Published in final edited form as:
Brain Res. 2011 January 7; 1367: 278–286. doi:10.1016/j.brainres.2010.10.030.

ERP correlates of source memory: Unitized source information increases familiarity-based retrieval

Rachel A. Diana[1,2], **Wijnand Van den Boom**[3], **Andrew P. Yonelinas**[1], and **Charan Ranganath**[1,2]

University of California, Davis

[1]Department of Psychology 134 Young Hall One Shields Avenue Davis, California 95616 [2]Center for Neuroscience 1544 Newton Ct. Davis, CA 95618 [3]Leiden University Section Cognitive Psychology Leiden, Netherlands

Abstract

Source memory tests typically require subjects to make decisions about the context in which an item was encoded and are thought to depend on recollection of details from the study episode. Although it is generally believed that familiarity does not contribute to source memory, recent behavioral studies have suggested that familiarity may also support source recognition when item and source information are integrated, or "unitized", during study (Diana, Yonelinas, and Ranganath 2008). However, an alternative explanation of these behavioral findings is that unitization affects the manner in which recollection contributes to performance, rather than increasing familiarity-based source memory. To discriminate between these possibilities, we conducted an event-related potential (ERP) study testing the hypothesis that unitization increases the contribution of familiarity to source recognition. Participants studied associations between words and background colors using tasks that either encouraged or discouraged unitization. ERPs were recorded during a source memory test for background color. The results revealed two distinct neural correlates of source recognition: a frontally-distributed positivity that was associated with familiarity-based source memory in the high unitization condition only and a parietally-distributed positivity that was associated with recollection-based source memory in both the high unitization and low unitization conditions. The ERP and behavioral findings provide converging evidence for the idea that familiarity can contribute to source recognition, particularly when source information is encoded as an item detail.

Keywords

source memory; recollection; familiarity; event-related potentials

Corresponding Author: Rachel A. Diana radiana@ucdavis.edu phone: 530-757-8865 fax: 530-757-8640 Center for Neuroscience 1544 Newton Ct. Davis, CA 95618.

1. Introduction

Dual-process theories of memory propose that an item can be recognized based on assessments of its familiarity or on the basis of the recollection of contextual information associated with the item (Jacoby 1991; Joordens and Hockley 2000; Mandler 1980; Reder et al. 2000; Yonelinas 1994). In contrast to item recognition tests, source memory tests are generally thought to rely primarily on recollection because judgments are made about the context associated with an item (e.g., font color, spatial location, orienting task, etc). In numerous behavioral, event-related potential (ERP), and functional magnetic resonance imaging (fMRI) studies, source memory tests have been contrasted with item recognition tests in order to isolate recollection (see Diana et al. 2006; Diana, Yonelinas, and Ranganath 2007; Rugg and Yonelinas 2003; Yonelinas 2002 for reviews).

Although many studies are based on the assumption that source memory tests rely exclusively on recollection, it is notable that some theories (e.g. M. K Johnson, Hashtroudi, and Lindsay 1993; Yonelinas 2002) explicitly predict that both familiarity and recollection can contribute to source memory decisions. For instance, Yonelinas (2002) has proposed that memory for source details can be supported by familiarity, particularly if the item and source information were processed in a *unitized* manner. For instance, memory for an arbitrary association between an item ("shirt") and a color ("blue") could be supported by familiarity if one were orienting to the color as an integral feature of the item ("a blue shirt"). Thus, if item and source information are unitized during encoding, the familiarity of the unitized item can subsequently provide information about the source, without relying on recollection.

In recent studies, we have used receiver operating characteristic (ROC) analyses to test whether familiarity can contribute to source memory (Diana, Yonelinas, and Ranganath 2008; Diana, Yonelinas, and Ranganath 2010). In these experiments, we manipulated the extent to which item and source information (i.e., the association between a word and a background color) were treated as a single unit and examined the effects of this manipulation on source recognition ROCs. The ROCs were then fit using the dual-process signal detection (DPSD) model (Yonelinas, 1994, 1999), which assumes that recollection is a threshold process (i.e., some proportion of items are recollected, others are not) that supports relatively high confidence responses, whereas familiarity reflects a signal detection process that contributes to a wider range of confidence responses. When source memory decisions rely primarily on recollection, the model predicts relatively linear source ROCs in probability space (Yonelinas et al., 1999). Because familiarity is expected to reflect a signal detection process, the model predicts that as the contribution of familiarity increases, the ROCs should become more curvilinear due to the Gaussian nature of the familiarity strength distributions (Parks & Yonelinas, 2007; Yonelinas, 1994). We found that unitization of item and source information increased the curvilinearity of source ROCs. Based on the assumptions of the DPSD model, the results were consistent with the idea that familiarity can support source recognition.

