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Memory for drawings in locations: Spatial source memory and event-related potentials

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Abstract

Event-related potentials (ERPs) were recorded during recognition tasks for line drawings (items) or for both drawings and their spatial locations (sources). Recognized drawings elicited more positive ERPs than new drawings. Independent of accuracy in the spatial judgment, the old/new effect in the source recognition task was larger over the prefrontal scalp, and of longer temporal duration than in the item recognition task, suggesting that the source memory task engaged a qualitatively distinct memory process. More posterior scalp sites were sensitive to the accuracy of the source judgment, but this effect was delayed relative to the difference between studied and unstudied drawings, suggesting that source memory processes are completed after item recognition. Similarities and differences between spatial source memory and memory for conjunctions of other stimulus attributes are discussed, together with the role of prefrontal cortex in memory.

Descriptors: Memory, Event-related potentials, Source memory, Spatial memory, Drawings

Some outstanding questions about human memory concern how people store distinct aspects of an event (or attributes of a single stimulus), retrieve these attributes, and evaluate whether or not the combination does indeed correspond to a unitary prior experience. Failures to recover all of the relevant aspects of an event are commonplace in everyday life: we may remember a story about some individual, but not who told us the story (which may bear on our eventual judgment as to whether it is rumor or fact), that we parked our car, but not where we parked it, and so on. Miscombinations of attributes can also lead to faulty memories: an eyewitness may recall a man with red hair and a gun instead of a red-headed bystander and a dark-haired robber. Memory for multiple attributes and their linkages has variously been called *episodic memory* (Schacter & Tulving, 1994), *recollection* (Jacoby & Kelley, 1992), *memory for context, memory binding* (Chalfonte & Johnson, 1996), and *source memory* (Johnson, Hashtroudi, & Lindsay, 1993). The choice of terms often reflects an implicit contrast with some other sort of memory or memory process. Episodic memories are contrasted with semantic memories, which lack the spatial and temporal features present in episodic memories. The experience of conscious recollection is typically described as including some contextual information, and contrasted with a sense of familiarity that arises from more automatic perceptual processes. Both "episodic memory" and "recollection" thus focus attention on the possibility that greater or lesser detail may reflect qualitatively distinct forms of memory. In contrast, terms such as "memory binding" focus attention not on the diagnostic value of number of features per se, but on what processes are required to correctly combine individual attributes during learning and/or retrieval.

"Source memory" includes aspects of all of these definitions in that experimental paradigms designed to contrast source memory with *item memory* include variations in both the specificity of the memory reports demanded, and the need to combine attributes of a single stimulus to produce these reports. An item memory task may ask participants to determine whether a test stimulus was studied previously or not (recognition), or to provide the answer to a question that corresponds to a previously learned fact (recall). Source memory tasks demand retrieval of additional detail, for example whether a male or female experimenter presented the stimulus originally, whether the stimulus occurred in List 1 or List 2, whether the word was studied in the auditory or visual modality, whether the fact was learned during the course of the experiment or previously known, and so forth. Source memory tasks also place high demands on the ability to correctly combine attributes, particularly given that one attribute ("the source") is typically paired with many other attributes ("the items") during the initial study phase—a female voice, for instance, may have spoken many different words. Note that recognition or recall tasks can be unambiguously described as "item memory tasks" or "source memory tasks" based on the instructions and response options offered to experimental participants. Which attribute of a given stimulus should count as the "item" and which corresponds to the

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"source" has not always been defined as clearly. We adopt the most common nomenclature of using "item" to refer to a stimulus attribute that occurs only infrequently during an experiment (e.g., the identity of a word), and "source" to refer to an attribute which reoccurs across multiple stimuli (e.g., a particular voice).

Not surprisingly, source memory tasks nearly always result in lower accuracy than item memory tasks. The greater difficulty of source memory tasks may be due to the simple demand for greater detail, a more specific demand to retrieve the right combination of attributes, or perhaps the difficulty of evaluating whether some combination of familiar features presented at test corresponds to a combination that was actually studied. A host of interesting and fundamental questions about the functional organization of memory lurk behind the simple question of how source memory tasks differ from item memory tasks, including whether different attributes of a single experience are stored separately or together, what determines the memorability of different attributes, how different attributes are linked at retrieval, and how and when stimuli that share attributes are distinguished from one another. These functional questions are, of course, closely linked to neural questions about which brain areas and physiological processes are invoked during learning and retrieval of different sorts of stimuli, and how those vary with different task demands. Although scalp-recorded event-related potentials (ERPs) provide only coarse anatomical information, they are well suited to addressing many of these issues because of their temporal resolution, and the ease of separating brain activity elicited by studied and unstudied items contingent on the success or failure of recognition.

Over the past 20 years, numerous ERP studies have demonstrated robust differences in the brain activity elicited by studied versus unstudied items in recognition tests, and have indicated that this old/new effect can be attributed to successful retrieval of studied items rather than nonspecific cognitive factors peculiar to yes/no recognition tests (Bentin & Peled, 1990; Friedman, 1990; Neville, Kutas, Chesney, & Schmidt, 1986; Paller & Kutas, 1992; Rubin, Van Petten, Glisky, & Newberg, 1999; Rugg & Doyle, 1994; Sanquist, Rohrbaugh, Syndulko, & Lindsley, 1980; Smith & Halgren, 1989; Smith & Guster, 1993; Swick & Knight, 1997; Van Petten & Senkfor, 1996). The conclusion that old/new differences in recognition tests are a fairly direct reflection of successful retrieval is secure enough that ERP studies have begun to include tests that require retrieval of more than one stimulus attribute.

We have recently compared two recognition tests for words studied in either a male or female voice (Senkfor & Van Petten, 1998). In the item recognition test, subjects responded "old" or "new" based on word identity, regardless of the correspondence between the speaker's voice in the study and test phases (same voice in both phases, or different voices). In the source recognition test, subjects were asked to judge both word identity and voice by making judgments of "old word, same voice," "old word, different voice," and "new word." We focused on the differences in ERPs elicited by old and new items, because this difference is prima facie related to memory rather than nonspecific aspects of task difficulty. In both recognition tests, studied words elicited more positive ERPs than unstudied, beginning about 400 ms after word onset. As in many previous simple recognition tasks, this old/new effect was distributed broadly across the scalp. In the source recognition task, the basic old/new effect was accompanied by a later difference between studied and unstudied items, shown in Figure 1. The second old/new effect did not begin until some 700 ms after word onset, and displayed a focal scalp distribution over prefrontal cortex. The topographic difference between the general

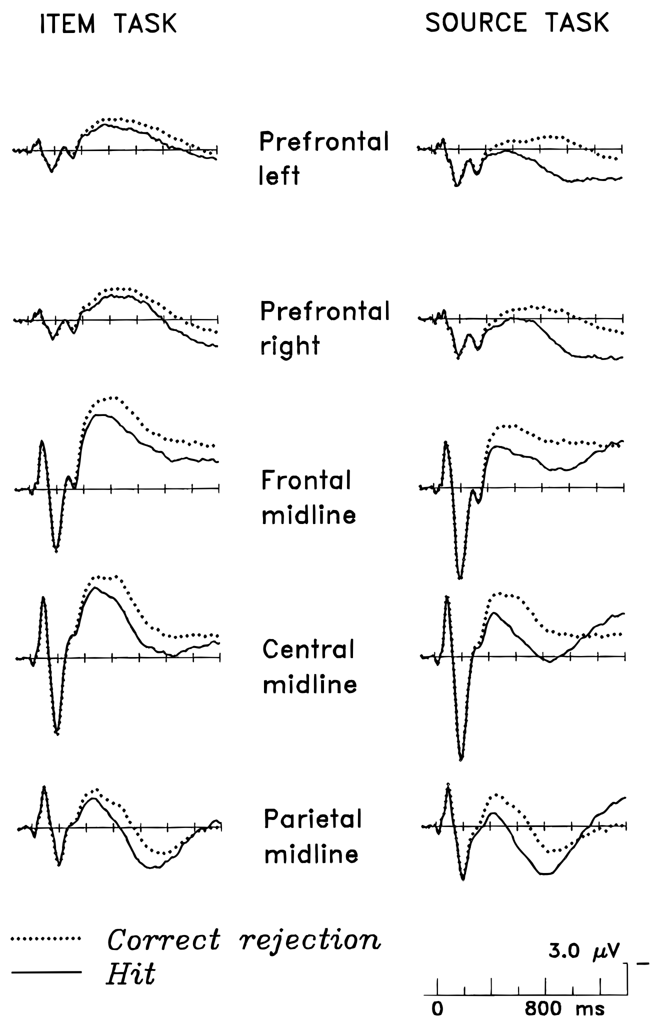

Figure 1. Grand-average event-related potentials (ERPs) for the 24 subjects of a previously published experiment (Senkfor & Van Petten, 1998). In the item recognition task, subjects responded "old" or "new" to auditory words. In the source recognition task, subjects responded "new" to new words, but "old same voice" to studied words occurring in the same voice as during the study phase, and "old different voice" to studied words that occurred in a different voice from the study phase. Hits are correctly recognized old words (independent of the accuracy of the voice judgment), correct rejections are correctly categorized new words.

old/new effect and that observed only in the source task indicated a qualitative distinction between the two recognition memory tasks, and ruled out quantitative interpretations based on level of detail alone.

