Published in final edited form as:

Psychol Sci. 2013 December ; 24(12): 2398–2408. doi:10.1177/0956797613492426.

Paying attention to attention in recognition memory: Insights from models and electrophysiology

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Abstract

Reliance on remembered facts or events requires memory for their sources, that is, the contexts in which those facts or events were embedded. Understanding of source retrieval has been stymied by the fact that uncontrolled fluctuations of attention during encoding can cloud important distinctions between competing theoretical accounts. To clarify the issue, we combined electrophysiology (high-density EEG recordings) with computational modeling of behavioral results. We manipulated subjects' attention to an auditory attribute, whether the source of individual study words was a male or female speaker. Posterior alpha band (8–14 Hz) power in subjects' EEG increased after a cue to ignore the gender of the person who was about to speak. Receiver-operating characteristic (ROC) analysis validated our interpretation of oscillatory dynamics. With attention under experimental control, computational modeling showed unequivocally that memory for source (male or female speaker) reflected a continuous, signal detection process rather than a threshold recollection process.

Imagine the following scenario. You recently learned about a genetically-engineered tomato-tobacco hybrid plant, 'Tomacco.' Unfortunately, you cannot remember whether you learned about Tomacco from *The New York Times* or from an episode of 'The Simpsons.' This failure to recall the source of your memory leaves you unsure of Tomacco's veracity. Clearly, knowing a memory's source is very important. Source memory can prevent serious *faux pas* (e.g., relaying the Tomacco development as fact), and can aid recognition of stimuli that are encountered in new contexts (Mandler, 1980).

Source memory is commonly assessed using a paradigm in which subjects study a list of visually-presented words varying in some contextual detail such as spatial location or gender of a voice speaking the word (Johnson, Hashtroudi, & Lindsay, 1993). Next, a recognition test is given. Previously-studied and new words are presented in random order. Subjects must decide whether each word is 'Old' or 'New' (item recognition), and make a decision as to any remembered word's source (e.g. male or female voice; source retrieval). One important aspect of the paradigm is its combination of traditional recognition measures (item recognition) with a cued recall measure (source retrieval).

Item recognition can be bolstered by recall of source details. This process, termed ‘recollection’ (Parks & Yonelinas, 2009), may complement a graded feeling of familiarity. Although most accounts of recognition agree that item recognition depends upon a graded familiarity signal, there is disagreement about the nature of the recollection process. The influential Dual-Process Signal Detection model (DP_{SDT}; Yonelinas, 1994, 1999) describes recollection as a threshold process: attempts at recollection either do or do not retrieve a detail. When recollection succeeds, it is always accurate and always produces highly-confident ‘Old’ responses. A competing model, Unequal-Variance Signal Detection Theory (UV_{SDT}; Mickes, Wais, & Wixted, 2009), assumes all responses reflect a single, continuously-distributed memory strength variable. That is, UV_{SDT} assumes recollection is a continuous process.

Importantly, both models focus on retrieval operations, and have no parameters describing encoding processes. However, recent UV_{SDT} extensions acknowledge the importance of encoding-related factors (Hautus, Macmillan, & Rotello, 2008). Additionally, assessments of the competing views of recollection have often focused on either neuroimaging or cognitive modeling (see Malmberg, 2008 for review). Our approach combines both methods, and incorporates an encoding-specific design. This hybrid methodology allows us to characterize attention’s role in recognition memory and to provide a clear assessment of the nature of recollection.

DP_{SDT} was motivated by a distinctive regularity in ratings-based receiver-operating characteristics (ROCs). These functions, which plot the Hit Rate ($P(\text{“Old”}|\text{Old})$) against the False Alarm Rate ($P(\text{“Old”}|\text{New})$) at varying levels of response confidence for fixed accuracy, are typically asymmetric for item recognition. Specifically, accuracy at the leftmost (‘Sure Old’) ROC point is higher than simpler models predict. DP_{SDT} attributes this result to threshold recollection’s selective generation of highly-confident ‘Old’ responses (Yonelinas, 1994).

