Published in final edited form as:

Neuropsychologia. 2009 January ; 47(2): 303–313. doi:10.1016/j.neuropsychologia.2008.08.027.

Left and right memory revisited:

Electrophysiological investigations of hemispheric asymmetries at retrieval

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Abstract

Hemispheric differences in the use of memory retrieval cues were examined in a continuous recognition design, using visual half-field presentation to bias the processing of test words. A speeded recognition task revealed general accuracy and response time advantages for items whose test presentation was biased to the left hemisphere. A second experiment recorded event-related brain potentials in the same design and replicated these behavioral effects, but found no electrophysiological support for the hypothesis that test words biased to the left hemisphere elicit superior recognition. Instead, successful retrieval was accompanied by memory components of identical strength regardless of test field. That robust visual field effects in response accuracy and speed were not mimicked in memory components that generally do correlate with such behavioral differences suggests that patterns in overt responses may be dominated by the left hemisphere's superior ability to apprehend words. Differences between the data pattern observed in the present study with lateralized retrieval and that in a prior study with lateralized encoding support the notion that hemispheric processing is highly integrated in the intact brain, and highlight the need to treat lateralization at different stages as distinct.

Keywords

Laterality; Verbal retrieval; Old/new effect; P2; Hemispheric interaction

1. Introduction

It is well known that the functions of the two cerebral hemispheres differ more than their at least superficially similar structures would suggest. Hemispheric biases in language processing have been extensively studied, with early reports of strong left-lateralization now shifting towards a more cooperative model (e.g., Beeman & Chiarello, 1998; Federmeier, 2007). Although normal language comprehension and production are inextricably tied with memory demands, relatively little work has focused on the hemispheres' relative strengths and weaknesses in verbal memory. In recent years, a better understanding of hemispheric biases in verbal encoding has emerged (see Evans & Federmeier, 2008, for review). However, a gap remains in our understanding of the equally important processes operative during memory retrieval. To address this need, the following experiments investigate hemispheric biases in the utilization of retrieval cues, by reporting behavioral and electrophysiological responses to lateralized retrieval probes in an explicit recognition test.

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Biased hemispheric processing is often elicited via the visual half-field method, in which lateralized visual stimuli project directly only to the primary visual cortex of the contralateral hemisphere. This direct perceptual input grants the contralateral hemisphere preferential access to the information relative to the hemisphere ipsilateral to presentation, which receives at best a transferred signal that is delayed and degraded. When subsequent, higher-order operations are performed, their processing is generally dominated by the contralateral hemisphere, confirming the effectiveness of this method (reviewed in Banich, 2002; Young, 1982). Studies using the divided visual field (VF) design have revealed numerous differences in the manner in which each hemisphere analyzes words and other verbal stimuli (see Beaumont, 1982; Hellige, 1993; White, 1969 for reviews). When given the task of simply naming a lateralized stimulus, participants identify words presented in the right visual field (RVF)/left hemisphere (LH) more accurately and rapidly than those presented in the left visual field (LVF)/right hemisphere (RH) (Jordan & Patching, 2004; Jordan, Patching, & Thomas, 2003; Mishkin & Forgy, 1952). In accuracy, this RVF/LH advantage extends to pronounceable pseudowords (even if they are named letter-by-letter rather than as a whole: Young, Ellis, & Bion, 1984), but not to unpronounceable letter strings (Jordan et al., 2003; Young et al., 1984) or to isolated letters (Jordan & Patching, 2004). Thus, RVF/LH advantages arise when elements of a verbal stimulus can be perceived as a whole unit, rather than a random assembly of letters, making the pattern of reading biases consistent with the proposal that the LH has denser top-down connections of the sort that would support the unitization of words and word-like stimuli (Federmeier, 2007). These reading biases have consequences for the quality of processing at later stages in all word-based VF studies. For example, in a memory experiment that uses lateralized words, if LVF/RH words are read more slowly, then RVF/LH words have a 'head start' and may reach subsequent memory judgment stages before LVF/RH words; this would reduce overall response times for RVF/LH words, even if the actual process of evaluating words as old or new were equally long for both conditions. Similarly, if LVF/RH words are read less accurately, then memory judgments may be based on the wrong word more often following LVF/RH presentation. Critically, such differences arise at the word identification stage preceding the response selection stage to which response time and accuracy effects are often attributed.

In addition to the quality of initial word identification, VF presentation impacts what aspects of a stimulus are retained and subsequently recruited during recognition judgments. Specifically, the LH's rapid processing and effective integration of top-down information have been proposed to produce gist-like representations that are stripped of superficial stimulus characteristics (e.g., Federmeier, 2007; Marsolek, 1995, 1999; Metcalfe, Funnell, & Gazzaniga, 1995). In contrast, the RH, which is generally superior for spatial processing (e.g., Berrini, Della Sala, Spinnler, Sterzi, & Vallar, 1982; Kimura, 1966), seems biased to retain memory traces that are more faithful to the original input and include elements such as physical form (e.g., Marsolek, Kosslyn, & Squire, 1992; Marsolek, Squire, Kosslyn, & Lulenski, 1994; Metcalfe et al., 1995). When lateralized verbal materials (e.g., words or letter pairs) are tested for recognition after some delay, memory studies using short study-test retention lags have reported greater accuracy (Berrini et al., 1982; Blanchet et al., 2001; Federmeier & Benjamin, 2005; Hines, Satz, & Clementino, 1973) and speed (Federmeier & Benjamin, 2005) of responses following RVF/LH presentation. However, as information must be held for longer periods of time and against mounting interference, repeated words initially studied in the RVF/LH show a sharper increase in response time than is observed for LVF/RH-studied items (Federmeier & Benjamin, 2005). Biases induced by the VF of a study word thus have consequences for how rapidly that information can be retrieved and evaluated at test, and this pattern interacts with the retention interval.

Encoding asymmetries have also been observed in neuroimaging studies, which generally find that during verbal memory encoding, the LH is more active (particularly in prefrontal and

medial temporal regions, which are consistently associated with memory processing: Schacter & Wagner, 1999) than homologous regions of the RH (Golby et al., 2001; Kelley et al., 1998; McDermott, Buckner, Petersen, Kelley, & Sanders, 1999; Wagner et al., 1998). During the memory retrieval phase, however, activation is more bilateral, with broad LH activation being complemented by unique RH contributions from the right frontal polar cortex (Buckner, 1996; McDermott et al., 1999) and generally more widespread RH activity than is apparent at encoding (Habib, Nyberg, & Tulving, 2003). This pattern has led to the controversial hemispheric encoding/retrieval asymmetry (HERA) model, which initially proposed that the encoding of verbal materials is a left-lateralized process, whereas verbal retrieval is right-lateralized (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). This view has been widely challenged by studies finding that both encoding and retrieval are left-dominant for verbal materials and right-dominant for non-verbal materials, suggesting a material-specific, rather than process-specific bias (e.g., Golby et al., 2001; Kelley et al., 1998; Wagner et al., 1998). Accordingly, more recent instantiations of the HERA model posit that for verbal information the LH is more active in encoding than retrieval, whereas the RH is more active in retrieval than encoding (Blanchet et al., 2001; Habib et al., 2003). Although it is not clear what design features or analysis factors have led to these discrepant findings, common to both sets of data is the tendency for a more bilateral pattern during retrieval than is apparent at encoding.