The prefrontal scalp focus of the late old/new effect in our previous source recognition task is consistent with reports that patients with damage to prefrontal cortex are disproportionately impaired in source memory tasks relative to item memory tasks (Janowsky, Shimamura, & Squire, 1989; Johnson, O'Connor, & Cantor, 1997), and that source memory performance in healthy elderly individuals is correlated with neuropsychological measures thought to tap the integrity of prefrontal regions (Glisky, Polster, & Routhieaux, 1995). The sensitivity of the prefrontal old/new effect to the demands of source recognition is also broadly consistent with other recent ERP studies that have not directly compared item and source recognition within the same subjects. Wilding and Rugg

(1996) reported a frontal old/new effect in a source recognition task also using words and voices and concluded that "the prominence of this old/new effect here, as opposed to its lack of prominence in previous ERP studies of recognition memory, may be a consequence of the requirement explicitly to retrieve information about the study context of each item" (p. 903). Trott and colleagues used a source discrimination based on temporal rather than perceptual context, and similarly observed a large frontally distributed old/new effect in young adults (Trott, Friedman, Ritter, & Fabiani, 1997). Relative to these young adults, older adults in Trott's experiment showed reduced accuracy in discriminating whether test words had been presented in the first or second study list, paired with fairly good accuracy in discriminating both sorts of words from unstudied words. This pattern of age differences in memory performance was paralleled by a dramatic age difference in the prefrontal old/new effect and a weaker age difference in the more posterior old/new effect, also leading to the conclusion that the frontal effect is linked to source memory (Trott et al., 1997; see Senkfor & Van Petten, 1996, for similar aging results, but Mark & Rugg, 1998, for dissimilar results). Finally, two studies have compared item and source recognition tasks without focusing on the old/new effect, but have similarly observed greater task differences at frontal than posterior electrode sites (Johnson, Kounios, & Nolde, 1997; Ranganath & Paller, 1999).

Despite broad agreement on a central observation—that source memory tasks elicit greater prefrontal activity than simple yes/no recognition tasks—a review of existing ERP results also reveals discrepancies concerning: (1) the latency of the prefrontal old/new effect, (2) the scalp distribution of the ERP difference between trials with correct and incorrect source judgments, and (3) the lateralization of the prefrontal old/new effect. These empirical issues are (respectively) relevant to functional and neural questions about (1) whether item and source retrieval processes act in parallel or hierarchically, (2) whether prefrontal cortex is engaged only by retrieval effort, or is also sensitive to retrieval success, and (3) whether or not ERP data support Tulving's proposal that right prefrontal cortex is preferentially engaged by retrieval, in contrast to the left hemisphere's role in encoding (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). These issues are elaborated below.

In our word/voice study, we proposed that the prefrontal effect reflected an attempt to retrieve the relevant voice information for a word that had already been recognized. This proposal was grounded in two observations. First, the prefrontal effect was substantially later than the spatially widespread old/new effect. In a latency window spanning 400–800 ms poststimulus onset, the old/new difference was spatially diffuse; a prefrontal maximum was not evident until the 800–1200-ms latency window. This pattern of results, shown in Figure 2, supports Johnson's conclusion from a response-deadline procedure that source retrieval is contingent on successful item recognition (Johnson, Kounios, & Reeder, 1994). However, other ERP studies have not observed a clear temporal separation between the widespread standard old/new effect and the prefrontal effect; Wilding and colleagues reported that "distributional differences [between early and late time windows] were not statistically reliable" (Wilding, Doyle, & Rugg, 1995, p. 765). Our proposal that retrieval of items and sources are hierarchically ordered has thus not received clear confirmation, and deserves further attention.

The second part of the proposal—that the prefrontal old/new difference reflected an attempt to retrieve source information, but not the success of that attempt—bears on an issue that has also been contentious in positron emission tomographic studies (Fletcher, Frith, & Rugg, 1997; Kapur et al., 1995). Our conclusion was based on the observation that ERPs at prefrontal scalp sites did not vary as a consequence of the accuracy of the source judgment (Senkfor & Van Petten, 1998). *Hit/hit* trials (both word, and word/voice conjunction correctly judged) did not differ from *hit/miss* trials (word judged as old, but incorrectly categorized as the same or different voice) at prefrontal scalp sites. Instead, hit/hit trials differed from hit/miss only at more posterior scalp sites. Wilding and Rugg (1996) observed a spatially diffuse (rather than frontal) difference between hit/hit and hit/miss trials, but in the work of Trott et al. (1997), the largest influence of source accuracy was observed at prefrontal sites. Finally, Wilding (1999) reported a substantial difference between hit/hit and hit/miss trials at both prefrontal and parietal sites, and suggested that "two distinct sets of processes, only one of which is contingent on retrieval success, are subserved by prefrontal cortex" (p. 452).

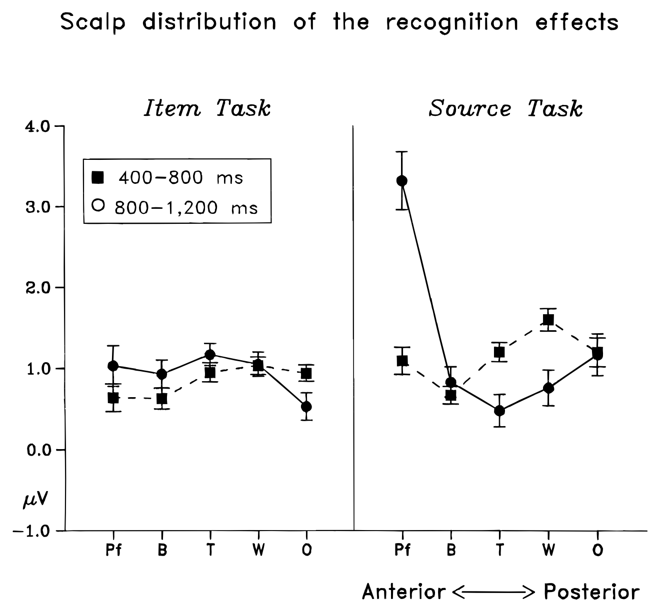

Figure 2. Amplitude of the differences between hits and correct rejections as a function of recognition task, latency window, and scalp site. Pf denotes the average of right and left prefrontal scalp sites close to Fp1 and Fp2, B denotes a pair of inferior frontal sites (roughly over Broca's and its right homologue), T are a pair of midtemporal sites, W a pair of temporoparietal sites (roughly over Wernicke's area and its right homologue), and O is the average of O1 and O2 (placements described in more detail in the Methods section). Data from Senkfor and Van Petten (1998).

Procedural differences among experiments may be important in accounting for these inconsistent results, and thus relevant to the "attempt versus success" debate. In any recognition test, it is wise to manipulate list length and retention interval so that the test is neither too difficult nor too easy (avoiding both floor and ceiling effects). Given the greater difficulty of source than item memory judgments, we calibrated accuracy by using long study lists for sessions requiring old/new judgments only (item memory), and short study lists in separate sessions requiring a judgment about both item and source (Senkfor & Van Petten, 1998). During the source test, subjects thus correctly classified 97.5% of the words as studied or unstudied (whereas their judgments about voice were less accurate). This result means we can be fairly confident that trials labeled as “hit/miss” truly reflected accurate retrieval of the words, and that hit/hit versus hit/miss trials differed only in the success or failure of source retrieval. In contrast, other studies have used only single recognition tests in which subjects made both item and source judgments on each trial (Trott et al., 1997; Wilding, 1999; Wilding et al., 1995; Wilding & Rugg, 1996). Given the mandate to avoid floor and ceiling effects for both item accuracy and source accuracy, the single-test format resulted in substantial numbers of studied words going unrecognized by the subjects (14%–32% across experiments). These error rates for simple old/new classification raise the possibility that some of the trials classified as “hit/miss” reflected only weak memories for the words, and that these hit/hit versus hit/miss contrasts reflected some mix of item retrieval accuracy, confidence in item retrieval, and source retrieval accuracy. A new comparison of hit/hit and hit/miss trials under conditions that elicit high accuracy in old/new classification is thus worthwhile.

A comprehensive review of asymmetries in ERP memory paradigms is beyond the scope of this study, but most studies that have reported significant asymmetries for simple old versus new comparisons (without a source judgment) have noted a left-greater-than-right lateralization, at least for right-handed subjects and verbal materials (see Senkfor & Van Petten, 1998; Van Petten et al., 1991). Rugg and colleagues have recently suggested that a differential asymmetry of posterior and prefrontal old/new effects serves as an additional means of distinguishing the two effects, which have been summarized as “left parietal” versus “right frontal” (see Allan, Wilding, & Rugg, 1998, for review, and Ranganath & Paller, 1999, for different comparisons favoring a “left prefrontal” hypothesis). However, it is less than clear whether reports of differential asymmetries within a single experiment reflect gradients along the anterior to posterior axis, or changes over time. For instance, we observed a shift from a left-greater-than-right old/new effect in an early latency window to a later, bilaterally symmetric effect. Because the later time window was also dominated by a prefrontal scalp distribution, it would be tempting to conclude that the change in lateralization over time reflected a shift in the direction of a “right frontal” effect, but in fact the hemispheric asymmetries were most pronounced at temporal sites (Senkfor & Van Petten, 1998). If prefrontal old/new effects are most prominent at long latencies, and old/new effects over the right scalp are also more prolonged than over the left, two separable phenomena could be conflated into a single “right frontal” effect. Thus, the hemispheric asymmetries of memory effects also warrant additional attention.