An alternative explanation of these results, however, could be that recollection is not always a threshold-like process, and therefore that unitization of item and source information may simply affect the way in which recollection contributed to source memory. For instance, using computational modeling, Elfman and colleagues (2008) recently demonstrated that a model of recollection based on the neural properties of the hippocampus produced relatively linear source recognition ROCs when items had relatively low feature overlap, whereas it produced more curvilinear ROCs under conditions of high feature overlap. Thus the shape of the ROCs may be affected by feature overlap even though the proportion of recollection and familiarity do not change. This prediction was supported by empirical experiments showing that increasing feature overlap increased the curvilinearity of source memory ROCs. The previous unitization findings (Diana, Yonelinas, and Ranganath 2008) do not rule out the possibility that the ROCs measured a change in the recollection process as opposed to an increasing contribution from familiarity. Given that other studies have proposed that recollection remains the primary process even in tasks that integrate item and context information (e.g. Staresina and Davachi 2008), an alternative measurement technique is needed to more conclusively evaluate the role of familiarity in source retrieval.

We used ERPs to assess the extent to which recollection and familiarity contribute to source recognition. Most prior ERP studies of recognition processes have examined item recognition rather than source recognition (for a review, see Rugg and Yonelinas 2003). ERP studies of item recognition memory have identified two complimentary old-new effects that have been differentially linked to familiarity and recollection. The “mid-frontal old-new effect” (Curran 2000; Curran 2004; Curran and Cleary 2003; Duzel et al. 1997; Rugg and Nagy 1989; but see also Paller, Voss, and Boehm 2007) is manifest as a positive shift in ERPs for familiar items, occurring at approximately 300-500 msec over frontal electrode sites. The “parietal old-new effect” is topographically- and functionally distinct from the mid-frontal old-new effect and is manifest as a positive shift in ERPs for recollected items from approximately 500-800 msec post-stimulus, maximal over left parietal electrode sites. In addition, several studies of item recognition have also assessed source recognition by sorting item retrieval ERPs based on correct vs. incorrect source judgments. The results indicate that accurate source memory is associated with increases in the size of the parietal old-new effect but not the mid-frontal old-new effect (e.g. Wilding, Doyle, and Rugg 1995; Wilding 2000; Duarte et al. 2004; Woodruff et al. 2005). In the previous experiments, source information was operationalized as a contextual detail which was not directly relevant to the processing of each item. We hypothesized that contribution of familiarity to source recognition may be significantly increased if source and item information were integrated, or “unitized”, during encoding. Accordingly, in the present study, we investigated the effects of unitizing item and source information on ERP correlates of source recognition.

In the current study, we manipulated the encoding of source information (red and green backgrounds) such that the subjects were told either to encode the source and item information in an integrated manner (high unitization condition) or to encode source information as contextual information, external to the item (low unitization condition). In the high unitization condition, subjects were instructed to imagine each item in the color indicated by the background screen color (i.e., imagine the item being red), in order to encourage them to treat the source information as a feature of the item (Diana, Yonelinas, and Ranganath 2008; Diana, Yonelinas, and Ranganath 2010). In the low unitization condition, they were instructed to imagine why the item would be associated with a stop sign (red background) or dollar bill (green background). We reasoned that, in this condition, participants would process the item and the source as separate pieces of information.[1]

ERPs were recorded during a source recognition test in which participants made confidence ratings about the color that had been previously associated with each word. We predicted that source retrieval in both the high unitization and low unitization conditions would be associated with ERP correlates of source recollection (i.e. differing between source recollection responses and incorrect source responses), which we expected to occur across

[1]We have chosen to use the terms “high unitization” and “low unitization” rather than the terms “unitized” and “non-unitized”, which were used in previous publications, in order to highlight the fact that some degree of unitization may incidentally occur in all conditions. Our high unitization condition is intended to increase the likelihood that the item and source would be treated as a single unit (i.e., a red elephant) compared to the low unitization condition in whish the item and source were treated as two separate units (i.e., an elephant beside a red stop-sign).

parietal electrodes (Duarte et al. 2004; Wilding 2000; Wilding, Doyle, and Rugg 1995; Woodruff et al. 2005). We also predicted that accurate source recognition responses in the high unitization condition would be associated with ERP correlates of source familiarity (i.e. differing between high confidence source responses and incorrect source responses), which we expected to occur across frontal electrodes and prior to the recollection effects (Curran 2000; Curran 2004; Curran and Cleary 2003; Duzel et al. 1997; Rugg and Nagy 1989; but see also Paller, Voss, and Boehm 2007).