An alternative explanation is that recent exposure increases old items’ memory strength, and as this increase varies in magnitude across items, the variance of old item strength increases (Starns, Rotello, & Ratcliff, 2012). This explanation forms a central assumption of UV_{SDT}, illustrated in Figure 1. In this model, subjects respond ‘Old’ whenever a test item’s strength exceeds a response criterion, and respond ‘New’ otherwise. Memory strength is continuously-distributed in UV_{SDT}, with higher average strength assigned to old items. By plotting the response proportions predicted at each of several criteria, a curved, asymmetric ROC is generated.

A key point about UV_{SDT} is its conception of recollection and familiarity as aggregate strength. Regardless of the number of processes recognition involves, they are assumed to be adequately described by a single, continuously-distributed memory strength variable. That is, UV_{SDT} assumes recollection is a continuous process (Mickes et al., 2009; Rotello, Macmillan, & Reeder, 2004).

To evaluate the competing views of recollection, one can assess ROC data for tasks varying in the degree to which recollection is required. For source recall, one can plot $P(\text{“Male”}|\text{Male})$

Male) against $P(\text{"Male"}|\text{Female})$ at different levels of source confidence, for items correctly identified as old. According to DP_{SDT} , the fact that source responses are collected via cued recall (i.e. only recollection can be used) means the resulting source ROCs should be linear, as predicted if threshold recollection were operating alone. Yonelinas (1999) reported the first source ROCs, and concluded the functions were indeed linear, consistent with DP_{SDT} . However, subsequent work suggests a simpler explanation for source ROC linearity. Specifically, fluctuations in attention to the source dimension during the study phase could produce test trials on which little or no source information is available. The resulting low-accuracy, low-confidence source responses would 'flatten' the source ROCs (Slotnick & Dodson, 2005). UV_{SDT} extensions incorporating this assumption fit existing source ROCs well, supporting the attention-fluctuation hypothesis (Hautus et al., 2008).

Despite this success, direct tests of the attention-fluctuation hypothesis are lacking: support for it has been largely inferred through goodness-of-fit. Fortunately, recent advances in the electrophysiology of attention suggest novel ways to (i) test the attention-fluctuation hypothesis directly and (ii) track and control attention.

To understand how, we consider electroencephalograph (EEG) oscillations in the alpha (8–14 Hz) frequency band. Recent studies have exploited pre-stimulus alpha-band oscillations as a marker of selective attention for an upcoming stimulus. Visual attention entails both a decrease in pre-stimulus alpha activity over cortical regions responsible for actively encoding a stimulus (Thut, Nietzel, Brandt, & Pascual-Leone, 2006), and an increase in regions whose function must be reduced to suppress task-irrelevant processing (Freunberger, Fellinger, Sauseng, Gruber, & Klimesch, 2009; Payne, Guillory, & Sekuler, 2013).

Recent work has documented analogous effects in audition. For example, Banerjee, Snyder, Molholm, and Foxe (2011) reported a right parieto-occipital electrode topography for auditory alpha. As they demonstrated, this pattern differs from those reported in studies of vision, which tend to be most pronounced in centro-occipital electrodes.

Alpha power is an attractive candidate for linking attention at encoding to theories of recognition. However, the generality of the auditory effect remains to be established. If Banerjee et al.'s results reflect some general signature of auditory attention, then a similar effect and topography should hold for more complex tasks, like source monitoring. Furthermore, such a signature would provide a unique opportunity to test the attention-fluctuation hypothesis. Specifically, trials on which high alpha power precedes the auditory source stimulus should be associated, during subsequent recognition testing, with lower performance and source ROCs nearer to chance for those items. Moreover, trials on which pre-stimulus alpha power is low should produce high-accuracy source ROCs. If the attention-fluctuation hypothesis is correct, its implications for memory models are clear: the corresponding source ROCs should be clearly curvilinear, contrary to the results of previous studies that neither measured nor controlled attention at encoding (e.g., Yonelinas, 1999). Finally, changes in item ROCs with the addition of recollection have been central in motivating DP_{SDT} . Thus it is important to know how the addition of attended source information actually impacts the corresponding item ROCs (Wixted, 2007).

