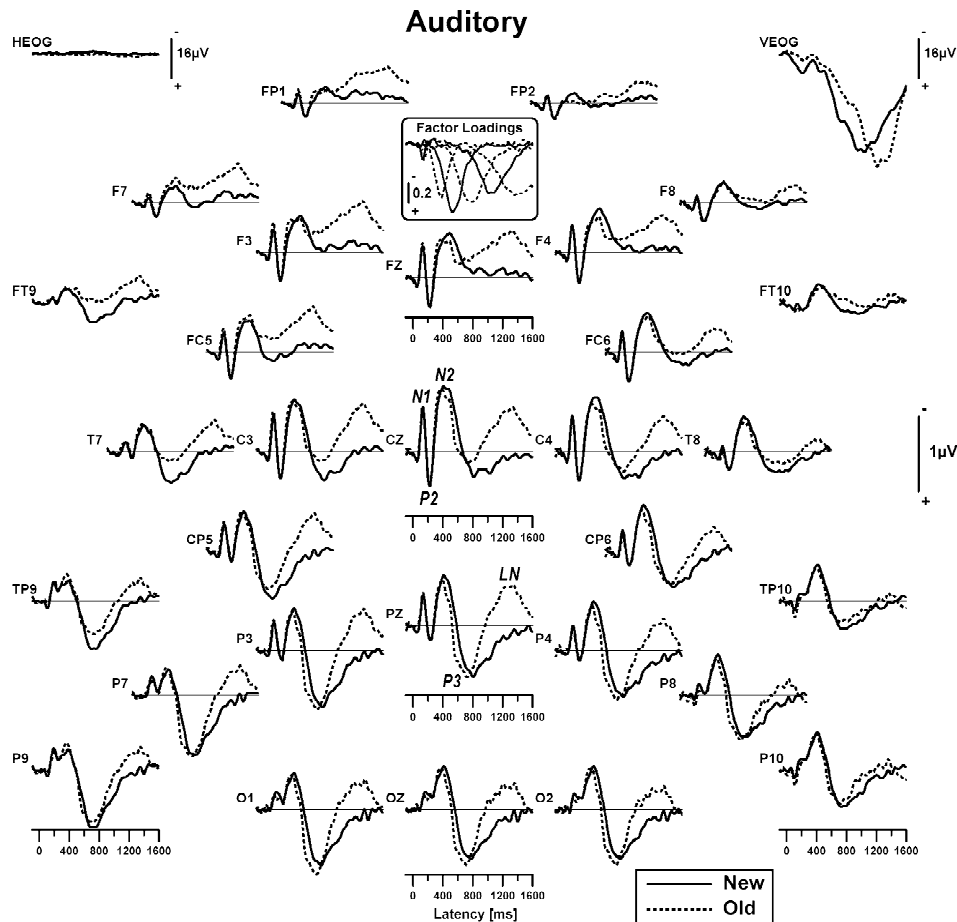


Fig. 3. Grand average event-related potentials ( $N=16$ ) for correctly identified new (solid) and old (dashed) words for the auditory modality at all recording sites. Auditory ERPs were normalized within this modality by vector scaling across time, electrodes, condition and lag following the procedure suggested by McCarthy and Wood [47]. Auditory ERP components (in italics) are indicated at sites where they are prominent (i.e. N1, P2, and N2 at site Cz, and P3 and LN at site Pz). Factor loadings (in inset) and eye channels are as indicated in Fig. 2.

### 3. Results

#### 3.1. Behavioral data

Table 1 summarizes the behavioral data for both modalities. The participants' ability to distinguish old from new items was well above chance, as can be seen from both the correct responses for old items and the sensitivity measure ( $d_L$ ), and revealed no differences between the visual and auditory modality. However, mean response latency was significantly shorter in the visual than auditory task, particularly for new items (Table 1). There were no significant main or interaction effects involving lag for any behavioral measure, and there were no other significant effects involving modality.