2. Results

2.1 Behavioral Results

Figure 1A shows the ROCs in the high unitization and low unitization conditions, with the high unitization encoding condition resulting in slightly greater area under the curve, indicating greater source accuracy. In order to assess the curvilinearity of the ROCs, we conducted a linearity analysis on the ROCs of each subject. The linearity analysis of the probability space ROCs indicated that the average quadratic for the high unitization and low unitization ROCs was −2.23 and −1.51, respectively (a negative quadratic indicating an inverted U-shaped function). The quadratic for the high unitization condition was significantly more negative than the quadratic for the low unitization condition, $t(12)=2.50$, $p<.05$. Thus, the high unitization condition led to a more curvilinear ROC than the low unitization condition, as predicted.

Further analyses of the ROCs were conducted by fitting the ROCs with the DPSD model (Yonelinas, 1994, 1999). The model was fit to each subject's ROCs using a regression method in which estimates were derived for familiarity (measured in d') and recollection (measured as probabilities) for items studied in green (Rgreen) and those studied in red (Rred). Figure 1B shows the average estimates of recollection and familiarity in source memory for the high unitization and low unitization conditions. As predicted, the familiarity estimate was greater in the high unitization source condition than the low unitization source condition, $t(12)=3.73$, $p<.005$, indicating that unitization increased the extent to which familiarity contributed to source memory. Estimates of recollection indicated that approximately 18% of the source judgments were based on recollection in each condition. The recollection estimate did not differ significantly between the high unitization and the low unitization conditions, for either the red, $t(12)=0.01$, $p=.98$, or green items, $t(26)=.68$, $p=.51$.

The behavioral results showed that unitization increased the curvilinearity of the probability space ROCs, which is consistent with previous behavioral studies (Diana, Yonelinas, and Ranganath 2008). Based on the DPSD model, this suggests that familiarity can support accurate source recognition and that this occurred to a greater degree in the high unitization condition. ERP analyses of the retrieval data were conducted in order to further test the hypothesis that unitization of item and source information increases the contribution of familiarity to source judgments.

2.2 ERP Analysis Strategy

Grand average waveforms for all 32 electrode sites are depicted in Supplemental Figures 1 (high unitization) and 2 (low unitization). We separately examined trials associated with recollection-based source responses ("source recollection", corresponding to correct "1" or "6" responses), trials associated with familiarity-based source responses ("source familiarity", corresponding to correct "2" or "5" responses) and trials that were associated with incorrect, low confidence ("incorrect source", corresponding to incorrect 3 or 4 responses).[2] This analysis approach was taken so that ERP indices of source memory retrieval for putatively recollection- and familiarity-based responses could be compared against a common baseline. With this approach, we could examine whether recollect and high-confidence responses differed qualitatively (as would be expected by many dual-process theories) or in a quantitative manner (as would be expected by pure signal-detection theories). We identified frontal and parietal electrodes to serve as our areas of interest. Fz was chosen as the representative electrode for frontal effects based on previous findings (e.g. Curran 2000). Parietal effects in previous work were often centered over P5, because P5 does not exist in a 32 electrode array under the 10-20 system, we used a cluster centered around the typical P5 location: P7, P3, and PO3 (e.g. Wilding 2000). Analysis of these electrodes of interest identified two contiguous time blocks that were then subjected to additional topographic analyses.

2.3 Electrode of Interest Analyses

We examined the mean amplitude for Fz and the parietal electrode cluster (P7, P3, and PO3) in 250 msec time bins for the high unitization and low unitization conditions, conducting *t*-tests for source recollection vs. incorrect source and source familiarity vs. incorrect source (α =.05).[3] We predicted that source recollection effects would be found for the parietal cluster in both the high unitization and low unitization conditions, and that source familiarity effects, which may occur for recollection and familiarity responses, would be found at electrode Fz for the high unitization condition but not the low unitization condition.

The first time bin at which we found a significant difference between correct source and incorrect source waveforms was 750-1000 msec. As shown in Figure 2A, we found that high unitization familiarity responses were significantly more positive than incorrect source responses at electrode Fz from 750 to 1000 msec ($t(1,12) = 1.84$, $p < .05$). High unitization recollection responses were also significantly more positive than incorrect source responses at electrode Fz during this time window ($t(1, 12) = 1.98$, $p < .05$). As we predicted, correct source responses for the low unitization condition were not significantly different from incorrect source responses during this time window in electrode Fz.