Methods

Subjects

Eleven subjects (eight female) participated. Subjects' mean age was 21 years ($SD = 1.95$). All had normal or corrected-to-normal vision as measured with Snellen targets, reported no hearing deficits, and denied psychological or neurological disorders. Subjects were naive to the purpose of the experiment, and were paid for participation.

Stimuli

Singular nouns were presented visually and auditorily. Each had four to eight letters and one to three syllables. Average written frequency was 123 ($SD = 117$; Kůcera & Francis, 1967). Words were displayed in lower case on a 21-inch CRT monitor (99.8-Hz refresh rate; screen resolution = 1280x960 pixels). Displays were viewed binocularly from a distance of 57 cm. Audio files were presented at 48 db SPL, with average length = 490 ms ($SD = 102$ ms). Average frequency of the male speaker's files (computed over full duration) was 111 Hz ($SD = 15.27$ Hz); the female's files averaged 235 Hz ($SD = 20.33$ Hz).

Procedure

Encoding—Figure 2 illustrates the encoding procedure. Trials were of two types: Attend Voice (AV) and Ignore Voice (IV), with 40 trials of each randomly intermixed. AV trials began with a (300 ms) fixation screen (white font on a black background). A red box followed (500 ms), cuing subjects to ignore the upcoming stimulus. Boxes were centrally-presented, subtending 0.70° v.a. Next, the trial's study word was presented briefly (100 ms), in either an italic or non-italic font. Pattern masks bookended the stimulus (rows of Xs, 100 ms each). A green box then cued subjects to attend the upcoming (male or female) voice, which spoke the study word. A 700 ms blank screen interval onset with the recording, which offset at a variable period before the blank screen's offset. A 300 ms fixation screen followed. Subjects were then asked to indicate the voice's gender via key-press. RTs > 3000 ms were followed by the words "Too Slow" (500 ms). Trials ended with the (non-italic) presentation of the study word (3,250 ms). This interval gave subjects an opportunity to fully attend to and more deeply encode the words presented on each trial. Specifically, they were instructed to use this time to study the word for an upcoming memory test.

IV trials resembled AV trials, except that the cues traded positions: font presentations were attended and voices ignored. Subjects indicated whether the font was italic or non-italic. Our main goal is to examine the effects of changes in attention to male and female voices (the source variable explored in key studies of source retrieval), so we fixed the order of the font and voice intervals, relying on font trials to draw attention away from the voice during IV trials. Thus, the key interval of each condition for our analyses contains the second attention cue and auditory source stimulus, as emphasized in Figure 2.

Test—All 80 old words, and 40 new words, were randomly presented.¹ Below each was a 6-point confidence rating scale ranging from 1 (“Sure New”) to 6 (“Sure Old”). Subjects rated their confidence that each word was old or new. Each old/new scale was followed by a source scale ranging from 1 (“Sure Female”) to 6 (“Sure Male”). Subjects rated their confidence that the word had originally been spoken in a male or female voice. They were instructed that source ratings would follow even their new responses, the essential question being “Assuming your ‘New’ decision was wrong, what would your best guess be for the voice.” This was in keeping with previous experiments that collected these responses for theoretical reasons; we do not consider them further.

Analyses—Ratings ROCs were constructed for a) source recall at each level of source attention and b) item recognition varying in whether the old items’ source dimensions were attended at encoding. These functions allowed us to (i) assess whether source recollection for attended items is best described as a continuous or threshold process, and to (ii) characterize old/new performance in conditions varying in the extent to which recollection contributes.