Finally, we interpreted the prefrontal effect in our word/voice study as a general memory phenomenon rather than a material-specific effect pertaining to memory for voices. The similarity of our results with others using only printed words (Trott et al., 1997) is reassuring, but all studies to date have used verbal materials. The present study used a design much like the word/voice experiment but with line drawings and spatial locations. Drawings and spatial locations differ from words and voices on two major dimensions—visual instead of auditory, nonlinguistic rather than linguistic—so that a similar pattern of results in comparing item and source memory tasks would be persuasive evidence that the ERP effects reflect general rather than material-specific aspects of retrieval. In both experimental sessions, subjects studied line drawings that appeared in different locations on a computer monitor. In the first session, subjects were tested for item recognition alone by asking them to indicate whether line drawings are studied or unstudied. In the second session, subjects were asked to judge not only if a drawing was old or new, but also to indicate whether old drawings appeared in the same or a different location as during the study phase.

Methods

Participants

Sixteen young adults (9 men, 7 women) were paid for their participation. All reported normal vision and no history of neurological or psychiatric disorders. Their mean age was 24.6 years (range 21–35 years), with an average of 15.6 years of formal education (ranging from 1 year of college to a Master’s degree). Twelve were right handed, four were left handed. Of the right-handed participants, 4 reported a first-degree relative who was left handed.

Stimuli

Images. The stimulus set consisted of 540 monochrome line drawings. The stimuli were obtained from multiple sources, and included digital images from Snodgrass and Vanderwart (1980), and from Cycowicz, Friedman, Snodgrass, and Rothstein (1997), paper line drawings that we digitized, and a few digital images downloaded from various web sites offering “clip art.” All images were presented in green on a black background. Image size varied somewhat across stimuli given the different shapes of the drawings, but averaged 4.2° of visual angle in both the horizontal and vertical dimensions. Sample stimuli are shown in Figure 3.

Spatial location. During all phases of the experiment, images were presented one at a time on a 17″ video monitor, in one of nine spatial locations defined by an invisible 3×3 grid. The distance between adjacent locations (center to center) was 5.1° horizontally and 3.9° vertically. Location was randomly varied from trial to trial, with the constraint that all locations were equally probable in each condition. Prior to the onset of each image, participants were cued about the upcoming location via the appearance of a small crosshair at that location. The crosshair appeared 2 s before image onset, and remained visible for 1.7 s. The cueing procedure was used to avoid eye movement artifacts during the epoch of interest (100 ms before image onset and 1,400 ms after image onset). Participants were instructed to move their eyes to the signaled location when a crosshair appeared, and then fixate for the remainder of the trial.

List composition. The stimuli were split into eight sets of 67 (or 68) drawings so that individual drawings could be rotated through the eight primary conditions formed by crossing the factors of (1) type of recognition test (item vs. source), (2) studied versus unstudied item at test, and (3) appearance in the same spatial location during study and test versus different locations in the study and test phases. Across subjects, each drawing appeared equally often in each of these eight conditions, and no drawing appeared more than once except when it served as an old item during a recognition test (one presentation during the immediately preceding study phase, followed by one presentation during the recognition test for those stimuli). Both the item and source recognition tests for each subject thus included 135 new drawings, 67 (or 68) studied drawings appearing in the same spatial location as during initial study, and 67 (or 68) studied drawings appearing in a different spatial location from the study phase.

Procedure

The experiment was conducted in two sessions lasting about 2 hr each. The first session included an old/new item recognition test;

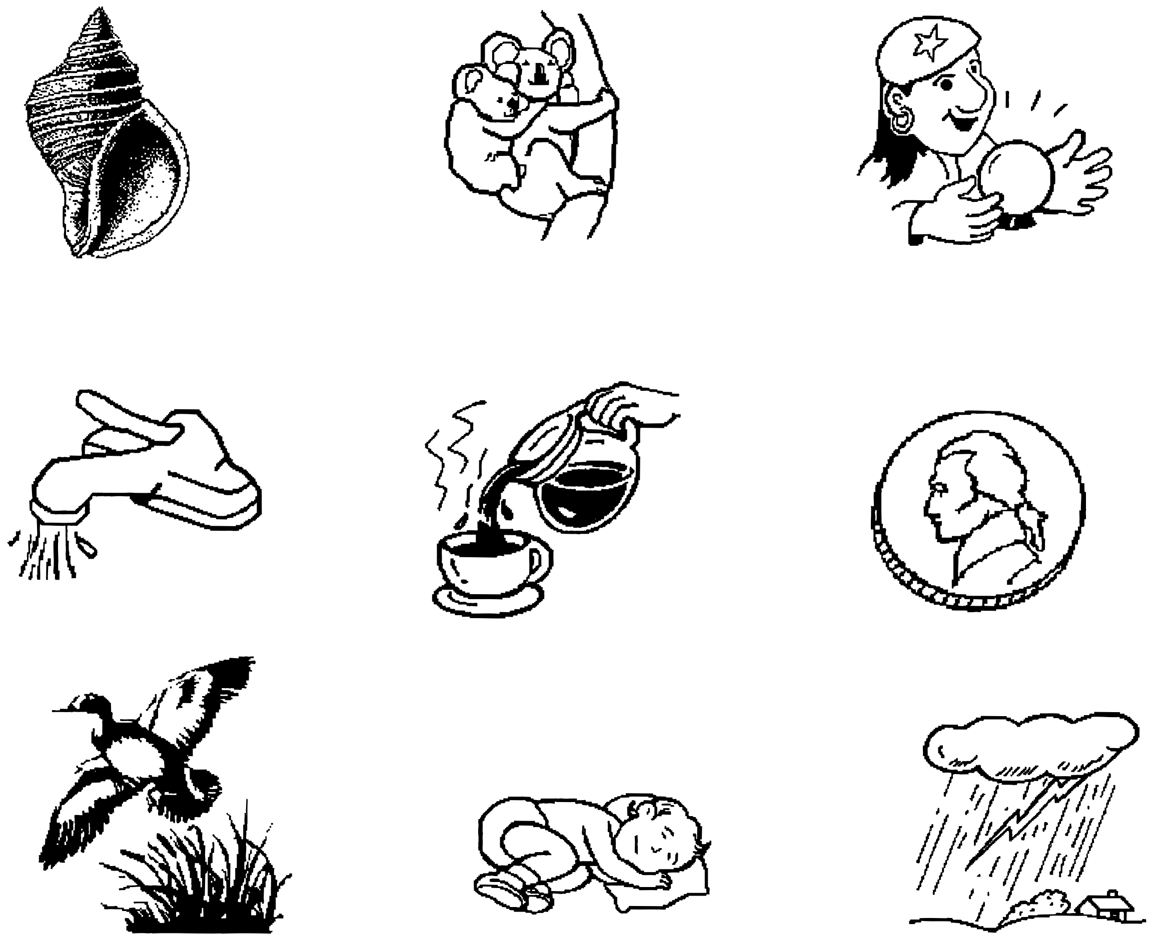

Figure 3. Examples of the line drawings used in the present experiment.

the second session included a source recognition test in which participants decided not only if a drawing was old or new, but also whether old drawings occurred in the same spatial location as they did during the study phase. The item memory session always preceded the source memory session to prevent carryover effects (i.e., spatial memory judgments when these were not required).

Item memory session. In the first session, participants studied a list of 135 drawings divided among the nine spatial locations. Images were presented for 250 ms; image onset was followed by a fixation cross to initiate the next trial 2 s later. Participants were informed about the nature of the upcoming recognition test before each study phase, but were also given an elaborative encoding task: indicating whether the object or scene would be more likely to be encountered indoors or outdoors (with left and right button presses, counterbalanced across subjects). Indoor (e.g., bathtub, dice) and outdoor (e.g., ladybug, letter carrier) drawings were roughly equiprobable in the stimulus set, although some images were fairly neutral in this regard (e.g., pants, flashlight). The study phase was preceded by a list of 12 practice drawings.

Immediately after the item study phase, participants were given a mental arithmetic task for 30 s to prevent rehearsal. The item recognition test consisted of all 135 old drawings intermixed with an equal number of new drawings. Half of the old drawings were presented in the same spatial location as during the study phase, half in a different location. The spatial correspondence between study and test was not described to the participants, and was irrelevant to their assigned task of deciding if a drawing had appeared during the previous study phase or not. Both old and new drawings were divided among the nine possible screen locations. Stimulus duration was 250 ms; image onset was followed by a fixation cross to initiate the next trial 4 s later. Participants made key-presses with the right and left index fingers to indicate whether a drawing was studied or unstudied; the mapping between right/left and old/new was counterbalanced across subjects.