Our next analyses focused on ERP effects observed in a cluster of parietal electrodes (P7, P3, and PO3). These analyses revealed a significant difference between correct source recollection responses and incorrect source responses in the parietal cluster beginning during the 750 msec time window (high unitization: $t(1,12) = 2.26$, $p < .05$; low unitization: $t(1, 12) = 1.90$, $p < .05$), as seen in Figure 2C in electrode PO3. These recollection effects extended through the end of the recording interval. Source familiarity responses were not different from incorrect source responses in the parietal cluster or electrode PO3 for either high unitization or low unitization trials, during any time bin.

2.4 Topographic Analyses

The electrode of interest analyses revealed two temporally-distinct ERP effects: a familiarity effect at Fz from 750-1000 msec for the high unitization condition only and a recollection effect in left parietal electrodes, which occurred from 1000-2000 msec in both unitization conditions. Topographic maps shown in Figure 2 (B and D), revealed that the familiarity effect had a mid-frontal topography, whereas the recollection effect had a centroparietal scalp topography. In order to determine whether the familiarity and recollection effects were

[2]It should be noted that this type of analysis does not exclude familiarity from the recollection contrast. That is, participants are instructed to make a recollection response when details about the study episode are retrieved, regardless of familiarity. Therefore it is likely that recollected items are also familiar to some degree.

[3]A pattern of effects similar to the parietal cluster as a whole was observed in electrode PO3, which was used in the accompanying figures to avoid the appearance of differences between the frontal and parietal electrodes of interest based on averaging multiple electrodes (e.g. cleaner timecourses).

NIH-PA Author Manuscript

NIH-PA Author Manuscript

qualitatively different from one another, we conducted topographic analyses comparing the frontal and parietal effects. The topographic analyses are based on difference waves that reflect a contrast between source recollection and source incorrect trials (recollection) and between source familiar and source incorrect trials (familiarity). We used repeated measures ANOVAs with factors of condition (e.g. low unitization recollection) and electrode (32 locations) to formally assess the overall pattern of electrical activity in each time period. The raw data were normalized prior to statistical analysis using a scaling method designed to rule out the possibility that magnitude changes between conditions produced a spurious interaction (e.g. McCarthy and Wood 1985).

An ANOVA comparing the difference waves from the low unitization source recollection condition during the late (1250 to 1500 msec) time period to the difference waves from the high unitization source familiarity condition during the early (750 to 1000 msec) time period produced a condition by electrode interaction: $F(1,12)=4.80$, $p<.001$. A condition by electrode interaction was also found for the ANOVA comparing high unitization source recollection during the late (1250 to 1500 msec) time period to high unitization source familiarity during the early (750 to 1000 msec) time period: $F(1,12) = 5.64$, $p<.001$. These findings indicate that the overall pattern of the recollection effect in the 1250-1500 msec time period was different than the overall pattern of the familiarity effect in the 750-1000 msec time period.

Finally, although the electrode of interest analyses did not specify any additional effects, inspection of the topographic maps indicates a frontopolar effect (occurring in Fp1, Fp2, AF3, and AF4) that was specific to the low unitization conditions beginning at 750 msec. This effect does not seem to differentiate between the source recollection and source familiarity responses and was not predicted *a priori*.

3. Discussion

The present study was designed to test the claim that encouraging the unitization of item and source information should increase the contribution of familiarity to source recognition. The behavioral results replicate our previous findings (Diana, Yonelinas, and Ranganath 2008; Diana, Yonelinas, and Ranganath 2010) in showing that unitization of item and source information leads to an increase in familiarity estimates, but does not increase recollection estimates. The current study additionally showed that unitization affected the ERP correlates of familiarity-based recognition, providing additional support for the idea that unitization increases familiarity-based recognition. In addition, in line with the behavioral results, the ERP correlates of recollection were found to be less affected by the unitization manipulation.

The earliest ERP difference we observed between correct and incorrect source trials occurred at frontal electrodes in the high unitization condition for familiarity-based responses. This first ERP effect was diminished for recollection-based responses in the low unitization condition and absent for familiarity-based responses in the low unitization condition. Thus, the pattern of the ERP frontal effect was quite similar to the pattern of the behavioral familiarity measure, consistent with the claim that unitization increased familiarity-based recognition. A second ERP difference was observed between source correct and incorrect trials that was maximal over left posterior sites. This later effect was statistically significant for recollection-based responses in both the high and low unitization conditions, which is consistent with the behavioral results in suggesting that unitization did not greatly influence recollection-based recognition. No difference was observed between correct and incorrect source trials for familiarity-based responses in either condition for parietal electrodes.