We assessed source ROC linearity by fitting UV_{SDT} to each function, and comparing its fit to that of a threshold model (essentially, DP_{SDT} without the SDT component) that is consistent with the assumptions of DP_{SDT} as applied to source decisions (Yonelinas, 1999). UV_{SDT} predicts curvilinear ROCs for above-chance performance, while the threshold model predicts linear source ROCs. By assessing the relative fit of these two models, conclusions can be drawn regarding ROC form and the likelihood that threshold recollection is driving source responses. We used standard model comparison and fitting methods. UV_{SDT} requires a mean and variance for the ‘male’ source distribution, and 5 ratings criteria. The threshold model requires ‘male’ and ‘female’ recollection probabilities, and 5 bias parameters. Thus both models use 7 parameters to fit the 10 independently-varying points of a given attention condition. Models were fit using the *optim()* procedure in R (R Development Core Team, 2006) to minimize $G^2_{df=3}$.

To measure variation in recollection across the item ROCs, we conducted conventional tests of changes in the Hit Rate (HR) at a given False Alarm Rate (FAR), as well as fits of DP_{SDT} . For the latter, we first fit a baseline DP_{SDT} model to the two item ROCs. This model required 9 parameters: two recollection probabilities and two distribution means (for attended and ignored old items), and one set of five ratings criteria. This model fit 15 independent datapoints ($df = 6$). To preview, we found no difference in familiarity estimates across conditions, and therefore adopted an 8 parameter model with one distribution mean for our analyses. We compared its fit to that of a restricted model incorporating one value of $P_{Recollection}$. The difference in fit, G^2 , is χ^2 -distributed with df equal to the difference in the number of free parameters (i.e. 1).

¹ One subject served in a version of the experiment that was identical to the current protocol, except for the number of study/old (120) and new words (60). This subject’s data were similar to those of other subjects, and excluding the subject changed none of our results or conclusions. Thus we report the data with this subject included.

EEG signals were recorded using a 129-electrode array (Electrical Geodesies Inc.) and high-impedance amplifiers. All channels were adjusted for scalp impedance $< 50k\Omega$. Sensor signals were sampled at 250 Hz with a 0–125 Hz analogue bandpass filter. Periocular electrodes recorded from above and below each eye, and near each outer canthus.

EEG signals were preprocessed using Matlab's EEGLAB toolbox (Delorme & Makeig, 2004). Recordings were re-referenced to the grand average. The 0.5-Hz Butterworth high-pass and 60-Hz Parks-McClellan notch filters were applied. Epochs containing muscle artifacts, blinks, or saccades were rejected via independent components analysis and visual inspection. Wavelet analysis, cluster permutations, and visual display were performed using Matlab's FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). Time-frequency representations were computed using Morlet wavelets with width = 4 cycles/wavelet, with 1–70 Hz centers, in 1-Hz steps.

Alpha amplitude was defined by mean oscillatory power in the band 8–14 Hz. Wavelet alpha power for all electrodes was calculated for the epoch from cue onset through stimulus offset. A cluster-based, non-parametric, randomization test (Maris & Oostenveld, 2007) compared AV and IV. The cluster-based test statistic was calculated by comparing alpha power for the two conditions at every sensor, leaving the time window open from cue offset to stimulus offset. All sensors for which the t -value exceeded the .05 level were clustered via spatial adjacency. The sum of t -values from the cluster with the maximum sum was then used as the test statistic, thereby avoiding the problem of multiple comparisons. A reference distribution of test statistics was generated by randomly permuting the data across the two conditions 1000 times. A cluster was characterized as significant if the proportion of randomized values larger than the observed test statistic fell below the 0.025 level.