#### 3.2. Electrophysiological data

Figs. 2 and 3 show the normalized grand mean ERPs for the visual and auditory task, respectively, comparing the

waveforms for new and old words. The differences of these waveforms, that is, the time courses of the old/new effect for visual and auditory modalities, are shown in Fig. 4. For the visual task, distinctive ERP components were identified as P1, N1, and N2, particularly over left lateral-parietal sites (e.g. see P9 in Fig. 2), and as P3 and a late negativity (LN) over posterior sites (e.g. see Pz in Fig. 2). For the auditory task, distinctive ERP components were identified as N1, P2, and N2, particularly over central sites (e.g. see Cz in Fig. 3), and as P3 and LN over posterior sites (e.g. see Pz in Fig. 3). As expected, peak latencies and topography of individual components varied according to modality.<sup>2</sup>

Modality- and condition-specific ERP variance was

<sup>2</sup>Animated topographies of the grand mean normalized surface potentials for both modalities, comparing old and new items and the corresponding task difference maps (old-minus-new), can be obtained at <http://psychophysiology.cpmc.columbia.edu/cbr2002>.

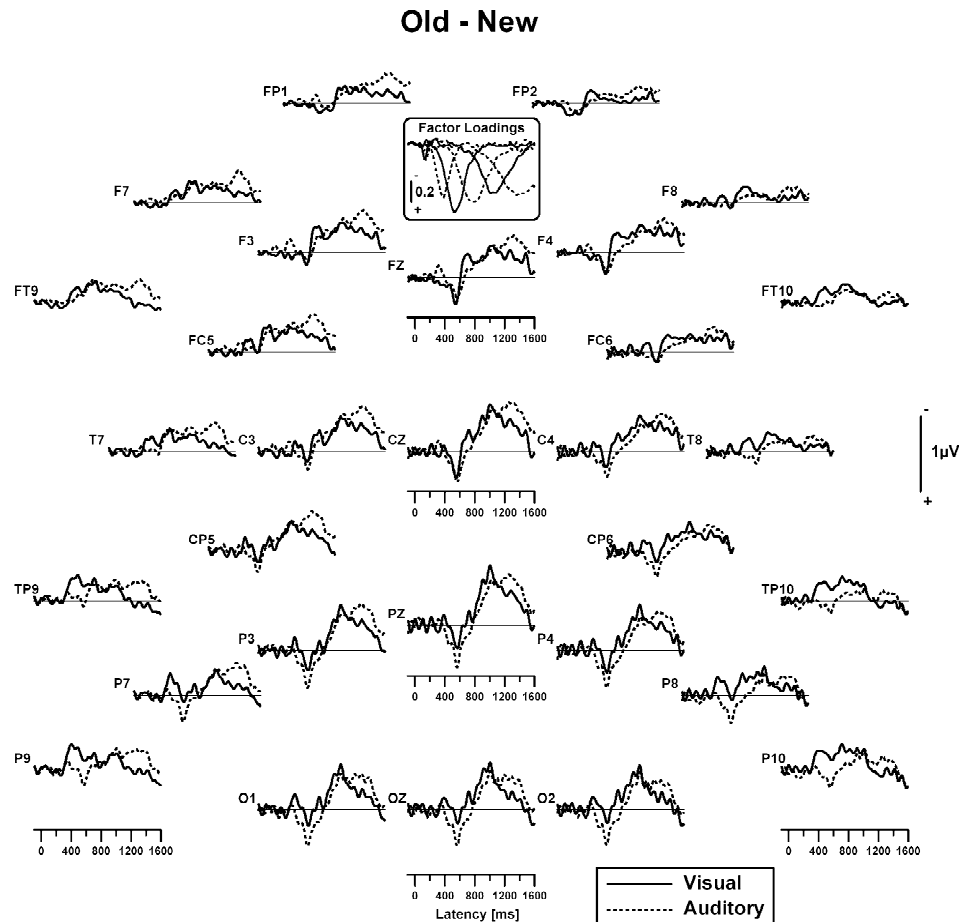


Fig. 4. Event-related potential old/new effect (old-minus-new difference waveforms) for visual (solid) and auditory (dashed) modalities. Factor loadings (in inset) are as indicated in Fig. 2.

effectively represented by the extracted PCA factors, which can be seen by comparing the ERP waveforms with the PCA factor loadings (see inset in Figs. 2–4). The statistical effects for the analyses of the associated PCA factor scores at midline sites are summarized in Table 2. Mean amplitudes of those four PCA factors revealing significant old/new effects are plotted in Fig. 5 for each modality across midline sites.