Previous studies have identified putative ERP correlates of familiarity and recollection in paradigms which assessed both item and source recognition. These studies have consistently identified an early-onsetting central effect related to familiarity and a later left posterior effect related to recollection (e.g. Leynes and Phillips 2008; Senkfor and Van Petten 1998; Wilding, Doyle, and Rugg 1995; Wilding and Rugg 1997).[4] The current study also revealed a parietal positivity, largest from 1250 to 1500 msec, that was associated with source recollection and a mid-frontal positivity from 750 to 1000 msec that was associated with familiarity-based responses in the high unitization condition. However, the latency of the ERP source memory effects was much later than what is typically observed in item/source memory studies, so it is unclear whether the present ERP effects are analogous to what has been previously reported. Importantly, given the design of the present study, interpretation of the present ERP results does not hinge on how they relate to previously reported ERP modulations. The present data indicate that recollection was associated with a late-onsetting modulation for both high- and low-unitization trials, and that an earlier-onsetting modulation was seen specifically for correct source judgments in the high-unitize condition.

Although no previous study has examined the effects of unitization on ERPs in a source recognition task, the current findings are consistent with results indicating that manipulations of unitization increased the ERP correlate of familiarity seen in item recognition (Ecker, Zimmer, and Groh-Bordin 2007) and associative recognition (Rhodes and Donaldson 2008; Bader et al. 2010). Together with the present results, these studies present a compelling case that unitization increases the contribution of familiarity to recognition.

In addition to the mid-frontal and parietal ERP source memory effects, we also observed a right frontopolar positivity that was associated with recollection-based source recognition for the low-unitization items. As we did not predict this effect, it is difficult to do more than speculate about its functional significance. It is possible that correct source memory in the low unitization condition was more consistently associated with retrieval of specific object information (stop signs or dollar bills) than source memory in the high unitization condition (which can be associated with any reason that an object would be red or green).Thus the right frontopolar positivity may be a correlate of the retrieval or imagery of the stop sign or dollar bill. Also, the associations formed during the encoding lists may have been more spatial in the low unitization condition (associating two objects may encourage processing of the spatial relationship between them) than the high unitization condition. Thus, retrieval of low unitization source information may be more likely to involve memory for spatial details and the right frontopolar positivity may be a correlate of spatial processing. Both of these possibilities are consistent with previous work identifying a frontal correlate of modality-specific processing in source memory (J D Johnson, Minton, and Rugg 2008).

In conclusion, the present ERP results provide converging evidence for our hypothesis that unitization of item and source information increases the contribution of familiarity to source judgments. ERPs related to familiarity-based responses were observed at mid-frontal electrode sites and were more positive for correct source memory judgments in the high unitization condition than for incorrect source responses. This effect was not evident for high confidence responses in the low unitization condition. The results are consistent with the hypothesis that unitization increases the contribution of familiarity to source memory rather than changing the threshold nature of recollection to appear similar to familiarity.

[4]An additional component that is not present for item recognition tasks has also been found in previous source memory experiments. This late posterior negativity (LPN) is not typically modulated by source accuracy but may relate to the degree of uncertainty during processing. Thus, this effect may contribute to the late parietal effect that we identify. (Cycowicz, Friedman, and Snodgrass 2001; Friedman, Cycowicz, and Bersick 2005; Leynes and Phillips 2008; Mecklinger et al. 2007; Wilding and Rugg 1997).

These findings converge with behavioral findings using ROC methodologies and provide support for the dual-process model of recognition memory.

4. Experimental Procedure

Participants were 17 right-handed undergraduate students from the University of California, Davis who received credit towards the Psychology Department research requirement for their participation. Data from 13 of 17 participants were included in the analysis. A participant was excluded from the analysis if the dataset included fewer than 15 artifact-free trials in any condition.

Stimuli for this study were 360 three- to eight-letter English nouns, selected with use of the MRC Psycholinguistic Database (Coltheart 1981). The selected words had an average Kucera-Francis written word frequency of 30.39 (Kucera and Francis 1967). All words were also chosen for concreteness (min: 400; max: 670) and imageability (min: 424; max: 667).

Each participant was shown 360 words during both the study (four blocks) and the test phase (four blocks). Each study word was randomly assigned to one of the two background colors (red vs. green) and to one of the two conditions (high unitization vs. low unitization). Red and green were selected for use as background colors because the colors were approximately equal in terms of the number of study items that could be red or green in the real world. Participants were tested individually in a moderately lit, sound attenuated room. They were seated approximately 30 inches from the monitor on which the stimuli were displayed. Behavioral responses in both the study and the test phase were made using a small key pad held by the participant. EEG recording occurred during the test phase only.