Results

Behavioral results

Source results are plotted in Figure 3, conditional on an old/new rating of '6' ('Sure Old')². Performance (in d_a units) varies with attention: IV performance (Panels A and C) falls below AV performance (B and D), $t(10) = 3.76$, $p < .01$, $d = 1.13$, 95% CI [.40, 1.54]. IV performance is not above chance (i.e. $d_a = 0$; $t(10) = .27$, $p = .79$, $d = .08$, 95% CI [−.38, .48]). Unsurprisingly, both models fit the IV ROC well: $G^2_{df=3} = 2.92$ (UV_{SdT}) and .58 (threshold). As performance approaches chance, ROCs necessarily become more linear. The key data for assessing the nature of the source variable in our study are in the AV condition. These data, plotted in Panels B and D of Figure 3, are clearly curvilinear and well-described by UV_{SdT}, $G^2_{df=3} = 1.18$. The threshold model departs from the data, $G^2_{df=3} = 9.34$, $p < .05$. These results are inconsistent with the idea that these source recall responses are driven to a significant extent by threshold recollection. They are, on the contrary, well-described by a continuous model.

It is important to know how item recognition varies with the addition of this seemingly continuous source information. The item ROCs, plotted in Figure 4, are informative. When

²Our results did not differ when collapsing over the old/new confidence levels.

source recall is ‘added’ to item responses (green ROC), accuracy appears to increase primarily at the leftmost, high-confidence ‘Old’ operating point. As the FARs of these two functions are necessarily equal, we can assess the increase by comparing HRs. This test showed that HR is higher for AV than IV at the leftmost (‘Sure Old’) point, $t(10) = 2.85$, $p < .05$, $d = .86$, 95% CI [.02, .12], but fails to reach significance at any subsequent operating points (e.g. $t(10) = 1.42$, $p = .19$, $d = .43$, 95% CI [−.03, .12] for the immediately rightward Attend/Ignore pair). In other words, a seemingly continuous source variable has produced an effect in the item ROCs that is similar to that which originally motivated DP_{SDT}’s threshold recollection. At the very least, this demonstrates that a continuous variable can produce effects that will be misinterpreted as threshold recollection, so long as that continuous variable tends to produce high-confidence ‘Old’ responses.

To assess this implication directly, we fit DP_{SDT} to the item ROCs in Figure 4. We started with the 9-parameter full model, which fit well, $G^2_{df=6} = 8.05$, $p = .24$. Interestingly, its recollection estimates differ by .086: $P_{Recollection} = .454$ and .368 for AV and IV, respectively. That is, DP_{SDT} indicates a nearly 9 percent increase in recollection probability when source recall is ‘added in’. Familiarity estimates, however, do not differ across conditions ($d' = .67$ and .64 for AV and IV). Thus we evaluated the increase in recollection by comparing two nested DP_{SDT} models: each used 5 criteria and one value of d' , but they differed in whether $P_{Recollection}$ varied across conditions or whether a single value was estimated. This test showed $G^2_{df=1} = 4.18$, $p < .05$, indicating a reduction in fit in the restricted model. In other words, DP_{SDT} indicates a significant increase in ‘threshold recollection’ with added source recall.

EEG Results—Results of the cluster-based permutation test revealed a right-lateralized cluster of 13 posterior electrodes at which alpha power for the IV condition exceed that of the AV condition (Figure 5). This effect extended across a 200 ms epoch following the offset of the cue, but preceding the onset of the auditory stimulus. Figure 6 shows the time-frequency transforms averaged across these 13 electrodes.³ Together, the figures reveal that posterior alpha-band activity following a cue to ignore begins immediately upon cue offset and continues throughout the duration of the auditory stimulus. The brief alpha activity at the presentation of both cues and at the onset of the to-be-attended stimulus likely reflects the well documented alpha-band phase locking that occurs in response to a stimulus onset (Freunberger et al., 2009).