The characteristic old/new effect of increased positivity to correctly identified old compared to new items was evident for both modalities from approximately 480 to 620 ms (e.g. see midline sites in Figs. 2 and 3). Despite the difference in P3 peak latency for the visual (at Pz, 600 and 620 ms for old and new items, respectively) and auditory task (720 and 800 ms), the latency of this old/new effect was approximately the same for both modalities with a

Table 1  
Behavioral data summary: grand means (S.D.) and ANOVA  $F$  ratios

Modality	Correct responses [%]		Sensitivity [ $d_L$ ]		Latency [ms]	
	New	Old			New	Old
Visual	93.1 (5.9)	78.9 (11.3)	4.17 (1.07)		658 (86)	736 (89)
Auditory	92.6 (5.9)	79.5 (11.6)	4.07 (0.97)		905 (86)	910 (94)
Effect <sup>a</sup>	$F$	$P$	$F$	$P$	$F$	$P$
Modality					171.88	<0.0001
Condition <sup>b</sup>	17.8	0.0009	–	–	8.41	0.01
Modality $\times$ Condition <sup>b</sup>			–	–	23.22	0.0003

<sup>a</sup> For all effects,  $df=1, 14$ . Only  $F$  ratios with  $P<0.10$  are reported.

<sup>b</sup> Not applicable to  $d_L$  sensitivity measure.

Table 2

Summary of *F* ratios (and  $\epsilon$  corrections) from repeated measures ANOVA performed on PCA factor scores at midline sites

Variable	df	Factor				
		F370	F520	F750	F1000	F1350
COND	1, 14	5.74*	7.57*		22.55***	4.03
COND×MODA	1, 14					
COND×SITE	3, 42				13.25*** (0.58)	5.55* (0.48)
COND×MODA×SITE	3, 42		3.44* (0.63)			
MODA	1, 14		52.93***	5.90*		6.38*
SITE	3, 42	12.01*** (0.56)	7.85** (0.50)	16.64*** (0.58)	5.12* (0.48)	
MODA×SITE	3, 42	6.08* (0.50)	13.99*** (0.56)	30.72*** (0.59)	7.41** (0.52)	

COND=condition (new, old); MODA=modality (visual, auditory); SITE=electrode site (Fz, Cz, Pz, Oz). Only *F* ratios with  $P < 0.10$  are reported. \*  $P < 0.05$ ; \*\*  $P < 0.01$ ; \*\*\*  $P < 0.001$ .

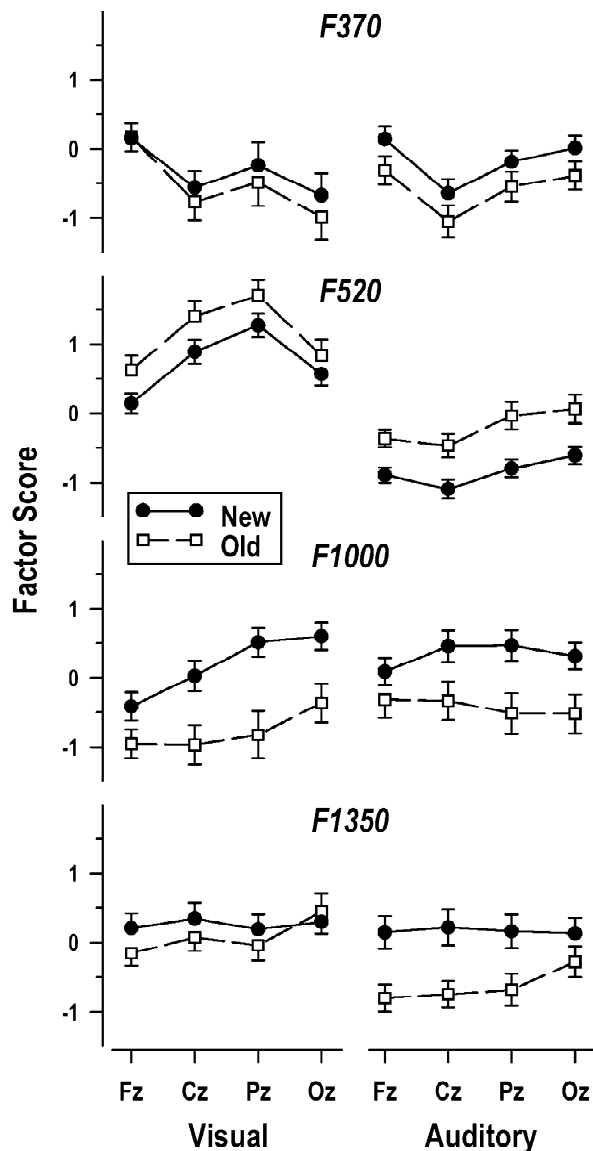


Fig. 5. Mean factor score amplitude (and standard error of the mean) of PCA factors *F370*, *F520*, *F1000*, and *F1350* at midline sites for new (solid) and old (dashed) words, plotted separately for visual (left panel) and auditory (right panel) modalities. The significant old/new condition effects of these four PCA factors are detailed in Table 2.