Each experimental session began by explaining the stimuli and tasks to the participants. Also, practice trials were given to make sure that the participant was familiar with the two encoding tasks. In the study phase, words were displayed against either a red or a green background. Below each word, one of two study questions were shown, either “Why is this item green (red)”, in the high unitization condition, or “Why is this item associated with a dollar bill (stop sign)”, in the low unitization condition. In the high unitization condition, participants were asked to imagine the word as though it was the same color as the background (red or green) and to develop an explanation as to why the item was this color in their imagination. For example, when presented with the word “elephant” on a red background, participants might imagine that the elephant went to the beach and got sunburned. In the low unitization condition, participants were told to associate the word with a stop sign if the background color was red or a dollar bill if the background was green, and develop an explanation for this association. For example, when presented with the word “elephant” on a red background, participants might imagine the elephant marching in a parade and stopping at the stop sign. Participants were told that the associations were important for the purpose of the study and should be as unique as possible. Participants were asked to make a key press response indicating whether it was easy or difficult to imagine the required scenario.

Each study trial began with a fixation cross for 500 msec followed by the word, which was presented together with the question and the background color for 6000ms. After 4500 msec, the text turned yellow, indicating that time for the trial was running out. List order was counterbalanced using an ABBA scheme, with half of the participants beginning with a high unitization encoding list and half beginning with a low unitization encoding list.

Following the study phase, participants were given a memory test, in which words were displayed on black background, asking whether the words shown were previously presented on either a red or a green background. Participants were asked to give red/green background responses using a confidence scale from 1 to 6, with 1 indicating recollection of the red background, 2 indicating a high confidence red response, 3 indicating a low confidence red response, 4 indicating a low confidence green response, 5 indicating a high confidence green response, and 6 indicating recollection of the green background. Recollection instructions were as follows:

> "Recollect means that you can recall specific details about what was occurring when you studied the word. If you can remember the story you made up for a particular word, you should choose Recollect. If you can remember any detail about what occurred during the time you studied that word that indicates the background color, you should choose Recollect."

The test phase stimuli consisted of the same 360 words shown in the study phase.

EEG recording occurred during the test trials. Each test trial began with a central fixation cross for an average of 1500 msec (jittered randomly between 1000 and 2000 msec). The fixation cross was replaced by the test word, also presented centrally, for 1000 msec followed by a 1000 msec fixation. After this 2000 msec recording period, the confidence scale was presented until a response was given or 4500 msec at a maximum. The word "blink" was then presented for 1500 msec to encourage participants to blink between trials. Participants were asked to remain as motionless as possible and minimize their blinks during the recording portion of the test trial. The test items were presented in 4 blocks. Items in the high unitization and low unitization conditions were randomly assigned to blocks at test, thus all four blocks contained items from both conditions.

4.1 EEG acquisition and analysis

Electrophysiological data were recorded using a BioSemi ActiveTwo system, with active Ag/AgCl electrodes mounted in an elastic cap with electrodes at the following positions: Fz, F3, F4, FC3, FC4, C5, C3, C1, Cz, C2, C4, C6, T7, T8, CP3, CP4, P7, P3, Pz, P4, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, and O2, using the international 10/20 nomenclature (Jasper 1958). The sampling rate was 1024 Hz with signals digitally high-passed filtered at 0.16 Hz and digitally low-passed filtered at 100 Hz.

Post-recording, the EEG was segmented into epochs from 200 milliseconds pre-stimulus to 2000 milliseconds post-stimulus. Electrodes located lateral to the left and right eyes were used to monitor horizontal eye movements and electrodes above and below the left eye were used to monitor vertical eye movements and eye blinks. The electrodes were referenced to the average of left and right mastoids. Each trial was visually inspected for eye blinks, muscle tension, and drift. Trials containing artifacts were removed from the analysis. Table 1 indicates the average number of artifact-free trials included in the analysis in each condition. Where appropriate, the Hyun-Feldt correction for violation of the sphericity assumption was used to estimate *p*-values.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by NIMH grants MH083734, MH068721, and MH059352, and K99 grant MH083945 to RAD.

References

Bader, R.; Mecklinger, A.; Hoppstädter, M.; Meyer, P. Recognition memory for one-trial-unitized word pairs: Evidence from event-related potentials. NeuroImage [Internet]. 2010. In PressCorrected Proof. Available from: http://www.sciencedirect.com/science/article/B6WNP-4Y34PWX-9/2/e31d172eb66defdd8efa3d41e9f18f6e

Coltheart M. The MRC psycholinguistic database. Quarterly Journal of Experimental Psychology. 1981; 33A:497–505.