In line with such evidence, behavioral studies using lateralized retrieval cues have found that the robust asymmetries emerging from lateralized encoding are not seen at retrieval. Experiments lateralizing both the study and test words have found that accuracy is affected only by the encoding VF, with RVF/LH study items leading to superior recognition regardless of test field (Leibner, 1982). Response time measures, however, are additionally sensitive to the test field, with shorter response times for RVF/LH test probes (Coney & MacDonald, 1988; Leibner, 1982); this response time pattern may reflect the previously discussed RVF/LH speed advantages in word reading (Jordan & Patching, 2004; Jordan et al., 2003; Mishkin & Forgas, 1952), as rapid identification of RVF/LH stimuli would make them available to memory evaluation processes sooner than LVF/RH words.

Accuracy effects for lateralized test words have been found in false alarm rates to unstudied test lures in false memory designs (i.e., studies that attempt to induce false alarms via strong semantic relations between study and test stimuli: Deese, 1959; Roediger & McDermott, 1995). When the presentation of study words is not biased to either hemisphere (e.g., presented at visual fixation or binaurally) but test words are presented with the visual half-field method, unstudied LVF/RH test lures are incorrectly endorsed more often than RVF/LH test lures (Ito, 2001; Westerberg & Marsolek, 2003). Interpretations of this phenomenon vary; responses to LVF/RH test words sometimes yield higher hit rates as well, indicating a general response bias to judge LVF/RH test words as 'old' irrespective of actual test status (Westerberg & Marsolek, 2003), but other studies find higher hit rates for RVF/LH test words, indicating a superior ability to discriminate old from new test words when retrieval cues are projected to the RVF/LH (Ito, 2001). As such, it is difficult to determine whether RVF/LH test probes are more effective retrieval cues, or whether they simply elicit a more stringent response criterion that reduces false alarms at the cost of hits.

The extant literature offers little to clarify this issue. Few standard recognition experiments (i.e., those in which 'new' test words are not designed to remind participants of studied words) have biased only the test phase by presenting study words at fixation and test words lateral to fixation. One such study of word recognition found that RVF/LH test words evinced only modest accuracy advantages over LVF/RH test words (Blanchet et al., 2001), but another study using unpronounceable letter pairs (which cannot readily be grouped into a single phonological unit) found no VF differences for lateralized retrieval (Berrini et al., 1982). That retrieval asymmetries are limited to stimuli that can be represented as whole units links these effects to

the previously discussed stimulus identification biases, and makes the contribution of pure memory effects difficult to isolate. Given concerns that LVF/RH presentation leads to impaired word apprehension and thus lower accuracy, accuracy alone is insufficient to disambiguate perceptual and memory biases. A promising approach would be to make comparisons among correct trials (when it is likely that lateralized retrieval cues were read properly), thus precluding concerns about asymmetric reading errors. Thus, the present work will examine response times (Experiment 1) and event-related brain potentials (Experiment 2) to correctly identified test words in a recognition memory design.

Experiment 1 continues in the tradition of previous studies by measuring explicit responses to lateralized test words, but with several important modifications that may uncover novel data patterns. First, a wider range of study-test repetition lags will be examined, in order to track the timecourse of retrieval asymmetries in greater detail. Additionally, lateralized words will be given a longer exposure time (200 ms) than previous studies, to improve the likelihood that the slower LVF/RH is provided with ample time to process lateralized words. Finally, response times to correctly classified words will be examined. Although response times are still influenced by the RVF/LH's reading speed advantage, such asymmetries are likely to be stable across conditions, whereas true memory biases may be affected by how long a study word must be remembered and how many words intervene between study and test presentation. To the extent that these factors may differ in degree or onset for LH and RH retrieval, asymmetries at immediate repetition (when memory should be nearly perfect for both the LH and the RH, but word reading ability favors the LH) can provide a baseline against which later asymmetries can be interpreted. Collecting response times also enables comparison with the response time pattern obtained by Federmeier and Benjamin (2005) with lateralization at the encoding phase. If similar effects obtain in this study, using the same lag structure but with only the retrieval stage lateralized, this would suggest that even during central encoding, each hemisphere builds and maintains its own representation that can then be accessed selectively by lateralized test probes. Comparing the response time patterns will thus provide some information about the nature of LH and RH contributions to central encoding.

Though it is important to obtain a data set with these modifications, it is possible that perceptual biases could still dominate asymmetries. Indeed, since behavioral measures necessarily aggregate across processing stages, it will always be difficult to determine how much of an observed performance difference in accuracy or response time is due to asymmetries in the use of memory retrieval cues versus asymmetries in the stimulus identification that precedes such judgments. What is needed to isolate retrieval-specific processes is a measure that is more temporally and functionally constrained, such as that provided by event-related potentials (ERPs). ERPs are electrical changes in brain activity that are time locked to specific events, such as the presentation of a word. ERP measures are often functionally specific, as many deflections in the waveform occur not only with predictable timing and/or scalp topography, but also under well-defined stimulus and task conditions, thus licensing a component-to-function mapping. Several aspects of the ERP have been shown to be sensitive to memory, including the N400 and the late positive complex or LPC (changes on which are sometimes jointly referred to as the ERP "old-new" effect), and the frontal P2.

The N400 is a negative component peaking around 400 ms after the presentation of a word or other potentially meaningful stimulus, and its amplitude is sensitive to the ease of lexico-semantic retrieval (Kutas & Federmeier, 2000; Kutas & Hillyard, 1980). With repetition of a word, this process is facilitated and N400 amplitude is reduced (becoming less negative) (Rugg, 1985; Rugg & Doyle, 1994). The LPC is a broad positive deflection occurring approximately 500-800 ms after the presentation of a repeated word; like the N400, it too is more positive for repeated items, particularly during tests of explicit memory (Rugg & Doyle, 1994). Both the N400 and the LPC repetition effects are focused over medial, central-parietal scalp channels,

though these scalp-recorded changes are believed to reflect different generators. Evidence from intra-cranial recordings suggest that repetition effects on the N400 reflect processing in the anterior temporal lobe and parietal cortex (Guillem, Rougier, & Claverie, 1999), whereas the LPC is generated by sources in the anterior temporal lobe along with portions of the frontal lobe (Friedman & Johnson, 2000; Guillem et al., 1999).