peak at around 560 ms (Fig. 4). This effect was captured by factor *F520*, which revealed a robust condition main effect stemming from a more positive *F520* amplitude to old items for both modalities at all midline sites (Fig. 5). The condition main effect was modulated by a three-way condition×modality×site interaction. The origin of this triple interaction was clarified by systematically exploring simple effects, which revealed significant condition effects for the auditory modality at each midline site (all  $F_{1,14} > 6.22$ , all  $P < 0.05$ ), whereas for the visual modality only sites Fz ( $F_{1,14} = 3.86$ ,  $P = 0.07$ ) and Cz ( $F_{1,14} = 3.64$ ,  $P = 0.08$ ) attained marginal significance for simple condition effects. Apart from these condition effects, a modality-specific midline topography of factor *F520* was confirmed by main effects of modality and site and a modality×site interaction, which resulted from a classical P3b topography in the visual task (i.e. maximum at Pz), as opposed to a smaller and more homogenous *F520* topography in the auditory task (Fig. 5).

Similarly, factor *F750* reflected the P3 topography in the auditory task with maximum amplitude at Pz, while a smaller, vertex-maximum *F750* topography was observed in the visual task (Fig. 1). The modality specificity of *F750* was statistically supported by modality and site main effects and a modality×site interaction (Table 2). However, no condition-related effects were observed for this factor.

In addition to the characteristic old/new effect of increased positivity, an old/new effect for both modalities was evident for the LN component, which was almost exclusively observed for old items (Figs. 2 and 3). However, in contrast to the simultaneous occurrence of increased positivity to old words across modalities, the increased negativity to old words peaked earlier for the visual (around 1000 ms) than auditory modality (around 1250 ms), which can be seen in Fig. 4. The LN old/new effects were represented by factors *F1000* and *F1350*, which revealed condition main effects (marginally significant for *F1350*) and condition×site interactions (Table 2). Across modalities, the simple condition main effects were most robust for factor *F1000* at sites Pz ( $F_{1,14} = 33.7$ ,  $P < 0.0001$ ), Oz ( $F_{1,14} = 27.8$ ,  $P = 0.0001$ ), and Cz ( $F_{1,14} =$

17.3,  $P=0.001$ ), but less prominent at Fz ( $F_{1,14}=6.72$ ,  $P=0.02$ ), whereas simple effects for condition decreased for factor  $F1350$  from anterior to posterior sites (at Fz,  $F_{1,14}=7.41$ ,  $P=0.02$ ; at Cz,  $F_{1,14}=5.33$ ,  $P=0.04$ ; at Pz,  $F_{1,14}=3.78$ ,  $P=0.07$ ; at Oz,  $F_{1,14}<1.0$ ; see Fig. 5).  $F1000$  amplitude was roughly equivalent for both modalities, despite having a modality-specific topography, as indicated by a modality  $\times$  site interaction; in contrast,  $F1350$  amplitude was larger for the auditory than visual task (Table 2 and Fig. 5).

The midline negativity reflected by factor  $F370$  also revealed a significant condition main effect, which stemmed from a greater negative amplitude to old than new words (Fig. 5). Thus, this ERP old/new effect preceded the increased positivity old/new effect, and had the opposite polarity. Enhanced N2 amplitudes to old words were evident in the ERP averages at midline sites (Figs. 2 and 3), but were particularly prominent for the visual task over lateral-parietal sites (e.g. see sites P9, P7, P8, and P10 in Fig. 2). Although  $F370$  amplitude varied significantly across midline locations and modality (Table 2), being largest at Oz for the visual task, and at Cz for the auditory task, the condition effect did not interact with modality or site.

It is important to note that none of the statistical analyses revealed a condition  $\times$  modality interaction (Table 2), and a three-way condition  $\times$  modality  $\times$  site interaction was only observed for factor  $F520$ , as described above. This suggests that the reported old/new effects were largely unaffected by modality, but were superimposed on a modality-specific ERP component structure.