Curran T. Brain potentials of recollection and familiarity. Memory & Cognition. 2000; 28:923–938.

Curran T. Effects of attention and confidence on the hypothesized ERP correlates of recollection and familiarity. Neuropsychologia. 2004; 42:1088–1106. [PubMed: 15093148]

Curran T, Cleary AM. Using ERPs to dissociate recollection from familiarity in picture recognition. Brain Res Cogn Brain Res. 2003; 15:191–205. [PubMed: 12429370]

Cycowicz YM, Friedman D, Snodgrass JG. Remembering the color of objects: an ERP investigation of source memory. Cereb. Cortex. 2001; 11:322–334. [PubMed: 11278195]

Diana RA, Reder LM, Arndt J, Park H. Models of recognition: a review of arguments in favor of a dual-process account. Psychon Bull Rev. 2006; 13:1–21. [PubMed: 16724763]

Diana RA, Yonelinas AP, Ranganath C. Imaging recollection and familiarity in the medial temporal lobe: a three-component model. Trends Cogn Sci. 2007; 11:379–86. [PubMed: 17707683]

Diana RA, Yonelinas AP, Ranganath C. The effects of unitization on familiarity-based source memory: testing a behavioral prediction derived from neuroimaging data. Journal of Experimental Psychology. Learning, Memory, and Cognition. 2008; 34:730–40.

Diana RA, Yonelinas AP, Ranganath C. Medial temporal lobe activity during source retrieval reflects information type, not memory strength. Journal of Cognitive Neuroscience. 2010

Duarte A, Ranganath C, Winward L, Hayward D, Knight RT. Dissociable neural correlates for familiarity and recollection during the encoding and retrieval of pictures. Cognitive Brain Research. 2004; 18:255–272. [PubMed: 14741312]

Duzel E, Yonelinas AP, Mangun GR, Heinze HJ, Tulving E. Event-related brain potential correlates of two states of conscious awareness in memory. Proceedings of the National Academy of Sciences. 1997; 94:5973–5978.

Ecker UKH, Zimmer HD, Groh-Bordin C. Color and context: an ERP study on intrinsic and extrinsic feature binding in episodic memory. Mem Cognit. 2007; 35:1483–1501.

Elfman KW, Parks CM, Yonelinas AP. Testing a neurocomputational model of recollection, familiarity, and source recognition. J Exp Psychol Learn Mem Cogn. 2008; 34:752–768. [PubMed: 18605866]

Friedman D, Cycowicz YM, Bersick M. The late negative episodic memory effect: the effect of recapitulating study details at test. Brain Res Cogn Brain Res. 2005; 23:185–198. [PubMed: 15820627]

Jacoby LL. A process dissociation framework: Separating automatic from intentional uses of memory. Journal of Memory and Language. 1991; 30:513–541.

Jasper HA. The ten-twenty system of the International Federation. Electroencephalography and Clinical Neurophysiology. 1958; 10:371–375.

Johnson JD, Minton BR, Rugg MD. Content dependence of the electrophysiological correlates of recollection. Neuroimage. 2008; 39:406–416. [PubMed: 17933555]

Johnson MK, Hashtroudi S, Lindsay DS. Source monitoring. Psychological Bulletin. 1993; 114:3–28. [PubMed: 8346328]

Joordens S, Hockley WE. Recollection and familiarity through the looking glass: When old does not mirror new. Journal of Experimental Psychology: Learning, Memory, & Cognition. 2000; 26:1534–1555.

Kucera, H.; Francis, WN. Computational analysis of present-day American English. Brown University Press; Providence: 1967.

Leynes PA, Phillips MC. Event-related potential (ERP) evidence for varied recollection during source monitoring. J Exp Psychol Learn Mem Cogn. 2008; 34:741–751. [PubMed: 18605865]

Mandler G. Recognizing: The judgment of previous occurrence. Psychological Review. 1980; 87:252–271.

McCarthy G, Wood CC. Scalp distributions of event-related potentials: an ambiguity associated with analysis of variance models. Electroencephalogr Clin Neurophysiol. 1985; 62:203–208. [PubMed: 2581760]

Mecklinger A, Johansson M, Parra M, Hanslmayr S. Source-retrieval requirements influence late ERP and EEG memory effects. Brain Res. 2007; 1172:110–123. [PubMed: 17822684]

Paller KA, Voss JL, Boehm SG. Validating neural correlates of familiarity. Trends in Cognitive Sciences. 2007 Epub ahead of print.