Both the N400 and LPC are captured in the ERP “old-new” effect, (Rugg & Doyle, 1994), which characterizes the tendency for repeated items to elicit a more positive signal than items that are seen for the first time from approximately 250-800 ms over central-parietal scalp channels. In general, the extent of this positive change is correlated with memory strength, as its magnitude and breadth are enhanced by manipulations such as shorter repetition lags or greater numbers of study exposures, and generally correlate with other memory measures such as confidence ratings and speed of recognition (for extensive reviews, see Johnson, 1995; Paller, 2001; Rugg, 1995; Rugg & Doyle, 1994). The old-new effect is often reported as a difference wave (i.e., a point-by-point subtraction) of correctly recognized old test words minus correctly rejected new test words, hence the label “old-new.” Analyses of the old-new effect could be particularly useful in comparing retrieval success of RVF/LH and LVF/RH test words. Because this effect reflects memory signals obtained during correct trials, it should be less affected by word identification errors and more directly sensitive to the memory retrieval operations that follow word apprehension. Additionally, the use of a difference wave stabilizes comparisons of stimuli presented in different VFs because early sensory potentials that are sensitive to stimulus lateralization cancel out in the subtraction, leaving only the components of interest.

A number of memory experiments have also started to look at the P2, an early component associated with complex visual search and target detection (Luck & Hillyard, 1994). In recent years, the conception of the P2 as a basic-level sensory component has broadened, given evidence that its amplitude is sometimes influenced by higher-level cognitive operations. P2 amplitude increases with word repetition (Curran & Dien, 2003; Misra & Holcombe, 2003), suggesting that it may reflect the process of comparing visual input with either stored knowledge or generated expectations. In a memory experiment with lateralized study words, repeated words that had been studied in the LVF/RH were associated with a P2 repetition effect at test, but RVF/LH-studied words were not (Evans & Federmeier, 2007), bolstering the hypothesis that P2 effects reflect a sort of perceptual priming or comparison, as only the RH is believed to retain the sort of detailed physical form information necessary to support perceptual priming. Given that P2 repetition effects reflect the access of RH-encoded information, the presence of P2 repetition effects in experiments with centrally presented stimuli (Curran & Dien, 2003; Misra & Holcombe, 2003) indicates that the RH does contribute to central encoding, and that this information is consulted in subsequent decisions. However, it is possible that this is an artifact of centralized retrieval probes, which activate both hemispheres at retrieval. A more convincing demonstration of cooperative encoding would be to observe P2 repetition effects for test words that do not directly engage the RH, such as RVF/LH test words.

Recording ERPs in a lateralized retrieval paradigm can thus offer multiple measures that address questions about both retrieval asymmetries and the nature of central encoding. Behavioral data are also informative, particularly response times, which have not previously been investigated in designs of this kind. In ERP studies, it is necessary that participants respond as accurately as possible, even at the cost of response speed, in order to maximize the number of trials averaged into the final analyses. Such a priority threatens the integrity of response time data, necessitating a separate experiment to collect behavioral data outside the context and constraints of ERP recording. Experiment 1 will therefore record only accuracy and speed of responses to lateralized test words, using the discussed modifications of a broader range of

repetition lags and longer presentation duration than has been used previously. Experiment 2 will then use the same task and parameters (albeit without emphasizing response speed), but also record ERPs, which allow for a greater number of comparisons among correctly recognized words, many of which may be less affected by perceptual asymmetries.

2. Experiment 1: retrieval biases in overt responses

2.1. Method

2.1.1. Participants—Twenty-four undergraduates (12 female and 12 male) from the University of Illinois participated in this study for course credit or monetary compensation. Participants had a mean age of 18.9 years (range: 18-21), and were all native speakers of English with no early exposure (younger than 5 years old) to a second language. All participants were right handed, as indexed by the Edinburgh handedness inventory (Oldfield, 1971), which yielded a mean laterality quotient of 0.82 (range: 0.21-1.00, where 1.0 is strongly right-handed and -1.0 is strongly left-handed); ten participants reported having left-handed members of their immediate family.

2.1.2. Stimuli—Each participant viewed a total of 512 unique words, randomly selected from a set of singular nouns that were 4-6 letters in length, of low written frequency (2-60 per million: Francis & Kucera, 1982), and rated as highly concrete and highly imageable (each scoring 500-700 on a 100-700 scale), as provided by the MRC Psycholinguist Database (Coltheart, 1981). For each subject, the 512 words were evenly split across two experimental blocks, each of which contained 400 words: 144 words appeared twice, first as central study words and later as lateralized test words (*old* test words: all study words were later repeated, and no word was repeated more than once), and an additional 112 lateralized test words appeared only once (*new* test words).

Words were presented serially in a continuous recognition design. Old test words were separated from their study presentation by lags of 1 (immediate repetition), 2, 3, 5, 7, 10, 20, 30, or 50. For each participant, 32 words were repeated at each lag, 16 being tested in each VF. Randomly intermixed with the old test words were 112 new test words (56 tested in each VF). Twelve unique word lists and lag structures were created, and two participants viewed each list, with the test words appearing in opposite VFs for those two participants.

2.1.3. Procedure—Participants were tested individually, seated 100 cm from the computer screen. All words were presented in black sans serif font in capital letters, and a small, black fixation point remained in the horizontal center (0.5 visual degrees below the vertical center) of a white background throughout the experiment. Participants were instructed to maintain fixation on the central point, and to minimize saccadic eye movements and blinks. Study words, which participants were told to read and remember but not respond to, were centered directly above the fixation cross and remained on screen for 2000 ms, followed by an interstimulus interval of 2300 ms. Test words, which participants did respond to, were preceded by a red cross appearing over the fixation point to signal their approach and to prompt central fixation. 500 ms after the cross' appearance, a test word would appear for 200 ms with its central-facing edge two visual degrees from the horizontal center, and then disappear, leaving the red cross until a response was initiated; if no response was made within 5 s, the experimenter prompted continuation of the sequence and the trial was excluded from further analysis. 2500 ms after the response, a new stimulus would appear. Participants were instructed to "respond as quickly as possible, without compromising accuracy" by pressing the "yes" button for lateralized words that they had previously seen at any prior point in the experiment (old test words), and the "no" button for test words they had not seen (new test words). One response button was held in each hand, and the hand used to respond "yes" was counterbalanced across participants. After demonstrating task proficiency and adequate eye control in a brief practice block, participants

completed two test blocks lasting approximately 25 min each, separated by a 5-10 min rest period.