Source memory session. The source memory session was divided into nine study/test cycles, with study lists of 15 drawings followed by recognition lists of 30 drawings (separated by brief mental arithmetic tasks). Short study lists were mandated by the greater difficulty of the source recognition task; individual drawings were randomly assigned to one of the study/test cycles, with the constraint that the proportion of “indoor” and “outdoor” items in each cycle be approximately equal. The study phase task (indoor/outdoor) was identical to the item memory session. As in the item recognition session, study and recognition were separated by brief bouts of mental arithmetic; subjects were allowed short rest periods between study/recognition cycles. The composition of the recognition lists was identical to the item memory session: 25% old drawings presented in the same location as during study, 25% old drawings presented in a different location than the study phase, and 50% new drawings. Half of the participants were instructed to respond "old, same location" with the index finger of the right hand, "old, different location" with the middle finger of the right hand, and "new" with the left index finger. Half of the subjects used the opposite hands (left index and middle fingers for "old, same" and "old, different"). For all participants, response hands for old and new were reversed from the item recognition test in the first session.

Electrophysiological Recording

Electroencephalograms (EEG) were recorded from tin electrodes secured in a commercially available cap (Electrocap International). Recording sites included midline frontal (Fz), central (Cz), and parietal (Pz) together with lateral prefrontal (Fp1, Fp2) and occipital (O1, O2) scalp sites as defined by the 10-20 system. Six nonstandard lateral sites were included and were approximately over: Broca's area and its right hemisphere homologue (BL, BR), Wernicke's area and its right hemisphere homologue (WL, WR), and approximately midway along the extent of the temporal lobe (TL, TR). BL and BR were midway between F7 and T3, and F8 and T4 in the 10-20 system. TL and TR were located 33% of the interaural distance lateral to Cz. WL and WR were located 30% of the interaural distance lateral to Cz, and 12.5% of the nasion to inion distance posterior to Cz. An additional active electrode was placed over the right mastoid. Vertical eye movements and blinks were monitored via an electrode placed below the right eye (Le). The scalp sites and vertical electrooculographic (EOG) electrode were referenced to the left mastoid during recording, but re-referenced offline to an average of the left and right mastoids. Horizontal eye movements were monitored via a right to left bipolar montage at the external canthi of the two eyes. The EEG was amplified by a Grass Model 12 polygraph with half-amplitude cutoffs of 0.01 and 100 Hz, digitized online at a sampling rate of 250 Hz, and stored on optical disk along with stimulus codes for subsequent averaging. Trials with artifacts due to eye movements, blinks, or amplifier saturation were rejected before averaging.

Results

Recognition Performance

Accuracies and reaction times (RTs) in both recognition tasks are shown in Table 1. Overall accuracy (old and new drawings, hits plus correct rejections) in the item recognition task averaged 88%. For old drawings, hit rate was not influenced by the change of spatial location from study to test (same vs. different location, $F < 1$). Old drawings appearing in their studied locations received somewhat quicker responses than when they appeared in new locations, but not significantly so, $F(1,15) = 3.10$, $p = .10$.

In the source recognition task, responses to old drawings were classified according to two levels of accuracy depending on whether the conjunction between drawing and location was correctly categorized, or if only the drawing was recognized as studied. Hit/hit responses consisted of correct "old, same location" and "old, different location" judgments. Hit/miss trials included old drawings judged as old, but incorrectly assigned to the same or different location categories. The sum of the hit/hit and hit/miss categories provides a measure of item recognition during the source task when combined with correct responses to new drawings. This level of recognition averaged 96%, a higher proportion than in the item recognition task using longer study lists, $F(1,15) = 37.9$, $p < .0001$. For old drawings, presentation in the same location during study and test yielded no significant advantage in accuracy ($F < 1$) or RT, $F(1,15) = 2.91$, $p = .11$.

Table 1. *Recognition Performance*

Task and stimulus	Accuracy (%)	RT for correct trials (ms)
Item recognition		
Old	89.2 (1.8)	1028 (29)
Same location	89.1 (1.7)	1014 (29)
Different location	89.2 (1.7)	1042 (27)
New	86.1 (2.3)	1159 (30)
Source recognition (drawing)		
Old (Hit/Hit + Hit/Miss)	94.8 (1.8)	1429 (48)
Same location	96.4 (1.1)	1406 (56)
Different location	93.3 (3.4)	1460 (44)
New	98.1 (0.5)	1014 (27)
Location		
Old (conditional)	77.3 (3.6)	1396 (49)
Same location	80.1 (4.4)	1371 (58)
Different location	75.0 (3.4)	1427 (45)

Note: Standard errors in parentheses. "Hit/Hit": an old drawing was recognized as old, and its location was correctly categorized as same or different from the study phase. "Hit/Miss": an old drawing was recognized as old, but the same/different judgment about location was incorrect. The conditional accuracy measure for location judgments on old drawings = Hit/Hit divided by (Hit/Hit + Hit/Miss). RT = reaction time.

Only when a drawing was classified as old were subjects required to evaluate whether or not its location had changed from study to test. Source memory accuracy was thus computed as a conditional measure excluding the small number of unrecognized old drawings, as the number of hit/hit responses divided by the sum of hit/hit plus hit/miss. Source accuracy averaged 77% overall. Table 1 indicates that same-location drawings attracted slightly more correct source judgments than different-location drawings, and that these RTs were somewhat faster, but neither the accuracy nor the RT advantage was significant, $F\text{s} < 2.7$.

Analyses of the RT data support the intuition that the source recognition task is performed hierarchically, with an initial (covert) memory judgment about each drawing preceding a decision about the relationship between drawing and spatial location. Responses to remembered drawings (hit/hit and hit/miss trials) in the source recognition task were about 400 ms slower than the corresponding hit responses in the item recognition task, $F(1,15) = 92.6$, $p < .0001$. In contrast, correct responses to new words (which never called for a location judgment) were about 140 ms faster in the source than item task, $F(1,15) = 16.8$, $p < .005$.

Event-Related Potentials

The primary conditions in the ERP analyses below, together with the average numbers of trials per subject remaining after artifact rejection are: hits during the item recognition test (82), correct rejections during the item recognition test (78), hit/hits during the source recognition test (65), hit/misses during the source recognition test (18), and correct rejections during the source recognition test (65). The most common artifact causing a trial to be rejected was horizontal eye movement.

Studied Versus Unstudied Drawings

Item recognition task. The ERPs elicited by correctly classified old (hits) and new drawings (correct rejections) from the item recognition task are shown in Figure 4, beginning 100 ms prior to image onset and continuing to 1,400 ms poststimulus onset. Old drawings elicited more positive ERPs than new, beginning at about 250 ms after stimulus onset. The old/new difference was evident at all scalp sites, with only small variations in amplitude across the head. The old/new difference was largely concluded by 700 ms poststimulus onset, although a small amplitude effect continued to the end of the recording epoch at sites over the right hemisphere.

The item recognition data were split into two latency windows for analysis: 300–700 and 700–1,100 ms poststimulus onset; mean amplitudes in both windows were measured relative to the 100-ms prestimulus baseline. Analyses of the lateral scalp sites compared old and new drawings using two analysis of variance (ANOVA) factors reflecting scalp location (anterior-to-posterior, 5 levels) and hemisphere (left vs. right). Analyses of the midline scalp sites used old/new and anterior-to-posterior (3 levels) as factors. For the 300–700-ms window, both lateral and midline sites showed significant effects of old/new, $Fs(1,15) = 43.6$ and 62.8, respectively, $ps < .0001$. The relatively flat scalp distribution of the old/new effect in the item recognition task yielded no significant interactions with the anterior/posterior or hemisphere spatial factors. The old/new difference was no longer significant in the later 700–1,100-ms time window, nor were there any interactions between old/new and scalp site in this time window, all $Fs < 2.05$ in lateral and midline analyses.