#### 4. Discussion

Distinct ERP components were clearly evident in visual and auditory word recognition memory tasks, and revealed discrete topographies corresponding to the anatomy of visual and auditory information processing pathways. The use of temporal PCA to disentangle temporal and spatial characteristics of these overlapping ERP components across modalities yielded distinct factors associated with P3b-like positivities in the visual ( $F520$ ) and auditory task ( $F750$ ), two separate long-lasting negativities ( $F1000$  and  $F1350$ ), prominent early ERP potentials (N1, P2) with high topographic specificity for each modality ( $F130$  and  $F220$ ), and a negative potential largest over centroparietal midline sites ( $F370$ ), with N400-like electrophysiologic properties [46]. Condition-related effects were found for four of these components.

First and foremost, factor  $F520$  revealed that correctly identified old words elicited greater positivity than new words between approximately 400 and 700 ms after stimulus onset in both modalities. This replicates findings from previous studies using visually presented words [23,37,68], pictures [24,73], faces [8,79], and geometric

figures [9]. The findings from the current continuous recognition memory task add to this list an ERP old/new effect for verbal auditory material, which is consistent with previous findings using spoken words in a study-test paradigm [28]. While there was no difference in performance accuracy between modalities, response latencies were longer in the auditory than visual task, a likely result of the longer processing time required for the temporal analysis of auditory stimuli. To accurately perceive a word, subjects need to continuously process the sound over its entire duration in most instances, whereas full item information is available at stimulus onset during visual presentations. This behavioral difference was paralleled by a longer peak latency for auditory than visual P3, respectively represented by factors  $F750$  and  $F520$ , and may be ascribed to the increased stimulus-evaluation time for auditory stimuli [45]. However, despite the marked difference in peak latency of visual and auditory P3, the peak latencies of the old/new effect were strikingly similar across modalities. While the latency of the visual old/new effect approximately matched the peak latency of its late positive component, the auditory old/new effect occurred earlier than its P3 peak, and was superimposed on the auditory N2/P3 transition.

Modality-specific scalp distributions of P3 amplitude were observed for visual ( $F520$ ) and auditory ( $F750$ ) tasks, which is in agreement with evidence of modality-dependent generators for the P3 component ([32,33]; although, see Ref. [36]). In the visual modality, the topography of P3 had a mid-parietal (Pz) peak, but the auditory P3 was more broadly distributed over posterior-occipital areas, which is similar to the posterior, Oz-maximum P3 topography for environmental sounds [11]. Irrespective of these modality-specific P3 topographies, the topography of the old/new effect, which overlapped the visual P3 and the auditory N2/P3 transition, also differed between modalities, being evident across midline sites and largest at posterior locations for the auditory task, but more fronto-centrally distributed for the visual task.

The similarity in peak latency of the old/new effect suggests a common cognitive process that is independent of modality. The difference in scalp topography, however, indicates that the pattern of neural generator activity responsible for the old/new effect is different for visual and auditory modalities. Given the complexity of the process that is indexed by the old/new effect (i.e. memory retrieval), it is reasonable to assume that a single neural generator cannot account for the effect. In agreement with this, Johnson et al. [34] have described distinct patterns (spatial and temporal) of neural generator activity related to different aspects of memory retrieval that contribute to the visual old/new effect. By analogy, it is conceivable that the old/new effect in visual and auditory modalities reflects the same cognitive process (i.e. memory retrieval), which requires the integration of low-level and higher-order cognitive processes. However, due to the regional

organization of modality-specific processors in the brain and the unique processing demands imposed by each modality, different patterns of neural generator activity contribute to the overall scalp topography of the old/new effect.

Consistent with other studies employing auditory [92,94] and visual stimuli [37], the scalp distributions of early ERP components (P1, N1, P2) were evidently modality-specific, and within each modality, these early components were almost identical for new and old items (Figs. 2 and 3), presumably reflecting the activation of different neural generators associated with an early, low-level analysis of auditory and visual stimuli. The notion that certain aspects of semantic processes [46] contribute to the generation of N2 to verbal stimuli is consistent with convergent evidence demonstrating the involvement of the left posterior inferior temporal lobe in various linguistic subprocesses, independent of modality, starting as early as 200 ms after stimulus onset [37,51,52,59,61,70], and also compatible with the present data (see sites TP9 and P9 in Figs. 2 and 3). N2 amplitude was larger (i.e. more negative) for old than new items, as evident from the grand mean ERP waveforms and demonstrated by the statistical analysis of factor *F370* at midline sites. Thus, for both modalities, an enhanced negativity to old items preceded the enhanced positivity for old items, which appeared to be at odds with the majority of ERP studies reporting an enhanced positivity to old items that overlaps both N400 (N2) and P600 (P3b) in visual continuous recognition memory tasks [25]. However, before attributing this disparity post-hoc to procedural or sample characteristics, one should consider a crucial, but frequently overlooked study feature: the reference electrode. To the extent that any recording reference manifests condition effects, such effects are introduced (amplified) or removed (reduced) by choice of reference. Whereas most studies have used linked mastoids [9,19,28,34,48], linked ear lobes [29], or an average reference [74], we have consistently used a nose reference [37]. To facilitate a comparison of our findings to