2.1.4. EOG recording—The longer presentation duration used here (200 ms) is on the cusp of most estimates of the time required to program and execute a saccade (see Banich, 2002; Young, 1982, for reviews). Therefore, eye movements were recorded to guarantee that central fixation was maintained for all trials included in the final analysis. Eye movements were monitored using the electrooculogram (EOG) signal, recorded from two bipolar montages of silver/silver-chloride electrodes. A pair of electrodes on the outer canthus of each eye detected saccades, and a second pair positioned above and below the left eye detected blinks. A fifth electrode above the right eye served as a ground. Electrode impedances were 5 k Ohms or lower. EOG was sampled at 250 Hz, and Sensorium amplifiers applied a bandpass filter of 0.02-100 Hz, and a gain of 10,000.

Saccades were detected off-line by setting a peak-to-peak threshold individualized to the magnitude of each participant's eye movements. Trials in which the EOG signal exceeded the threshold were eliminated from further analyses. On average, this resulted in a loss of 8.5% of the experimental trials.

2.2. Results and discussion

2.2.1. Response accuracy—Both old and new test words were classified more accurately with RVF/LH presentation (84.42% hits and 86.04% correct rejections) than LVF/RH presentation (79.82% hits and 83.13%, correct rejections). To capture these differences, lag effects on accuracy were analyzed by submitting d' values¹ (see Fig. 1) to a 9 (lag: 1, 2, 3, 5, 7, 10, 20, 30, 50) $\times$ 2 (test VF: RVF, LVF) repeated-measures ANOVA. As expected, the ability to discriminate repeated words from new words decreased incrementally with lag, as verified in a main effect of lag ($F(8, 184) = 62.42, p < .001$). A main effect of Test VF ($F(1, 23) = 26.86, p < .001$) revealed that sensitivity was greater for RVF/LH test words, extending previous evidence for RVF/LH advantages (Berrini et al., 1982; Blanchet et al., 2001) to the greater range of lags examined here. Lag and Test VF did not interact, ($F(8, 184) = 1.08, p = n.s.$), indicating that the superior recognition of RVF/LH stimuli was stable across lag.

2.2.2. Response speed—Response times² for hits were subjected to a 9 (lag: 1, 2, 3, 5, 7, 10, 20, 30, 50) $\times$ 2 (test VF: RVF, LVF) repeated-measures ANOVA (see Fig. 2). This analysis revealed a main effect of lag ($F(8, 184) = 35.08, p < .001$), such that response times increased with lag, reflecting the increased difficulty of retrieving long lag items. There was a main effect of test VF ($F(1, 23) = 18.06, p < .001$), with quicker responses to correctly recognized repeated words that were tested in the RVF/LH than the LVF/RH. A marginal interaction between lag and test VF ($F(8, 184) = 1.93, p < .1$) reflects two patterns visually apparent in Fig. 2. First, relative to the stable RVF/LH advantage seen across medium lags, response time asymmetries were smallest at the shortest lags (lags 1 and 2). It is possible that at such short lags, the RH is able to employ the perceptual matching strategies at which it is particularly adept (e.g., Geffen, Bradshaw, & Nettleton, 1972; Gibson, Dimond, & Gazzaniga, 1972), thus reducing the otherwise robust RVF/LH advantages. Alternatively, it may be that the efficiency of processing retrieval cues declines more rapidly with lag for cues biased to the LVF/RH than the RVF/LH. A second factor contributing to the marginal interaction is the data at the longest lags, 30 and 50 (29 and 49 intervening words), with the otherwise consistent RVF/LH speed advantage absent at lag 30, and amplified at lag 50. Lags 30 and 50 are also the lag conditions at which

¹Hit rates of 1.00 were corrected using a substitution of .96,875 (corresponding to ½ of a missed trial).

²Response time medians were evaluated to protect against outlier effects. In all conditions, means were also analyzed, and there were no theoretically important differences in the statistical outcomes.

accuracy was worst (71.9% and 62.6%, respectively), suggesting that these anomalous effects may have resulted from low trial counts. Critically, this marginal lag $\times$ VF interaction reflects a pattern very different from that seen for lateralized encoding, when RVF/LH speed advantages were restricted to early lags (1-7) and reversed at longer lags (10-50), when LVF/RH studied words were recognized faster (Federmeier & Benjamin, 2005). The absence of a similar long lag LVF/RH response time advantage for retrieval suggests that when words are presented centrally, either the two hemispheres cooperate in forming a representation, or one hemisphere dominates encoding. Among unstudied test words, those that were correctly rejected were identified marginally faster with RVF/LH presentation (1079.25 ms) than with LVF/RH presentation (1113.58 ms): $t(23) = 3.67, p < .1$.

2.2.3. Summary—Overall, across a range of repetition lags, RVF/LH test words were recognized more accurately and quickly. It is possible that this reflects a bias for RVF/LH test words to provide better memory cues for centrally encoded words. Alternatively, the RH's relative disadvantage for basic aspects of word perception could distort any true retrieval biases. That RVF/LH advantages were evident at even the shortest lag intervals and for responses to new words is consistent with the hypothesis that the behavioral asymmetry reflects some non-memory factors. Indeed, prior work has shown that behavioral responses to lateralized stimuli can be dominated by perceptual processing asymmetries that may mask more subtle effects of memory (Nagae & Moscovitch, 2002), and that electrophysiological measures can uncover effects otherwise obscured in behavioral data (Evans & Federmeier, 2007).

To address this question, Experiment 2 provides ERP data obtained during a memory task using the same stimuli as Experiment 1. In order to maximize trial counts for stable ERP waveforms, participants in Experiment 2 were told to focus on the accuracy of their responses and were not given any specific instructions with respect to speed. As discussed earlier, two components are of interest. The old-new effect offers a quantitative comparison of LH and RH retrieval processes that is less susceptible to influences from perceptual decoding stages. If the behavioral data from Experiment 1 reflect genuine memory advantages for RVF/LH test words, then such superior memory should also yield a larger old-new effect for RVF/LH test words, relative to LVF/RH test words; the absence of any VF effects would instead suggest that the behavioral results reflect something other than a memory advantage, such as the perceptual differences that favor RVF/LH word reading. Lag-related changes on the old-new effect are also of interest. It is possible that the old-new effect will decay differentially for RVF/LH and LVF/RH test words. Additionally, to find greater old-new effects for LVF/RH test words at short lags would align with previous data on perceptual priming advantages for the RH, and to find larger old-new effects to LVF/RH test words at long lags would replicate effects seen with lateralized encoding. Tracking the P2 repetition effect, which is uniquely sensitive to RH encoding, may speak to the extent of RH involvement in central encoding, as well as the LH's use of RH-derived information. To see the P2 repetition effect for RVF/LH probes would suggest that the biased retrieval cues do not selectively engage an encapsulated representation formed by a single hemisphere.