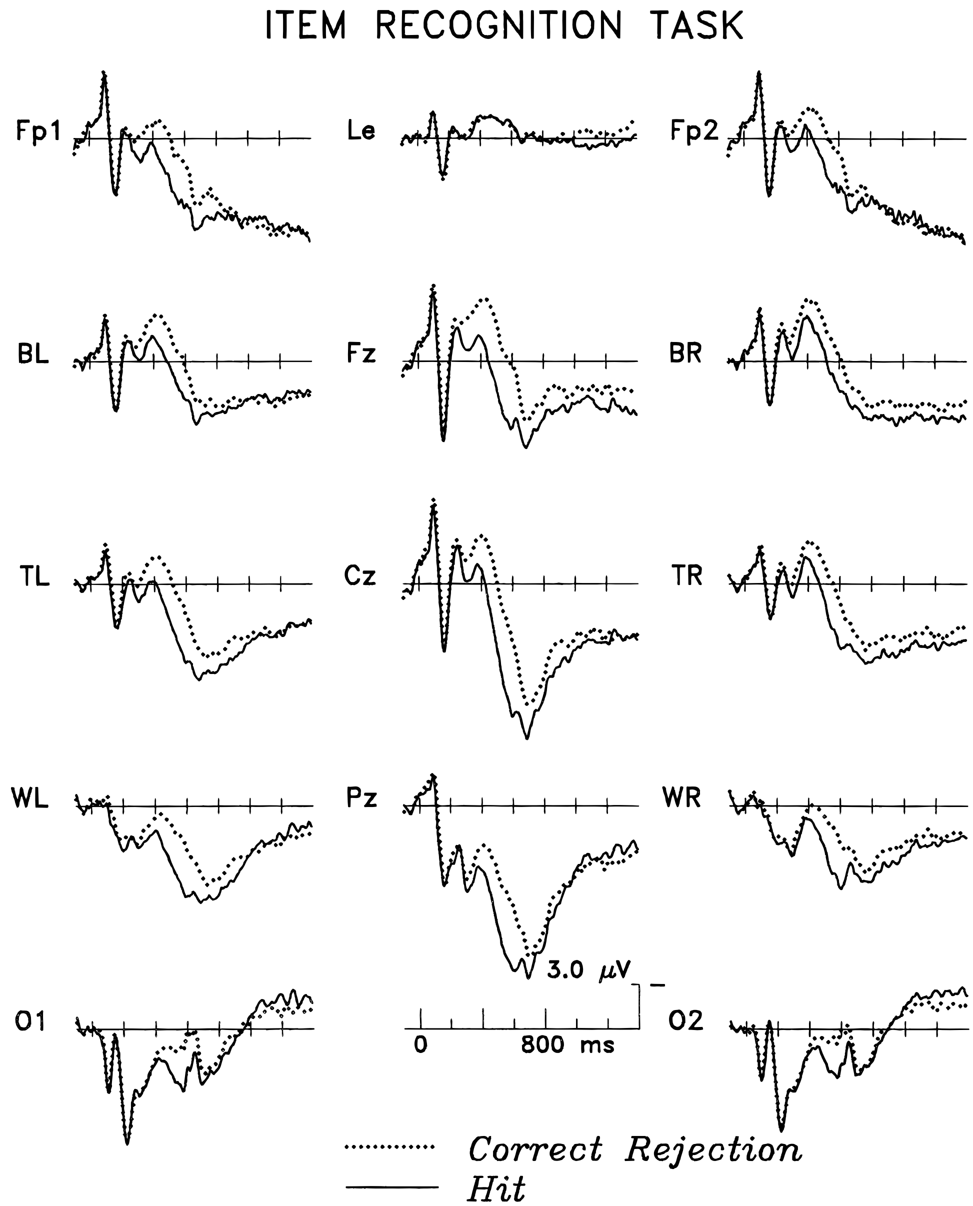

Figure 4. Grand-average event-related potentials (ERPs) elicited by correctly recognized old drawings (hits) and correctly categorized new drawings (correct rejections) during the old/new recognition task.

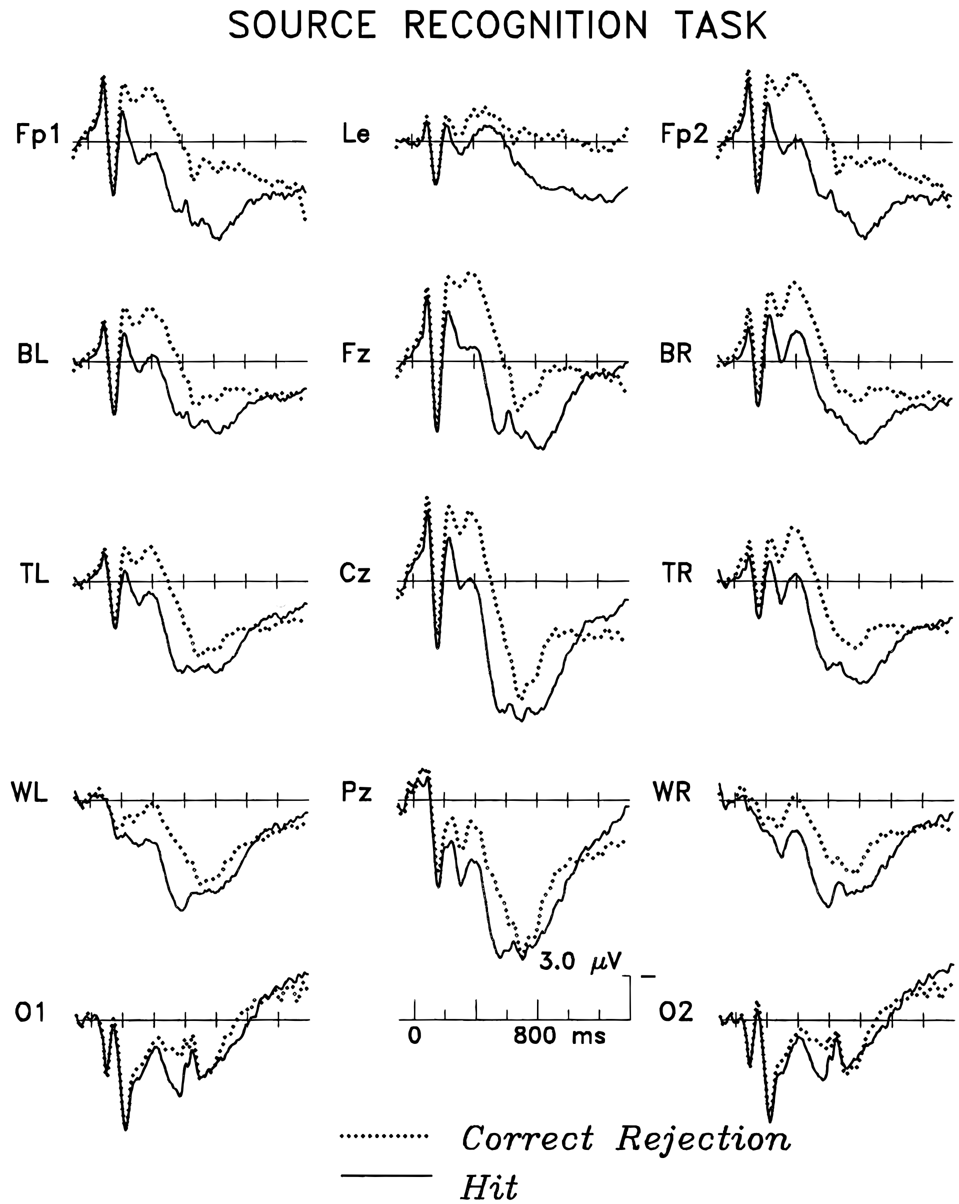

Figure 5. Grand-average event-related potentials (ERPs) elicited by correctly recognized old drawings (hits) and correctly categorized new drawings (correct rejections) during the source recognition task. Trials are defined as hits if a studied drawing was judged as old, independent of source recognition accuracy (i.e., hits are the sum of hit/hits and hit/misses).

Source recognition task. Figure 5 shows conditions from the source recognition task which are analogous to those of Figure 4. In Figure 5, "hit" refers to all studied drawings recognized as old, regardless of the accuracy of the source judgment (i.e., hit/hits and hit/misses are collapsed to form a single category). As in the item recognition task, recognized old drawings elicited more positive ERPs than new. However, two influences of the recognition task are immediately apparent in a comparison of Figures 4 and 5. The old/new difference was more prolonged in the source recognition task than in the item task, and clearly continued beyond 700 ms. Second, the old/new difference in the source task did not have a flat scalp distribution, but instead showed a prefrontal maximum. Indeed, the old/new difference during the source task is substantial at a recording site below the right eye (Le) whereas this electrode showed little to no memory effect during the item recognition task.[1]

Statistical analyses of the old/new memory effect in the source recognition task were parallel to those described above. The main

[1]The Le site is not included in any of the statistical analyses because it is located below the right eye, and there is no corresponding site on the left side of the face. The Le electrode was included primarily to detect and reject trials contaminated by EOG artifacts produced by vertical eye movements and blinks, although EEG is also visible at this site during an experiment. Note that the observed old/new differences at Le, Fp1, and Fp2 cannot be attributed to EOG artifacts because these artifacts would produce potentials of opposite polarity at sites above (Fp1, Fp2) versus below (Le) the eyes given our recording montage in which Le and all scalp sites were referred to the mastoids.

effect of old vs. new drawings was significant in the early 300–700 ms window at both lateral and midline sites, Fs$(1,15) = 91.2$ and 76.4 respectively, ps $< .0001$. In contrast to the item recognition task, the 700–1,100-ms time window also yielded significant old/new differences, Fs$(1,15) = 14.7$ and 9.29, ps $< .002$. For the lateral scalp sites, the anterior maximum of the old/new effect during the source task yielded significant interactions between old/new and the anterior-to-posterior location factor in both time windows, 300–700 ms: $F(4,60) = 13.9$, $p < .0001$, $\epsilon = 0.52$; 700–1,100 ms: $F(4,60) = 8.32$, $p < .002$, $\epsilon = 0.38$. Similar interactions between old/new and the anterior/posterior factor were observed in analyses of the midline sites, 300–700 ms: $F(2,30) = 12.8$, $p < .005$, $\epsilon = 0.64$; 700–1,100 ms: $F(2,30) = 8.02$, $p < .002$, $\epsilon = 0.65$. The more anterior distribution of the old/new difference in the source recognition task as compared with the item recognition task is illustrated in Figure 6. None of the interactions between the old/new factor and the laterality factor reached significance.