those based on data referenced to linked mastoids or earlobes, ERP waveforms were rereferenced to the average activity of our mastoid EEG recordings sites (TP9/10). Apart from shifting positive and negative ERP deflections and their peak latencies across scalp locations, the visual old/new effect became completely positive between 300 and 800 ms over posterior sites (Fig. 6). Moreover, ERP rereferencing caused notably more changes to visual than auditory waveforms. All of this is not surprising, considering the prominent visual N1 and N2 components recorded at the mastoids with a nose reference, which clearly revealed condition-related differences (greater negativity) beginning with the peak of N2 (see sites TP9 and TP10 in Fig. 2). The logical consequence of placing the EEG reference at or near these sites is to shift the very same ERP condition effect, with inverted polarity, to more remote scalp locations, in this case enhancing the ERP old/new effect at mid-parietal sites by simple summation.

Several conclusions may be drawn from this observation. First, rereferencing ERPs to linked mastoids reconciled our old/new effects with previous reports using a comparable reference (although it should be acknowledged that similar old/new effects have also been reported for a nose reference [23,24,43]). The degree to which this earlier condition effect of factor *F370* with its distinct topography corresponds to the N400 repetition priming effect [35,67] is not known, as the present comparison of first and second item presentations does not allow a separation of repetition priming and old/new effects. Separating implicit and explicit mnemonic processes, however, is not relevant for the purpose of the present study, and needs to be pursued in future studies including more appropriate manipulations. Second, modality-specific ERP components and related condition-effects may be severely reduced if the recording reference is placed in the vicinity or over regions where these components are most prominent, an obvious, but nevertheless important property of the reference. Third, systematic changes of reference in addition to more sophisticated analytic procedures (e.g. such as PCA meth-

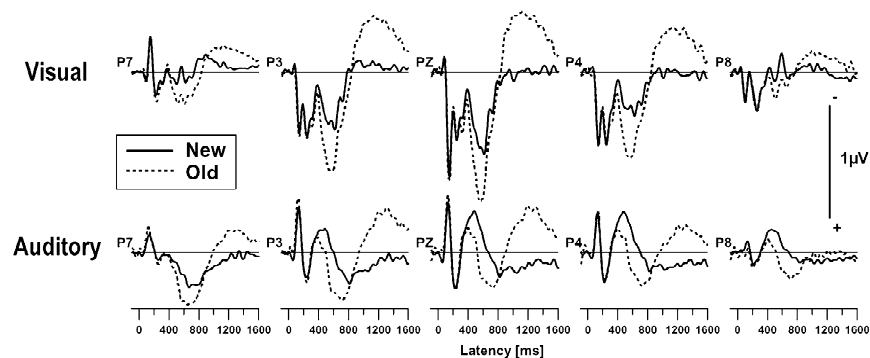


Fig. 6. Visual (top) and auditory (bottom) event-related potentials (ERPs) presented in Figs. 2 and 3 at selected sites across the parietal coronal plane, digitally rereferenced to linked mastoids (average of TP9/10). Due to the proximity of the new reference, early visual ERP components were markedly reduced at lateral-parietal sites, whereas the visual ERP old/new effect at mid-parietal sites was enhanced. Rereferencing effects were less obvious for auditory ERPs.

odology [42,41] and reference-free current source density measures [58,85]) should help to dissociate neural generators and their genuine contributions to ERP repetition priming and old/new effects, particularly when combined with suitable experimental variations [28,55].