3. Experiment 2: retrieval biases in electrophysiological responses

3.1. Method

3.1.1. Participants—Twenty-four undergraduates (12 female; 12 male) from the University of Illinois participated in this study either for course credit or hourly compensation. Mean age was 20.1 years (range: 18 - 26). All were native speakers of English with no early exposure (younger than 5 years old) to a second language, and were right handed, with mean laterality quotient 0.69 (range: 0.29-1.00) on the Edinburgh handedness inventory (Oldfield, 1971). Nine participants reported having at least one left-handed member of their immediate family.

3.1.2. Stimuli—The same 12 word lists from Experiment 1 were shown to participants in Experiment 2, and again two participants viewed each list, with VF of presentation reversed. Presentation parameters were identical to those in Experiment 1.

3.1.3. Procedure—The procedure was the same as in Experiment 1, with the exception that participants were now instructed to emphasize accuracy (they were given no instructions about response speed), in order to maximize the number of trials per condition and thusly to stabilize ERP measures. Also in the interest of increasing trial counts, data were collapsed across broader lag conditions during analysis, yielding three repetition conditions: short lag repetitions (1, 2, 3), medium lag repetitions (5, 7, 10) and long lag repetitions (20, 30, 50).

3.1.4. EEG recording—As in Experiment 1, saccades were detected via a bipolar montage of silver/silver chloride electrodes placed on the outer canthus of each eye. Additionally, one electrode placed below the left eye detected blinks. Scalp-recorded electroencephalography (EEG) data were collected from 26 electrodes, arranged in three circles concentric around the vertex and embedded in an electrode cap. A midline prefrontal electrode served as a ground. All impedances were kept under 5 kOhms. Excepting the bipolar montage detecting saccades, all electrodes were referenced online to the left mastoid process and later rereferenced to the algebraic mean of the left and right mastoids. Data were sampled at 250 Hz, bandpass filtered from 0.02 to 100 Hz online, and amplified with a gain of 10,000.

Prior to averaging, trials containing eye movements or other artifacts were rejected with thresholds individualized to each participant. Across participants, an average of 6.5% of critical trials were lost due to saccades, and an additional 3.1% were lost due to other recording artifacts such as electrode blocking and drift. Blinks were also detected individually for each subject, and were corrected for 17 participants using a procedure developed by Dale (1994); the remaining seven subjects did not have enough blinks to necessitate correction. ERPs were computed using a 100 ms pre-stimulus baseline, and the recording epoch extended to 920 ms after the onset of each word. Averages of artifact-free ERPs were calculated for each experimental condition, and subjected to a digital bandpass filter of 0.2-20 Hz. For all ERP analyses, the reported *p*-values reflect the Greenhouse-Geisser epsilon correction for repeated measures with more than one degree of freedom. Interactions with electrode sites are only reported when of theoretical significance.

3.2. Results and discussion

3.2.1. Behavioral responses—As in Experiment 1, response accuracy was greater for RVF/LH presentation (83.67% hits and 89.88% correct rejections) than LVF/RH presentation (80.35% hits and 89.21% correct rejections). A mixed-model 2 (Experiment: 1, 2) $\times$ 2 (VF: RVF, LVF) $\times$ 9 (lag: 1, 2, 3, 5, 7, 10, 20, 30, 50) ANOVA confirmed the similarity of *d'* patterns across experiments. This revealed a main effect of Experiment ($F(1, 46) = 4.35, p < .05$), such that discrimination between old and new items was greater in Experiment 2 than Experiment 1, which is not surprising, given that instructions for Experiment 2 stressed only accuracy. Across both experiments, main effects of VF ($F(1, 46) = 31.85, p < .001$) and lag ($F(8, 368) = 128.94, p < .001$) were robust, but lag effects were more pronounced in Experiment 2, as evidenced by a lag $\times$ experiment interaction ($F(8, 368) = 2.93, p < .05$). Experiment did not interact with any other factors: experiment $\times$ VF ($F(1, 46) = 1.61, p = \text{n.s.}$); experiment $\times$ VF $\times$ lag ($F(8, 368) = 1.43, p = \text{n.s.}$). For the lag thirds used to analyze the ERP data, mean accuracy was: RVF/LH: 96.25% at short, 84.25% at medium, and 70.13% at long lags; LVF/RH: 93.21% at short, 83.54% at medium, and 64.00% at long lags.

Although participants were not encouraged to focus on response speed, response times were recorded and analyzed. Response time data obtained under these conditions may not be

representative of processing speed, and may not correspond to the same processing that occurs under speeded conditions. However, the data did align with those of Experiment 1, showing incremental increases with lag, and superior speed for RVF/LH test words at all lags (in Experiment 2, however, the RVF/LH speed advantage was stable across lag). Subjective impressions of similarity were confirmed in a mixed-model 2 (Experiment: 1, 2) $\times$ 2 (VF: RVF, LVF) 9 (lag: 1, 2, 3, 5, 7, 10, 20, 30, 50) ANOVA. Although responses were (paradoxically) faster in Experiment 2, this difference did not attain significance ($F(1, 46) = 0.90, p = \text{n.s.}$), nor did Experiment interact with any variables: Experiment $\times$ VF ($F(1, 46) = 0.51, p = \text{n.s.}$); experiment $\times$ lag ($F(8, 368) = 1.42, p = \text{n.s.}$); experiment $\times$ VF $\times$ lag ($F(8, 368) = 1.41, p = \text{n.s.}$). For the lag thirds used to analyze the ERP data, the means of response time medians³ were: RVF/LH: 718.19 ms at short, 786.03 ms at medium, and 864.75 ms at long lags; LVF/RH: 740.00 ms at short, 823.89 ms at medium, and 915.61 ms at long lags. For correctly rejected words, median response times were 955.42 ms for RVF/LH stimuli, and 977.17 ms for LVF/RH stimuli; as in Experiment 1, this trend was only marginal ($t(23) = 2.35, p < .15$).