Reder LM, Nhouyvanisvong A, Schunn CD, Ayers MS, Angstadt P, Hiraki K. A mechanistic account of the mirror effect for word frequency: A computational model of Remember/Know judgments in a continuous recognition paradigm. Journal of Experimental Psychology: Learning, Memory, & Cognition. 2000; 26:294–320.

Rhodes SM, Donaldson DI. Electrophysiological evidence for the effect of interactive imagery on episodic memory: encouraging familiarity for non-unitized stimuli during associative recognition. Neuroimage. 2008; 39:873–884. [PubMed: 17950624]

Rugg MD, Nagy ME. Event-related potentials and recognition memory for words. Electroencephalography and Clinical Neurophysiology. 1989; 72:395–406. [PubMed: 2469564]

Rugg MD, Yonelinas AP. Human recognition memory: A cognitive neuroscience perspective. Trends in Cognitive Sciences. 2003; 43:67–88.

Senkfor AJ, Van Petten C. Who said what? An event-related potential investigation of source and item memory. J Exp Psychol Learn Mem Cogn. 1998; 24:1005–1025. [PubMed: 9699305]

Staresina BP, Davachi L. Selective and Shared Contributions of the Hippocampus and Perirhinal Cortex to Episodic Item and Associative Encoding. J Cogn Neurosci. 2008

Wilding EL. In what way does the parietal ERP old/new effect index recollection? Int J Psychophysiol. 2000; 35:81–87. [PubMed: 10683669]

Wilding EL, Doyle MC, Rugg MD. Recognition memory with and without retrieval of context: An event-related potential study. Neuropsychologia. 1995; 33:743–767. [PubMed: 7675165]

Wilding EL, Rugg MD. An event-related potential study of memory for words spoken aloud or heard. Neuropsychologia. 1997; 35:1185–1195. [PubMed: 9364489]

Woodruff CC, Johnson JD, Uncapher MR, Rugg MD. Content-specificity of the neural correlates of recollection. Neuropsychologia. 2005; 43:1022–1032. [PubMed: 15769488]

Yonelinas AP. Receiver-operating characteristics in recognition memory: Evidence for a dual-process model. Journal of Experimental Psychology: Learning, Memory, & Cognition. 1994; 206:1341–1354.

Yonelinas AP. The nature of recollection and familiarity: A review of 30 years of research. Journal of Memory and Language. 2002; 46:441–517.

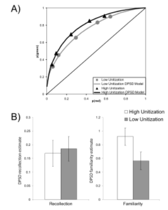

Figure 1.

A) Aggregate source recognition receiver operating characteristic (ROC) curves for the high unitization and low unitization conditions, collapsed across participants. Solid lines represent fits of the dual process signal detection (DPSD) model to the data. B) Parameter estimates from the individual source ROCs, based on DPSP model fits, in the high unitization and low unitization conditions for Experiment 1. Error bars indicate the standard error.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

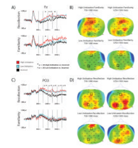

Figure 2.
A) Time course for the mid-frontal effect (Fz) contrasting source recollection vs. source familiarity vs. incorrect source for both the high unitization and low unitization encoding conditions. B) Topographic maps of the difference waves contrasting source familiarity vs. incorrect source for the high unitization and low unitization conditions during the critical time bins. C) Time course for the parietal effect (PO3) contrasting source recollection vs. source familiarity vs. incorrect source for both the high unitization and low unitization encoding conditions. Incorrect source waveforms are averaged across high and low unitization for ease of viewing (see the Supplemental Figures for the raw data). D) Topographic maps of the difference waves contrasting source recollection vs. incorrect source for the high unitization and low unitization conditions during the critical time bins.

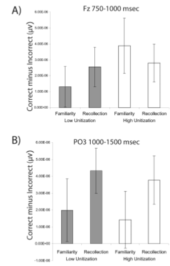

Figure 3.

Mean amplitudes across the 750-1000 msec time bin and the combined 1000-1500 msec time bin for high unitization and low unitization source recollection and source familiarity vs. incorrect source.

Table 1

Average number of artifact-free trials per participant. The standard deviation is presented in parentheses for each condition.

Condition	Correct Source Recollection	Correct High Confidence Source	Incorrect Low Confidence Source
High Unitization	54.77 (22.29)	21.39 (6.32)	22.39 (7.78)
Low Unitization	48.39 (19.38)	24.31 (11.36)	24.46 (10.56)