Comparisons between the tasks. The preceding analyses consider the two recognition tasks and two time windows via four sets of independent analyses. The data from the lateral electrode sites were also combined into an omnibus ANOVA using task and latency window as factors, combined with the usual factors of old/new, anterior-to-posterior scalp site, and left/right scalp site. This analysis yielded many significant interactions involving the old/new factor—Latency Window × Old/New, Task × Old/New, Anterior/Posterior × Old/New, Task × Anterior/Posterior × Old/New (all ps $< .01$)—interactions that are readily interpretable in the context of the preceding analyses as showing that the old/new effect in the source task was both more prolonged and more anterior than the analogous effect in the item recognition task.

Two additional ANOVAs on the lateral sites were performed to confirm the more anterior distribution of the old/new effect in the source task as compared with the item task. The amplitude measures in both latency windows were first scaled by dividing the value at each site by the square root of the sum of squares of all sites within a given condition and subject (see McCarthy & Wood, 1985). An ANOVA with orthogonal trend decomposition was then used to examine amplitude gradients from anterior to posterior site. The *linear component* of trend considers the five pairs of lateral sites as ordered levels in a single dimension, rather than simply five different levels. The early (300–700 ms) epoch showed a significant interaction between recognition task, old/new, and the linear component of the anterior/posterior factor, $F(1,15) = 4.20$, $p = .05$; the late epoch showed the same interaction, $F(1,15) = 4.37$, $p < .05$.

The omnibus ANOVA also yielded a significant interaction of Hemisphere × Latency Window × Old/New, $F(1,15) = 9.90$, $p < .01$. This interaction was unexpected given that the preceding analyses did not reveal significant asymmetries in the old/new effects for either task or latency window. However, inspection of the mean amplitudes of the old/new effects across tasks and latency windows showed that the old/new effect demonstrated a small leftward asymmetry during the 300–700-ms window, which shifted toward bilateral symmetry (item task) or right dominance (source task) later in the epoch. Figure 7 shows this pattern of results when collapsed across all right and all left scalp sites. The rightward asymmetry observed for the late epoch of the source task was mostly attributable to temporal and temporoparietal regions, reflected by an interaction of Hemisphere × Latency Window × Anterior/Posterior × Old/New in the omnibus ANOVA, $F(4,60) = 8.22$, $p < .005$, $\epsilon = 0.63$. Tests on pairs of electrodes for the late epoch of the source task showed a significant Hemisphere × Old/New interaction only for the TL/TR pair, $F(1,15) = 5.25$, $p < .05$; Fp1 and Fp2 showed symmetric old/new effects, $F < 1$.

Overall, the differential topographies of the recognition memory (old/new) manipulation across tasks and time windows shown in Figures 6 and 7 are consistent with a decomposition into two underlying phenomena: (1) an old/new effect that is confined to the 300–700-ms latency window, and distributed broadly across

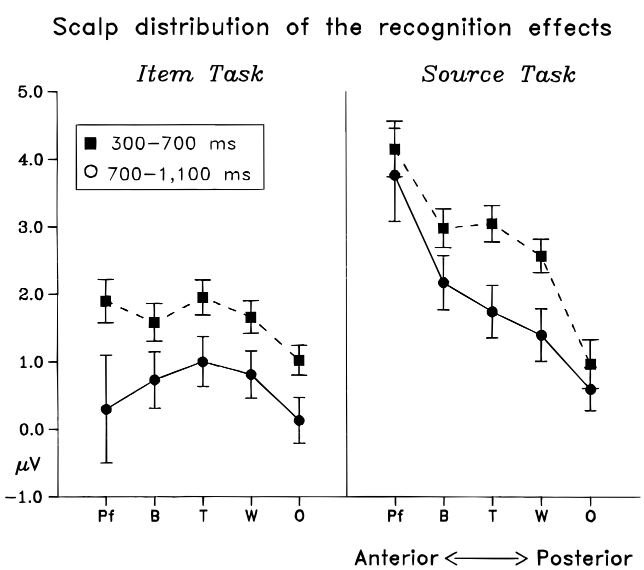

Figure 6. Amplitude of the differences between hits and correct rejections as a function of recognition task, latency window, and scalp site. Pf denotes the average of Fp1 and Fp2 sites; the other lateral pairs of electrode have been collapsed similarly across hemisphere to show scalp distributions in the anterior/posterior dimension.

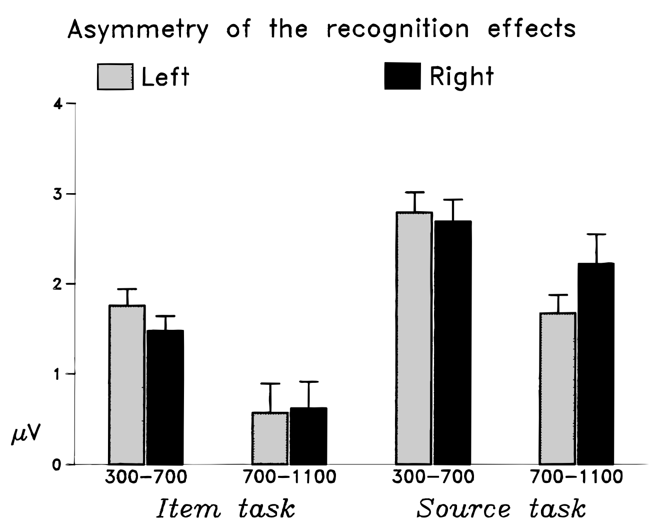

Figure 7. Amplitude of the differences between hits and correct rejections as a function of recognition task, latency window, and left versus right scalp sites. "Left" denotes the average of Fp1, Br, Tl, Wl, and O1 scalp sites; "right" denotes the average of the homologous sites over the right hemisphere.

the scalp, combined with (2) a frontal and right-lateralized recognition process that begins during the early time window, but reaches maximum amplitude in the 700–1,100-ms latency range. This description characterizes the difference between studied and unstudied drawings during the item recognition task as reflecting primarily the first phenomenon. In contrast, the early latency window of the source recognition task reflects overlapping contributions from the two recognition effects, whereas the late window presents a relatively pure reflection of the anterior and right-lateralized effect.

Same Versus Different Location Trials

In both sessions, drawings presented for recognition judgments could appear in the same spatial location as at study, or a different location. During the item recognition task, this spatial manipulation was irrelevant to the assigned task of discriminating studied from unstudied drawings, and neither accuracies nor RTs differed significantly for drawings presented in same versus different locations. During the source recognition session, retrieving the studied spatial location of a drawing and comparing it with the test location was part of the assigned task. But the behavioral data did not suggest that the outcome of the comparison process—a "same" or "different" judgment—influenced accuracy or RT. Figure 8 shows that the ERPs also showed no evidence of sensitivity to the correspondence between study and test locations in either task. Amplitudes of the ERPs elicited by recognized drawings in same and different locations yielded no significant effects or interactions involving the same/different factor at the lateral or midline scalp sites in either latency window.

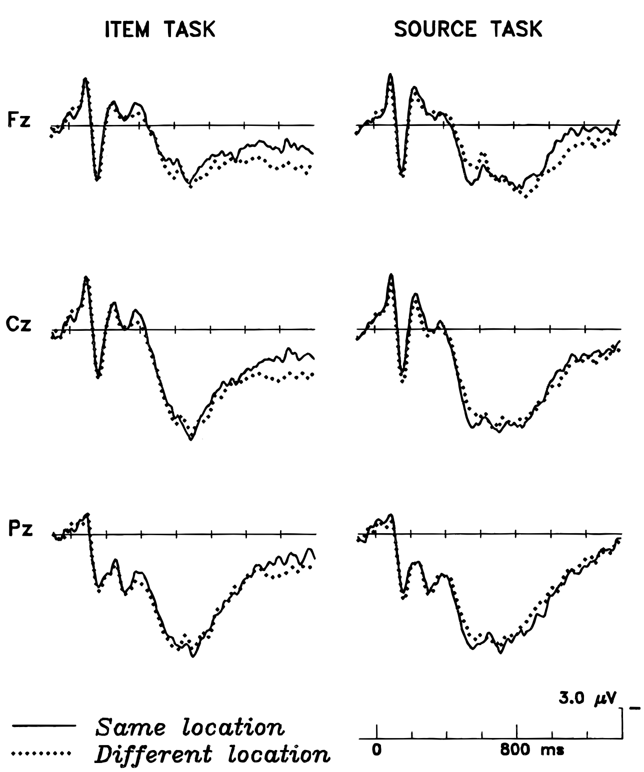

Figure 8. Grand-average event-related potentials (ERPs) elicited by recognized old drawings appearing the same or different locations as during the initial study phase, at three midline scalp sites.