3.2.2. ERP components—Fig. 3 shows grand averages to all new and old test words, separated by VF of test word. Test words from both conditions elicited similar early components, though these were strongly lateralized. Over posterior sites contralateral to the test VF, these early components include a positivity peaking around 105 ms (P1), a negativity peaking around 170 ms (N1), and a positivity peaking around 225 ms (P2). The timecourse and amplitude of these components was different over ipsilateral posterior sites, with P1s being larger and peaking later (around 140 ms) and N1s being both smaller and later (peaking around 200 ms); P2s were also slightly delayed over ipsilateral sites (peaking around 320 ms), but their amplitude was modulated more by repetition status than stimulus lateralization, as discussed below. Over frontal electrodes, sensory components were less influenced by the VF manipulation: N1s peaked around 140 ms contralaterally and 150 ms ipsilaterally, with a slight amplitude decrease over ipsilateral sites; P2 peak latency was also affected (peaking around 225 ms contralaterally, and 240 ms ipsilaterally), but its amplitude patterned solely with repetition. Effects of lateralized presentation continued even into late parts of the recording epoch, in the form of a posterior slow negativity (300–900 ms) that is larger over the contralateral hemisphere and larger for RVF/LH stimuli than LVF/RH stimuli; this effect has been reported in previous studies using lateralized verbal stimuli (e.g., Evans & Federmeier, 2007; Federmeier & Kutas, 1999; Neville, Kutas, & Schmidt, 1982). Also following the perceptual components were a negativity peaking around 400 ms (N400) and a broad positivity occurring between 500 ms and 800 ms (LPC). The N400 and LPC are clearly sensitive to repetition, with both components being more positive for old than new test words—this old-new effect is discussed in more detail below.

3.2.3. Old-new memory effect

3.2.3.1. Old-new effect distribution: The strength and distribution of the old-new effect for each VF were examined by submitting mean amplitudes (between 250 and 800 ms) of correctly identified old and new test words to a 2 (test VF: RVF, LVF) $\times$ 2 (test condition: new, old) $\times$ 2 (hemisphere: LH, RH electrode sites) $\times$ 2 (laterality: lateral, medial electrode sites) $\times$ 4 (anteriority: prefrontal, frontal, central/parietal, occipital electrode sites) omnibus ANOVA. This revealed a main effect of test condition ($F(1, 23) = 136.77, p < .001$), with greater positivity for old than new words. There was also a marginal effect of test VF ($F(1, 23) = 4.14, p < .1$), indicating greater positivity for RVF test words (new and old), but test condition and test VF did not interact ($F(1, 23) = 2.65, p = \text{n.s.}$), suggesting that this slow negativity is due to stimulus

³Because the lag third groupings contained three individual repetition lags (short: 1, 2, 3; medium: 5, 7, 10; long: 20, 30, 50), a group-wide median taken only from a single lag condition would not have been appropriate. We therefore averaged the median response times for each of the three individual lags, in order to obtain a response time measure that was representative of the constituent lag conditions.

lateralization and not a memory effect. Distributional interactions indicated that the old-new effect for lateralized test words has the typical medial central-posterior distribution: test condition $\times$ laterality ($F(1, 23) = 78.93, p < .001$); test condition $\times$ anteriority ($F(3, 69) = 105.64, p < .001$); test condition $\times$ laterality $\times$ anteriority ($F(3, 69) = 18.43, p < .001$). Given this distribution, subsequent old-new effect analyses will focus on nine medial channels over central-parietal regions that are representative of the effect (see head icon in Fig. 4 for channel locations).

3.2.3.2. Test VF and lag effects: The graded effects of lag for each VF are shown in Fig. 4. Statistical comparisons of the old-new effect for each VF were analyzed with difference waves (a point-by-point subtraction of hits minus correct rejections), in order to eliminate the standing effects of stimulus lateralization. From the resulting difference waves (Fig. 5), mean amplitudes were measured from 250 to 800 ms for each of the six conditions, and submitted to a 3 (lag group: short, medium, long) $\times$ 2 (test VF: RVF, LVF) $\times$ 9 (electrode) omnibus ANOVA. A main effect of lag group ($F(2, 46) = 33.41, p < .001$) indicated that the size of the old-new effect decreased with increasing lag. There was no lag group by VF interaction ($F(2, 46) = 1.02, p = \text{n.s.}$). Additionally, there was no main effect of VF ($F(1, 23) = 0.54, p = \text{n.s.}$), confirming that lateralization effects evident in Fig. 3 were effectively eliminated in the difference wave subtraction.

Planned comparisons of the old-new effect for each VF were performed for each lag condition, in a 2 (test VF: RVF, LVF) $\times$ 9 (selected electrodes) repeated measures ANOVA (see Fig. 5). For short lag repetitions, mean amplitudes of the old-new effect were numerically larger for LVF/RH-tested words ($5.42 \mu\text{V}$, as compared with $4.54 \mu\text{V}$ in the RVF/LH), but this trend did not reach statistical significance ($F(1, 23) = 3.02, p < .1$). At medium and long lags, there was no VF difference (medium: $F(1, 23) = 0.07, p = \text{n.s.}$; long: $F(1, 23) = 0.00, p = \text{n.s.}$).

3.2.3.3. Old-new effect summary: Consistent with well-established findings for centrally presented stimuli, responses to old items were more positive than responses to new test words between 250 and 800 ms over central-posterior electrode sites, and the magnitude of this effect was graded by repetition lag. This pattern parallels that seen for the response time to hits; however, whereas RVF/LH speed advantages occurred across repetition lags, the old-new effect analyses found no evidence of RVF/LH advantages at any repetition lag. Instead, at short lags, there was a trend for repeated LVF/RH test words to produce a stronger old-new effect than RVF/LH test words, which may reflect iconic matching processes that favor the RH at short retention intervals (Geffen et al., 1972; Gibson et al., 1972). It is also noteworthy that the larger old-new effect for LVF/RH-studied words repeated at long-lags uncovered in Evans and Federmeier (2007) was not apparent in the current design, reinforcing the conclusion that centrally presented words do not induce independent representations in each hemisphere.

3.2.4. P2 repetition effect

3.2.4.1. P2 distribution: Based on the frontal P2 timecourse observed in Fig. 3, a time window of 175-275 ms was used for analyses. Mean amplitudes from this timewindow for all correct trials were submitted to a 2 (test condition: old, new) $\times$ 2 RVF, (test VF: LVF) $\times$ 2 (hemisphere: LH, RH electrode sites) $\times$ 2 (laterality: lateral, medial electrode sites) $\times$ 4 (anteriority: prefrontal, frontal, central/parietal, occipital electrode sites) omnibus ANOVA. A main effect of test condition ($F(1, 23) = 14.92, p < .001$) indicated greater positivity to repeated words, particularly over medial electrode sites (test condition $\times$ laterality: $F(1, 23) = 8.35, p = .033$). Test VF did not have a main effect ($F(1, 23) = 0.0, p = \text{n.s.}$), and did not interact with test condition ($F(1, 23) = 1.25, p = \text{n.s.}$). (Test VF did interact with Hemisphere individually and in higher-order interactions, indicating the expected effects of stimulus lateralization for the P2.) The P2 repetition effect was examined further over a selected set of six medial frontal

channels (shown on head icon in Fig. 6), both to focus on representative channels for P2 repetition effects and to avoid overlap with posterior components such as the N400.