A slow-rising, broadly distributed late negativity, which followed the late positivities (*F520* and *F750*) in both visual and auditory tasks, was greater for old than new words. However, this late negativity was represented by two different PCA factors (*F1000* and *F1350*) due to its extended duration and later peak in the auditory than visual modality. Still, the *F1000* and *F1350* condition effects were approximately equal in both modalities and did not differ significantly in scalp distribution across modalities. Considering the long latency of this effect following the motor response, along with the longer response latencies in the auditory than visual task, it is likely that this activity represents a post-retrieval process. A similar condition effect on the late negativity has been described in other studies of recognition memory using words [23,35,37], pictures [24], and faces [79]. The fact that this effect has been observed with different types of visual stimuli, and now also with auditory stimuli, suggests that it is unrelated to stimulus features, but rather might reflect the lack of further processing for old compared to new words, as suggested by Friedman [23]. Since participants knew they would not encounter an old word again, further processing of that item for later recognition was not required and these items no longer needed to be kept in memory. Another, not necessarily mutually exclusive, possibility is that the greater late negativity for old items represents processes related to performance appraisal, resulting from a greater tendency to evaluate the accuracy of old rather than new responses. If reaction time can be taken as an indirect measure of confidence level, then the slower response latencies for old items in the visual task would indicate that participants were less confident in making an old decision and may need additional processing, which would lead to greater slow wave activity. Consistent with this interpretation, reaction times for new items were also faster in the two studies by Friedman [23,24]. However, this argument does not apply to the auditory task, which revealed similar response latencies for old and new items. Clearly, more study is needed to understand the meaning of this late old/new effect.

In summary, data from the present study demonstrate modality-specific differences in scalp topography and peak latency of N2 and P3 amplitudes, which are probably related to perceptual processing differences. Despite these differences, we found comparable old/new effects for both visual and auditory modalities, beginning around 300 ms and continuing for several hundred milliseconds, with maximum increase in positivity to old words coming at the same latency for each modality. This suggests that the activation of a common, modality-independent, high-level cognitive process, such as the retrieval of information from memory, is superimposed on the modality-specific ERP

component structure (i.e. N400/N2, P600/P3b). The implication is that the electrophysiological and functional properties commonly assigned to these components are independent of the overlapping old/new effect. This interpretation is particularly supported by the apparent dissociation of the auditory old/new effect from the auditory P3, which peaked beyond 700 ms, that is, clearly after the peak of the old/new effect at approximately 560 ms in each modality. Thus, the combined use of both auditory and visual paradigms should be particularly suited to isolate various aspects of the old/new effect and their underlying processes of recognition memory [25]. Considering that the timing of the old/new effect is coincident with the activation of medial-temporal lobe structures [30,69,80,81], which are reciprocally connected to multimodal association areas, our findings support models of recognition memory which emphasize time-locked multi-regional feed-forward and feedback activation of local convergence zones and uni- and multimodal association cortices [15].

In light of the similar cognitive demands across modalities, this paradigm may also be a useful tool to broaden the scope of clinical research on memory. Moreover, considering the similarity of auditory and visual ERP old/new effects in terms of magnitude and timing, it could be particularly important to examine differences between visual and auditory recognition memory when one attempts to apply this technique to patient populations that have dysfunction of auditory processing. Examining ERP correlates of visually presented stimuli alone may provide an incomplete assessment of memory abilities in these patients. For example, Kayser et al. [37] did not find significant differences between healthy adults and patients diagnosed with schizophrenia in the parietal old/new effect during a visual word recognition memory task, despite poorer overall memory performance of the schizophrenic patients. Given the evidence for impaired verbal learning abilities [13,27,72] and structural temporal lobe abnormalities in schizophrenia [4,5], and given that P3 abnormalities in schizophrenia are more robust for auditory ERP paradigms [22], further studies employing the auditory modality may provide a more sensitive measure of the pathophysiology of memory processes in this disorder. Likewise, in agreement with evidence of memory impairments in depression [10], another recent study found that depressed patients had a markedly reduced old/new effect and poorer memory performance in a visual word recognition memory task [17]. Extending such studies to the auditory modality could yield important insights concerning the neurocognitive and neurophysiologic processes contributing to memory deficits in these disorders.

### Acknowledgements

The authors would like to thank David Friedman for helpful advice in the design of the experiment, Douglas

Potter for useful comments on an earlier version of this manuscript, and Charles L. Brown for providing ERP waveform plotting software. Raw data were collected as part of Regan Fong's PhD dissertation. We greatly appreciate several helpful suggestions by three anonymous reviewers.

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