Accuracy of Source Retrieval: Hit/Hit Versus Hit/Miss Trials

Figure 9 contrasts two subsets of trials from the source recognition task in which drawings were correctly categorized as old. On hit/hit trials, the relationship between a drawing's location at study and test was also successfully categorized as "same" or "different," indicating that the conjunction of drawing-plus-location was successfully retrieved. Figure 9 shows that hit/hit trials elicited more positive ERPs than hit/miss trials in which participants failed to demonstrate memory for the relationship between a drawing and its location. The difference between hit/hit and hit/miss trials was of late onset, beginning only some 600 ms after stimulus onset. The difference was also distributed broadly across the scalp, rather than showing a prefrontal maximum. Analysis of the lateral scalp sites taking source accuracy (hit/hit vs. hit/miss), latency window (300–700 vs. 700–1,100 ms), anterior/posterior (five levels), and laterality as factors thus yielded only a significant interaction between accuracy and latency window, $F(1,15) = 5.10$, $p < .05$, with no interactions involving scalp site. Analysis of the midline sites similarly yielded an Accuracy $\times$ Latency Window interaction, $F(1,15) = 8.61$, $p < .01$. Separate analyses of the early latency window yielded no significant difference between hit/hit and hit/miss trials. Separate analyses of the late time window yielded a significant accuracy effect for the midline sites, $F(1,15) = 4.96$, $p < .05$, but not for the lateral sites where the difference between hit/hit and hit/miss trials was smaller in amplitude, $F(1,15) = 2.72$. In summary, source recognition accuracy was reflected in a late, spatially widespread positivity.

Discussion

The present results replicate our previous study with words and voices in many, but not all regards. Comparisons between the two studies will help address two central questions: the material specificity of old/new ERP effects in source memory tasks, and whether the prefrontal memory effect is tied to accurate retrieval of source information. The discussion below is structured around these two issues, and their relationship to functional interpretations of the ERP memory effects observed here.

Material Specificity of the Prefrontal Memory Effect

The present comparison of memory for line drawings versus memory for drawings plus their spatial locations bore several striking similarities to our previous study using words and voices (Senkfor & Van Petten, 1998). In both studies, the item recognition task elicited a spatially diffuse old/new difference, whereas the source memory task yielded an old/new effect that can be described most parsimoniously as a combination of the basic old/new effect plus a second effect largest at prefrontal scalp sites. We have suggested that the widespread old/new effect reflects successful retrieval of an item from memory, whereas the prefrontal effect reflects a distinct process that is more specific to the source memory task—either the attempt to retrieve a secondary stimulus feature (the "source") from memory, or the attempt to evaluate whether a test combination corresponds to a studied combination of features. Replication of the frontal task difference in the present experiment argues that the differential content of the "items" (drawings) versus the "sources" (locations) cannot account for the different scalp distributions of the old/new effects across item and source recognition tasks. It is worth noting that procedural variations between the item and source recognition tests in the present study are also unlikely to account for the different scalp distributions of the old/new effects across tasks. In particular, our previous study investi-

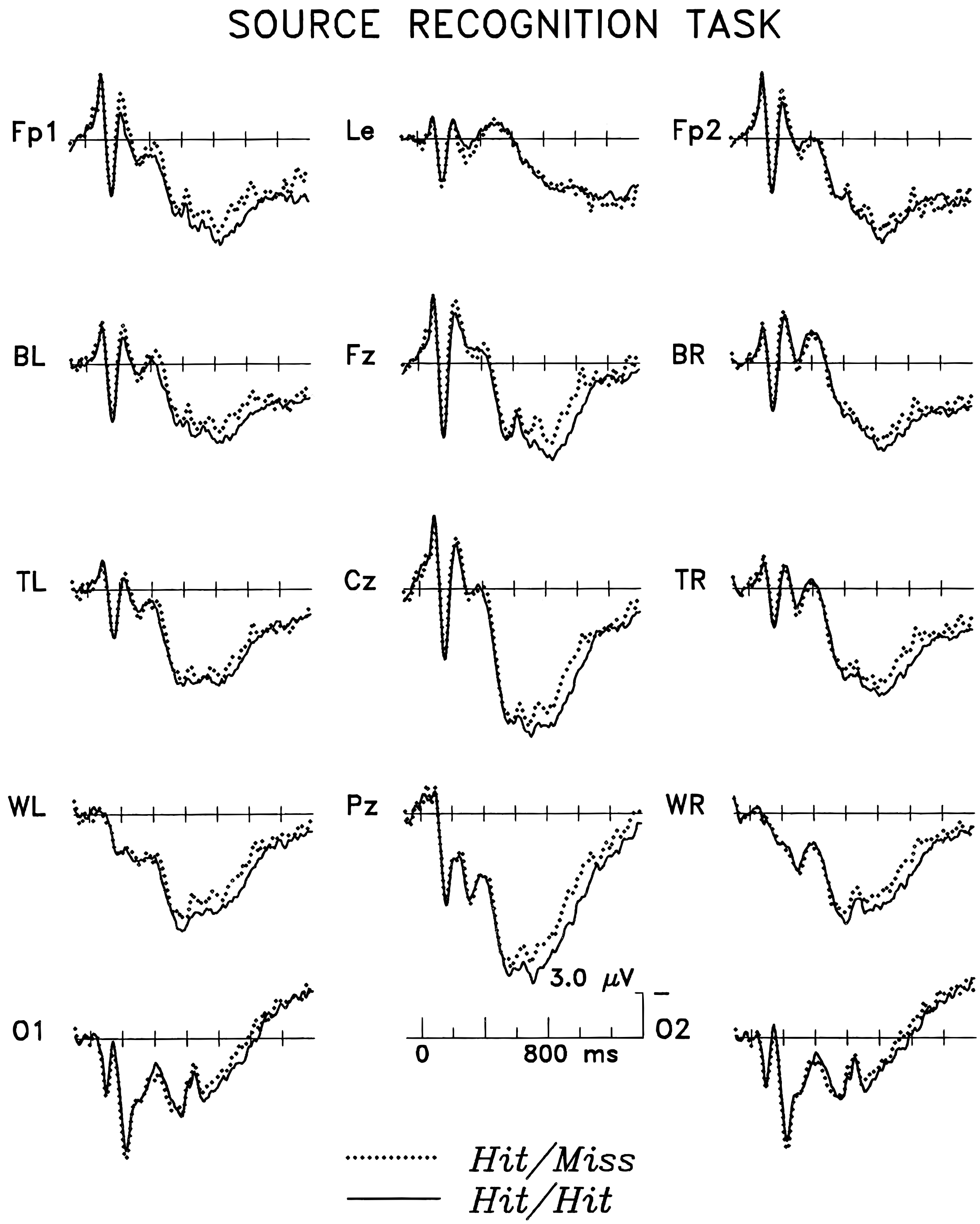

Figure 9. Grand-average event-related potentials (ERPs) elicited by recognized old drawings accompanied by accurate or inaccurate source judgments. Hit/hit trials are the sum of correct "old same location" and "old different location" judgments (i.e., both item recognition and source recognition were accurate). Hit/miss trials are the sum of incorrect "old same location" and "old different location" judgments (i.e., the drawings were recognized as old, but the judgment about the conjunction between drawing and studied location was inaccurate).

gated whether or not differences in study-list length (shorter in the source memory session) or the number of response alternatives (three in the source recognition task, two in the item memory task) yielded topographic differences in the old/new effect. Neither factor proved influential in that study (Senkfor & Van Petten, 1998). Other ERP studies of source memory tasks have not directly compared item and source memory tasks, but report frontal old/new effects in source memory tasks that use list lengths comparable to those typically used in item memory tasks (Trott et al., 1997; Wilding, Doyle, & Rugg, 1995; Wilding & Rugg, 1996).

Other evidence also suggests that the frontal lobe is an implausible candidate for initial recognition of the "sources" in either study—spatial locations or voices. Lesion and functional imaging results suggest that posterior parietal cortex is critical in long-term memory for spatial locations (Mishkin, Ungerleider, & Macko, 1983; Moscovitch, Kapur, Kohler, & Houle, 1995). ERP studies of short-term memory for spatial locations alone (independent of what object appeared in a given location) have similarly suggested that studied and unstudied locations yield old/new differences that are largest at posterior, rather than frontal, scalp sites (Mecklinger, 1998; Mecklinger & Minshausen, 1998). Neuropsychological studies indicate that damage to either right parietal, or bilateral temporal cortex impairs recognition and discrimination of voices, but also yield little suggestion that the frontal lobe plays a critical role in memory for voices (Van Lancker, Cummings, Kreiman, & Dobkin, 1988; Van Lancker, Kreiman, & Cummings, 1989). The frontal old/new effect thus requires a functional account based on general differences between item and source memory tasks rather than one that appeals to the content of the material that needs to be retrieved from memory. We suggest that this account should focus on the defining aspect of source memory tasks—the requirement to retrieve and evaluate a conjunction of stimulus attributes.