3.2.4.2. Test VF and lag effects: Lag effects were examined using the old-new difference waves calculated for the old-new effects, but focusing on an earlier time window and more frontal channels (see Fig. 6). Mean amplitudes from 175 to 275 ms for all six representative channels were compared in a 3 (lag group: short, medium, long) $\times$ 2 (test VF: RVF, LVF) $\times$ 6 (electrodes) ANOVA. There was no main effect of test VF ($F(1, 23) = 1.16, p = \text{n.s.}$), although numerically the P2 repetition effect was larger for LVF/RH test words ($0.86 \mu\text{V}$) than for RVF/LH test words ($0.40 \mu\text{V}$). Additionally, there was no effect of lag group ($F(2, 46) = 1.78, p = \text{n.s.}$), and these factors did not interact (lag group $\times$ test VF: $F(2, 46) = .93, p = \text{n.s.}$).

3.2.4.3. P2 summary: Across all lags, P2 repetition effects were apparent for words tested in *either* VF (though the effect was numerically larger for LVF/RH than for RVF/LH test words). Given previous evidence that the kind of perceptual facilitation reflected in the P2 requires the contribution of RH processing mechanisms at encoding (Evans & Federmeier, 2007), these results suggest that, at retrieval, perceptual matching processes supported by RH encoding strategies are used during the evaluation of test words biased to either hemisphere. The presence of RH-supported P2 repetition effects more clearly illustrates that RH encoding strategies are shared between the two hemispheres during central encoding, even when a lateralized retrieval cue selectively probes the LH.

4. General discussion

In the present pair of experiments, the nature of retrieval asymmetries was investigated by comparing recognition accuracy, response times, and ERP memory effects to lateralized test probes. Previous studies using lateralized test words had only measured response accuracy and had found discrimination to be better for RVF/LH test words (Blanchet et al., 2001). However, such results are difficult to interpret in the context of asymmetries favoring the RVF/LH for basic word reading, the effects of which may have been magnified by the use of short presentation durations (e.g., 100 ms in Blanchet et al., 2001). Here we used longer presentation durations and a wider range of repetition lags than had been previously examined, so as to enable comparison of forgetting functions associated with retrieval cues biased to the RVF/LH versus LVF/RH. We also introduced comparisons between correctly identified words (response times and ERP old-new effects), for which word perception was likely successful in both VFs.

In Experiment 1, with instructions emphasizing speed, both speed and accuracy yielded RVF/LH advantages that were seen at both short and long repetition lags. In Experiment 2, when participants were not prompted to emphasize speed, RVF/LH advantages in both speed and accuracy again occurred at both short and long lags. Overall performance decreased with lag as expected, but in neither study or measure did lag significantly interact with visual field. Thus, performance advantages for RVF/LH items remained consistent for spacings ranging from 0 to 49 intervening items (approximately 3 s to 3.5 min). That behavioral effects were stable across lag, and even numerically present for new words, indicates that increasing memory demands associated with decay and/or interference do not amplify VF effects in episodic retrieval. It is known that word identification is faster and more accurate with RVF/LH presentation than LVF/RH presentation (Jordan & Patching, 2004; Jordan et al., 2003); whether the advantages seen here for RVF/LH test words represent only perceptual asymmetries, or perceptual asymmetries compounded with memory asymmetries, could not be determined from the behavioral data alone.

To examine whether memories that are successfully triggered by RVF/LH retrieval cues are, in fact, associated with greater neural measures of memory strength, Experiment 2 recorded ERPs. Stimulus lateralization has dramatic general effects on the ERP waveform. Although overarching hemispheric differences in, for example, word perception might constitute part of such effects, they would be difficult to extract. Memory effects, however, can be analyzed effectively in difference waves (old-new), which remove more general VF-based asymmetries. To our knowledge, this was the first experiment to record ERPs to lateralized test words, and, for test words in each VF, we observed old-new effects with the expected morphology, timing, and distribution based on decades of work using centrally presented test words. Additionally, with increasing repetition lag, the old-new effect decreased in amplitude and increased in latency (in both VFs), verifying its sensitivity in the present design to factors that affect memory strength.

Although old-new effects for both RVF/LH and LVF/RH test words patterned with the behavioral data in these robust lag effects, the old-new effect data provided no evidence to suggest that memory retrieval was superior in response to RVF/LH as compared with LVF/RH test words. Indeed, ERP memory effects were strikingly similar in the two VFs at all lags, with a numerical tendency for larger old-new effects for LVF/RH test words at the shortest lags. Importantly, there is no doubt that stimulus lateralization succeeded in biasing the perception and later processing of test words to the intended hemisphere, as the expected effects of VF presentation were observed both on early sensory components and on the later selection negativity. Thus, the ERP results suggest that the speed advantages observed when test words are lateralized to the RVF/LH do not arise from differences in memory strength.

The disparity between the behavioral and ERP data is the pattern that would be predicted if RVF/LH response time advantages are driven by hemispheric biases in word apprehension. Old-new effects are more selectively sensitive to factors affecting memory, whereas response times measures are additionally sensitive to the amount of time it takes to perceive and identify the word, as well as how long it takes to prepare and execute a manual response. In prior studies looking at lateralized processing of study words (Evans & Federmeier, 2007; Federmeier & Benjamin, 2005), response time effects at test were not always associated with corresponding changes on ERP responses linked to memory, suggesting that, at least in some cases, perceptual encoding differences may dominate response speed (see also Nagae & Moscovitch, 2002 for a similar argument). The ERP data cannot speak directly to the nature of the observed accuracy differences, as old-new effects (calculated as the difference between correctly recognized repeated words and correctly rejected new words) index processing only for correct trials (and there were insufficient misses and false alarms to create stable ERPs for those classes of items). However, accuracy advantages can be explained by the same mechanism as posited for the response time differences: if words projected to the LVF/RH are more likely to be misread, then accuracy will be lower for LVF/RH presentation.