To further assess alpha power’s diagnosticity as an attentional index, we conducted a within-subject median split for the AV condition. We focused on this condition as performance was naturally at floor in the IV condition. This allowed us to examine within-subject EEG-defined High and Low Attention source ROCs, conditional on high confidence ‘Old’ decisions. The results, plotted in Figure 7, show higher accuracy in the Low Power than in the High Power condition ($d_a = 1.31$ vs. .47, respectively). A Wilcoxon test of ROC areas (Hanley & McNeil, 1983) confirmed this difference, $z = 2.97$, $p < .01$, 95% CI [.07, .31]. As predicted by the attention-fluctuation hypothesis, the difference appears to be primarily in

³³ We obtained analogous results for alpha power preceding attended and ignored font presentations. See the online supplement for details.

the middle of the ROCs. This can be seen by comparing the fits of the UV_{SDT} and threshold models to each function. As is clear in the figure, UV_{SDT} fits both ROCs well $G^2_{df=3} = 5.81$ (Low Power) and 4.82 (High Power). In contrast, the threshold model fits the High Power ROC quite well $G^2_{df=3} = 1.71$, but deviates significantly from the data in the Low Power condition, $G^2_{df=3} = 13.00, p < .01$.

To ensure that our results were not due to distortions from averaging over subjects, we compared groups of subjects with similar performance levels, sorting them into low ($n=4$), medium ($n=3$), and high ($n=4$) accuracy subgroups. In all three subgroups d_a is higher in the Low Power condition. The ($d_{a,Low}$, $d_{a,High}$) numbers in the three respective groups are: (.51, .04), (1.07, .57), (1.54, 1.39).

Discussion

Our behavioral results show that when attention to the source dimension is controlled at encoding, the resulting source ROCs are clearly curvilinear and consistent with the underlying strength distributions of continuous recollection models (Mickes et al., 2009). Further, the results demonstrate that continuous recollection may produce the same increase in high-confidence HR that originally motivated DP_{SDT} 's threshold recollection. Finally, the results illustrate that DP_{SDT} will falsely interpret a continuous variable as a threshold variable, so long as its contribution largely results in high-confidence 'Old' responses. This suggests that DP_{SDT} 's threshold recollection measure is not only unreliable, as others have already suggested (Rotello, Macmillan, Reeder, & Wong, 2005), but it may also be invalid.

Source ROC curvature may result if subjects are instructed to 'unitize' item and source information (Bastin et al., 2013). However, our design included no such instructions. Our old/new results also argue against this interpretation: if unitized information contributed to decisions, DP_{SDT} should not have indicated increased threshold recollection when source memory was added to item decisions. In fact, DP_{SDT} not only indicated an increase in threshold recollection, but it also indicated no change in familiarity. This means that, according to DP_{SDT} , source recall was based entirely on threshold recollection, and thus the AV source ROC should have been clearly linear. Our results contradict this prediction.

Our study revealed an increase in right-lateralized posterior alpha power following cues to ignore an upcoming voice stimulus. Topographically, this finding resembles effects of visual attention (Freunberger et al., 2009; Payne et al., 2013). However, the auditory effect's focus was more lateral than is found for vision. The right, parieto-occipital, attention-mediated cluster reported here is in agreement with previous findings (Banerjee et al., 2011), though we used a considerably more complex task. Within the frontoparietal network, implicated in top-down control of spatial attention, activation within subsets of regions differs between audition and vision (Krumbholz, Nobis, Weatheritt, & Fink, 2009). Evidence from these studies indicates a modality-sensitive attentional control region. Recent work with nonhuman primates suggests this control region may be subserved by cells in the intraparietal sulcus (Grefkes & Fink, 2005).

Increases in posterior alpha power have been demonstrated for to-be-ignored auditory stimuli including noise bursts (Banerjee et al., 2011) and speech streams (Kerlin, Shahin, & Miller, 2010). To those we add auditory source stimuli. Our results, which demonstrate the generality of alpha power as a dynamic marker of attention, constitute a first step toward a powerful new analytic strategy for recognition memory. Using the alpha signal, one can track attentional engagement across conditions, subjects, and even individual trials (Macdonald, Mathan, & Yeung, 2011). One can then verify the interpretation of such EEG oscillations by applying appropriate cognitive models whose fits are conditional on the trials of interest (Ratcliff, Philastides, & Sajda, 2009). Trials on which attention is low can then be safely removed or parameterized. Alpha power could also be treated as a covariate or used to inform the parameters of hierarchical models (Pratte, Rouder, & Morey, 2010). Our work also suggests that in conjunction with accurate retrieval indices, alpha power can be used to constrain or validate the attention parameters of existing and future models (Hautus et al., 2008).