Although the present source recognition task yielded a prefrontal old/new effect much like our previous word/voice experiments, the time course of this effect differed dramatically between the two studies. In the voice source task, the prefrontal old/new effect began substantially later than the widespread old/new effect observed during both the item and source memory tasks (see Figure 2). In the present results, the old/new difference at prefrontal sites had much the same onset latency as at more posterior sites, although it persisted for longer (in Figure 6, note that the old/new difference at prefrontal sites is of equivalent amplitude during the early and late time windows, whereas the old/new difference at more posterior sites is smaller during the late than early time window).

The latency difference between studies is likely to reflect material-specific processes, which proceed at different rates for drawings, locations, words, and voices, but these may consist of perceptual rather than mnemonic processes. During any episodic recognition test, a test stimulus can be compared only with studied stimuli after some initial processing of the test stimulus. If we grant that memory processes specific to the conjunction of two stimulus attributes (i.e., source memory processes) can proceed only after both features of a test stimuli have been identified, considering the relative speed of perceptual processing for the two attributes becomes worthwhile. In the present visual experiment, those two attributes were spatial location and drawing identity. The onset latency of the difference between studied and unstudied drawings during the item recognition task (about 250 ms) places an upper bound on the time required to identify the test drawings and begin matching them to memory representations. It seems likely that the widely spaced screen locations were identified at least as quickly as the drawings, if not more quickly. Visual attention experiments have typically shown earlier ERP differences between attended and unattended stimuli when attentional selection can be based on location rather than nonspatial features such as color or shape (Anllo-Vento & Hillyard, 1996; Harter, Aine, & Schroeder, 1982; Luck & Hillyard, 1995). If indeed both the drawings and their locations could be identified within 250 ms, an assessment of whether the conjunction of attributes had been studied could begin at much the same time, accounting for the similar onset latencies of the prefrontal effect in the source recognition task and the widespread old/new effect observed in both tasks. In contrast, there may be a larger temporal discrepancy between the identification of auditory words and speakers' voices, and this discrepancy may account for the delayed onset of the prefrontal old/new effect in our previous study. The spoken words in those experiments averaged 620 ms in duration, but work from our laboratory and others indicates that listeners can identify words of this duration after hearing only the first 350 ms of the auditory signal, on average (Marslen-Wilson & Welsh, 1978; Tyler & Wessels, 1983; Van Petten, Coulson, Rubin, Plante, & Parks, 1999).[2] The difference between studied and unstudied words during the item recognition task of our previous word/voice study began at about 400 ms, suggesting that 350–400 ms is a reasonable estimate of auditory word identification time. By contrast, research on voice identification has suggested that listeners need to hear rather long samples before they can identify even familiar voices (Bricker & Pruzansky, 1966; Cook & Wilding, 1997). In a task of distinguishing between two voices, Pollack, Pickett, and Sumby (1954) reported 80% accuracy only when the samples exceeded 650 ms. In a task of responding "famous" versus "unfamiliar" for a set of 60 voices, Schweinberger, Herholz, and Sommer (1997) reported only a 30% hit rate with 710-ms voice samples, increasing to 70% with 2,000-ms samples. These studies suggest that voice identification lags word identification by a considerable time period, and moreover that voice identification in our prior study proceeded more slowly that identification of the spatial locations used in the present study.

If the memory process(es) indexed by the prefrontal old/new effect can begin only after all the relevant attributes of the test stimulus have been identified, the more rapid onset of the prefrontal effect in a recognition test for drawings-plus-locations as opposed to words-plus-voices is an interpretable result. Moreover, the relatively early onset of the prefrontal old/new effect observed in source memory experiments from other laboratories can be attributed to the absence of a slowly analyzed perceptual feature in the test phases of those experiments. For instance, although Wilding and Rugg (1996) also used a speaker's voice as the "source" attribute in their experiment, words were presented visually during the recognition test, so that participants did not need to engage in voice identification as part of the test.

Item and Source Recognition Accuracy

In the present study, we equated successful retrieval of items with the ERP difference between correct old and correct new drawings (hits vs. correct rejections, Figure 4), and successful retrieval of source information with the difference between hit/hit and hit/miss trials (Figure 9) These two comparisons would, of course, be most comparable to one another if item recognition was assessed via a comparison of hits to misses in the item task, but too few studied drawings went unrecognized to form adequate averages for the miss category. However, a handful of studies indicate that hit versus miss and hit versus correct rejection contrasts yield fairly similar ERP differences in item recognition tasks, so that we believe the present contrasts are justified (Neville et al., 1986; Sanquist et al., 1980; Van Petten & Senkfor, 1996; Wilding et al., 1995; Wilding & Rugg, 1996).

[2] The procedure used to establish the minimum signal duration for spoken word identification in these studies was to truncate the word at different time points after onset (50 ms, 100 ms, etc.) and force listeners to guess what the word might be after hearing these shortened versions. In the Van Petten et al. (1999) experiment, listeners reached 90% accuracy with an average of 350-ms signals. The words in that experiment averaged 592 ms in duration, and were spoken by one of the two individuals who served as the speakers in the word/voice source memory experiment (Senkfor & Van Petten, 1998), so that the signal durations necessary for word identification in the two experiments are likely to be comparable.

The late onset of the source accuracy effect relative to the item retrieval effect is much like that observed in previous studies using a speaker's voice as the source attribute (Senkfor & Van Petten, 1998; Wilding & Rugg, 1996). The replication of this latency shift suggests that source memory processes are completed after item recognition processes, independent of the content of the items and sources. The source accuracy effect was of considerably smaller amplitude than the item retrieval effect, but similar in showing a widespread (rather than frontal) scalp distribution, replicating some previous studies (Senkfor & Van Petten, 1998; Wilding et al., 1995; Wilding & Rugg, 1996) but not all (Trott et al., 1997; Wilding, 1999). The reason for differing scalp distributions of the source accuracy effect across studies are still debatable, but we believe this effect is most clearly delineated when item accuracy is equivalent across conditions and only source accuracy varies. Because subjects showed near-perfect accuracy in discriminating studied from unstudied drawings during the source recognition task, we argue that the hit/hit versus hit/miss contrast here reflects only the success of source memory processes. Most evidence thus argues that the source accuracy effect is distinct from the prefrontal old/new difference engendered by the mere requirement to make a source monitoring judgment. To the extent that the old/new effect at frontal scalp sites reflects activity of prefrontal cortex, these data are consistent with neuropsychological theories that ascribe an executive role for prefrontal cortex in memory: directing retrieval strategies, and/or evaluating the veridicality of retrieved memories, rather than subserving retrieval or storage in any more direct fashion (Luria, 1973; Moscovitch, 1994; Swick & Knight, 1999).

Finally, the present data provide little support for the claim that prefrontal old/new effects are right lateralized. Instead, the late part of the recording epoch showed an old/new effect that was both frontal and right lateralized, but the hemispheric asymmetry was most evident over temporal sites. Further research using a variety of materials, both verbal and nonverbal, will no doubt be useful in describing the generality of asymmetric memory effects.

A more specific description of the functional process indexed by the ERP prefrontal old/new effect is desirable, but perhaps premature at this stage of research. Rugg and colleagues have proposed a *postretrieval operation*, specifically the generation or maintenance of a representation of the study episode long enough to use it in a goal-directed way (Allan, Wilding, & Rugg, 1998). This idea is compatible with existing results, but perhaps not specific enough to explain why item recognition tasks should differ from source recognition tasks. An alternative proposal that is also compatible with extant results (though not mandated) is that the prefrontal ERP effect is driven by the demand to reduce interference. Like most comparisons of item and source in the behavioral literature, the ERP experiments have been marked by the inclusion of a single attribute that re-occurs across a large number of individual stimuli, so that the "source" attributes are familiar at test. During an item recognition task, the familiarity of the source attributes provide no information useful to the old/new judgment, but neither does source familiarity provide any conflicting information because these attributes are simply irrelevant to the assigned task. During a source memory task, source attributes must be attended to make the correct decision, but their familiarity is an inappropriate basis for an accurate judgment about the conjunction of item and source. It may be this need to utilize source attributes, yet suppress their familiarity, which makes source memory tasks particularly difficult, and which elicits the prefrontal ERP effect.

A functional description of the prefrontal ERP effect in terms of memory interference is in much the same spirit as Shimamura's (1995) description of the role of prefrontal cortex in memory as one of "filtering or inhibiting irrelevant or extraneous neural activity in posterior cortex" (p. 151). Whether or not these two proposals prove to be linked concretely will depend, of course, on firm evidence that the old/new effect observed at frontal scalp sites is generated by prefrontal neurons. Such evidence may be beyond the scope of scalp-recorded data alone, but can be pursued fruitfully by ERP studies in patients with damage to prefrontal cortex, or perhaps by hemodynamic imaging studies. Aside from this anatomical question, however, the qualitative difference between ERPs elicited in item and source memory tasks provides evidence that a qualitatively distinct memory process is invoked by source memory tasks of the sort used here. Our proposal that this additional process consists of suppression of interference is a testable proposal given that source memory paradigms need not include the one-to-many mapping between source attributes and item attributes embodied in ERP studies to date. Paradigms that include "source" and "item" attributes that are not recombined across stimuli may be able to separate interference from the process of remembering combinations of attributes.

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