The differences between the ERP results and behavioral performance in the current studies echoes some extant inconsistencies in related work. Although behavioral studies have found advantages for RVF/LH test words (Blanchet et al., 2001), neuroimaging data have not found a clean-cut asymmetry, with test words initiating bilateral retrieval patterns over prefrontal regions; at times, the pattern of activation appears left-dominant (Wagner et al., 1998) and at other times right-dominant (Habib et al., 2003; Tulving et al., 1994), but never unilateral. The current studies also found speed and accuracy advantages for the recognition of RVF/LH test words, but, as in the neuroimaging work, use of a more functionally constrained measure (here, ERPs) instead pointed to bilateral contributions to memory, with evidence that test words biased to either hemisphere elicit retrieval processes of comparable strength. That retrieval asymmetries are limited to measures that are additionally sensitive to perceptual speed and quality, and fail to appear in more memory-specific indices such as those provided by

electrophysiological and hemodynamic measures, suggests that they likely reflect a process other than episodic retrieval. Strong evidence of superior RVF/LH word apprehension suggests that reading biases may instead be the cause of the behavioral effects, and this hypothesis is bolstered by overlap in the stimuli that elicit reading and retrieval biases, as both occur for words (Blanchet et al., 2001; Jordan & Patching, 2004), but not for unpronounceable letter clusters (Berrini et al., 1982; Young et al., 1984).

The data from the current studies are not only useful in inferring how the two hemispheres might retrieve information in isolation, but they also provide some information with respect to how the hemispheres work together. In a previous study in which the study words rather than the test words were lateralized and then tested at the same lags, ERP old-new effects were larger for LVF/RH-studied items tested at long lags and P2 repetition effects were observed at all lags, but only for words that had been studied in the LVF/RH (Evans & Federmeier, 2007). Neither of these patterns was seen in the present experiment when the (same) words were instead lateralized at test. Different effects of lateralizing study and test words have also been seen in studies of false memory, which have uncovered consistent RVF/LH advantages in rejecting lures when test words are lateralized (Ito, 2001; Westerberg & Marsolek, 2003), but behavioral and electrophysiological LVF/RH advantages when study words are lateralized (Fabiani, Stadler, & Wessels, 2000; Metcalfe et al., 1995). Taken together, such results suggest that central encoding does not result in the formation and maintenance of separate LH and RH representations, which can be queried independently by lateralized retrieval probes. Furthermore, that P2 repetition effects were observed for test words presented to either the LVF/RH or the RVF/LH suggests that aspects of RH encoding strategies are incorporated into a representation that is available at test to either hemisphere. It therefore seems most likely that central encoding is a cooperative process.

Juxtaposing the results obtained here using lateralized test words with those obtained previously with lateralized study words (Evans & Federmeier, 2007) illustrates that biasing hemispheric processing at one stage versus another can have dramatically different consequences, a point that has sometimes been overlooked. As mentioned previously, VF studies of false memory report LVF/RH advantages when study words are lateralized (Fabiani et al., 2000; Metcalfe et al., 1995) and RVF/LH advantages when test words are lateralized (Ito, 2001; Westerberg & Marsolek, 2003). Surprisingly, these results are often seen as spurious contradictions rather than complementary pieces of a whole. The differences seen across our work on verbal memory reiterate the need to view manipulations at encoding and retrieval as distinct. Additionally, the evidence that lateralized probes do not independently query isolated LH and RH representations suggests that this issue is important for all studies using the VF method (e.g., studies of priming asymmetries, which must choose whether to lateralize the prime, target, or both).

In summary, the LH clearly dominates some basic aspects of word processing, creating behavioral accuracy and speed differences for lateralized words that can make the assessment of other kinds of asymmetries - such as those in the domain of memory - difficult to assess. ERP measures, however, show that both hemispheres can efficaciously use retrieval cues to access information about prior experience. Furthermore, the results suggest that the nature of the representation formed during the typical encoding of a centrally apprehended word reflects a blend of the two hemispheres' encoding strategies. This, in turn, points to a need to better understand the individual and joint contributions of the hemispheres to verbal memory in order to build a complete understanding of the mechanisms that underlie this critical aspect of cognition.

Acknowledgements

We gratefully acknowledge support from NIA grant AG26308 to KDF, and NIH training grant T32 MH-1819990 to KME. We also thank members of the Cognition and Brain Lab for helpful comments throughout this project, and the undergraduate assistants who helped with data collection.

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Fig. 1.

Shown are mean d' values for each lag, as a function of test VF. RVF/LH test probes were classified with greater sensitivity at all lags, and the degree of sensitivity decreased across lag conditions. Though there was no significant interaction of VF and lag, asymmetries at the shortest lags were small and then increased and stabilized throughout the longer lags.

Fig. 2.

Median response times for correctly identified repeated words are plotted across lag for each VF. More rapid identification of RVF/LH repeated words is evident at all lags except lag 30, as is the general lag-related increase in response time that was seen for both VFs.

Fig. 3.

Plotted are data from all 26 scalp sites for correctly classified new and old test words, with RVF/LH test words plotted at left, and LVF/RH test words plotted at right. Here, and in all subsequent figures, negative is plotted up. The effects of stimulus lateralization are apparent in the timing and amplitude of labeled posterior sensory components. The effects of stimulus repetition can be seen broadly across the head, and particularly on the N400 and LPC at medial central-parietal sites, where the old-new effect is typically greatest.

Fig. 4.

Repetition and lag effects on the N400 (300-500 ms) and the LPC (500-800 ms) are shown at a representative medial parietal channel (indicated by X on head icon). Relative to correctly rejected new test words, correctly recognized old words tested at all lags are more positive in both the N400 and LPC time windows. Additionally, lag was associated with a graded effect on old-new effect amplitude, with the greatest positivity for short lags, the least positivity at long lags, and intermediate amplitude for medium lags. The dotted circle on the head icon encompasses electrodes used in statistical analyses of the old-new effect.

Fig. 5.

VF effects in the old-new difference wave are plotted for each lag group, at a representative medial parietal channel (indicated by X on head icon). Difference waves were obtained by subtracting, within VF, the correct rejections (dot-dash lines in Fig. 4) from the hits corresponding to the appropriate lag group (plotted in Fig. 4). The trend for greater amplitude of LVF/RH test words is apparent at the shortest lags, as is the lack of any VF-related difference at medium or long lags.

Fig. 6.

Shown are P2 repetition effects for each VF at a representative medial frontal electrode (indicated by X on head icon), separated by lag group. Note that a more restricted portion of the recording epoch (500 ms) is plotted, in order to focus on the early-occurring P2 effects. For both VFs, P2 repetition effects are apparent and are maintained across lags. The dotted circle on the head icon indicates electrodes used in statistical analyses of the P2 repetition effect.