In sum, we showed that attentional fluctuations affect behavioral measures of item and source memory, and that such fluctuations can distort memory data and result in misinterpretations by models, like DP_{SDT} , that fail to account for attentional variation. Fortunately, such problems can be avoided by dual consideration of EEG oscillations at encoding and cognitive modeling of test performance. Our results show that models of complex cognitive processes such as recognition and cued recall should follow the lead of recent SDT extensions (Hautus et al., 2008) by accounting for variations in subjects' attention during encoding. The combination of electrophysiology with cognitive modeling constitutes a powerful tool for improving our understanding of recognition and attention's role therein.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Supported in part by CELEST, an NSF Science of Learning Center (NSF OMA-0835976), NIH T32-NS07292 and AFOSR FA9550-10-1-0420.

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Figure 1.

The unequal-variance signal detection model of recognition memory (Mickes et al., 2009).

Figure 2.

Illustration of an encoding trial's event structure. Each trial began with a fixation cross that oriented the subject to the region of the computer display within which the trial's stimuli would be presented. The fixation point was replaced either by a green square or a red square. The green square cued the subject that the font (italic or non-italic) of the ensuing word should be attended; a red square cued the subject to ignore the word. A cue-stimulus interval of 600 ms followed, and then the word was presented. Thereafter, a second cue was presented. This cue was a square that was green if the first cue had been red, or red if the first cue had been green. Following a second 600 ms cue-stimulus interval, an audio clip of the word spoken in either a male or female voice was played. The auditory presentation was followed by the trial's probe. Top row: on half the trials, the font display was to be ignored and the auditory presentation was to be attended. The probe prompted subjects to respond with a keyboard key press whether the voice that spoke the auditory word belonged to a male or to a female. Bottom row: on half of the trials, the font display was to be attended and the auditory presentation was to be ignored. For these trials, the probe prompted subjects to indicate whether the stimulus had been in an italic font or non-italic font. Every trial ended with a study period during which that trial's word was visually presented for 3250 ms.

Figure 3.

Source recall ROCs varying in whether the source dimension was attended (green) or ignored (red) at encoding. Fits of UV_{SDT} and the linear threshold model show that when source information was attended at encoding (Panels B and D) the subsequent test data are best described by a continuous SDT process.

Figure 4.

Item ROCs varying in whether the contributing old items' source dimension was attended (green) or ignored (red) at encoding. Values on the x-axis are repeated at each level of attention. The data show that increasing the contribution of source information to decisions about old/new status of test items produces a significant difference ($p < .05$) in Hit Rates solely at the leftmost point of the functions. This is consistent with the predictions of DP_{SDT} , which inferred a change in threshold recollection but no change in familiarity when source information was added via attention. However, the source variable producing the difference was best described as continuously-distributed.

Figure 5. Topographical display of auditory alpha (Ignore Voice > Attend Voice cluster; $p < 0.01$). Electrodes within the cluster showing a significant difference between the two test conditions at the 0.05 level are indicated by an asterisk (*).

Figure 6.

Grand-averaged, time frequency wavelets averaged across the cluster of 13 posterior electrodes for the Attend Voice (left panel) and Ignore Voice (right panel) conditions. Cue onset at Time = 0 and voice onset at Time = 1100 are marked by solid white lines. Dashed lines mark the presentations' offsets.

Figure 7.

Source recall ROCs varying in whether pre-stimulus alpha power was high (red) or low (green) at encoding. All data are from the AV condition, and were categorized based on a within-subject median split. Fits of UV_{SDT} and the linear threshold model show that when alpha power was low at encoding (Panels B and D) the subsequent test data are best described by a continuous SDT process.