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Prefrontal cortex contributions to episodic retrieval monitoring and evaluation

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ABSTRACT

Although the prefrontal cortex (PFC) plays roles in episodic memory judgments, the specific processes it supports are not understood fully. Event-related potential (ERP) studies of episodic retrieval have revealed an electrophysiological modulation – the right-frontal ERP old/new effect – which is thought to reflect activity in PFC. The functional significance of this old/new effect remains a matter of debate, and this study was designed to test two accounts: (i) that the effect indexes processes linked to the monitoring or evaluation of the products of retrieval in service of task demands, or (ii) that it indexes the number of internal decisions required for a task judgment. Participants studied words in one of two colours. In a subsequent retrieval task, old (studied) and new words were presented in a neutral colour. Participants made initial old/new judgments, along with study colour judgments to words thought to be old. They also indicated their confidence (high/low) in the colour decision. Right-frontal ERP old/new effects were larger for high than for low confidence correct colour judgments, and the magnitude of the right-frontal effect was correlated with the proportions of low confidence judgments that were made. Because the numbers of decisions associated with these response categories are equivalent, these findings do not support a decision-based account of the right-frontal ERP old/new effect. Rather, the correlation between confidence and the magnitude of the effect links it with retrieval monitoring and evaluation processes.

1. Introduction

Common to several accounts of episodic memory retrieval is the view that 'post-retrieval' processes can be engaged in order to monitor and evaluate the contents of retrieval in service of specific retrieval goals (Burgess & Shallice, 1996; Johnson, 1992; Mecklinger, 2000; Norman & Bobrow, 1979). Deficits in memory accuracy following damage to the prefrontal cortex (PFC) have been explained via recourse to impairments in post-retrieval processing (Burgess & Shallice, 1996; Janowsky, Shimamura, & Squire, 1989), and this broad class of control processes has also been employed in order to ascribe functional roles to PFC sub-regions in which activation has been revealed in positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies of memory retrieval (e.g. Cabeza & Nyberg, 1997; Fletcher & Henson, 2001; Ranganath & Knight, 2003; Rugg & Henson, 2003).

The concept of post-retrieval processing has also been considered in attempts to delineate the functional significance of a right-lateralised frontal event-related potential (ERP) modulation that has been observed in electrophysiological studies of retrieval and which is considered to reflect activity generated within the PFC (Friedman & Johnson, 2000; Kuo & Van Petten, 2008). In one of the earliest reports of the *right-frontal ERP old/new effect*, Wilding and Rugg (1996) suggested that it indexes processes necessary for forming successfully a representation of a prior episode. This proposal was motivated by the fact that the effect was larger (more positive-going relative to the activity elicited by new items) for test words that attracted correct rather than incorrect source (context) judgments. The findings in subsequent studies, however, suggest that this account is likely to be incorrect, because the effect does not predict the accuracy of source judgments under all circumstances (e.g. Senkfor & Van Petten, 1998; Van Petten, Senkfor, & Newberg, 2000).

In combination, these data points encourage a somewhat more generic retrieval processing characterisation for the right-frontal old/new effect than that offered by Wilding and Rugg (1996). This generic perspective has been emphasised further in recent work, where it has been shown that the effect is not only engaged in tasks requiring episodic retrieval. In two experiments, Hayama, Johnson, and Rugg (2008) contrasted the right-frontal old/new effects that were obtained in tasks requiring either source retrieval or semantic retrieval. Equivalent right-frontal old/new effects were obtained in both cases.

Hayama et al. (2008) considered these findings in the context of two possible accounts of the functional significance of the right-frontal ERP old/new effect. The first account was generated on the basis of a proposal driven by fMRI studies of the functional role of the dorsolateral prefrontal cortex (DLPFC). Dobbins and Han (2006) showed that neural activity in right DLPFC was greater in tasks requiring same/different source judgments than in tasks requiring

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a forced choice source judgment. Dobbins and Han (2006) argued that both of these conditions required recovery of episodic information, but only the same/different condition required an additional decision based upon the correspondence between the recovered information and the test cue. On the basis of these as well as subsequent complementary findings (Han, Huettel, & Dobbins, 2009) they have suggested that DLPFC is sensitive to the number of internal decisions that need to be made. If this decision-number account is correct, and if the right-frontal old/new effect is generated at least in part by right DLPFC, then this account could also apply to the electrophysiological effect described above. Conversely, the failure of the right-frontal old/new effect to predict the number of decisions required would suggest that this scalp-recorded effect is not solely a reflection of neural activity in DLPFC.

At a first pass, the decision-number account might be seen to be ruled out by findings reported by Woodruff, Hayama, and Rugg (2006), who acquired ERPs during the test-phase of a modified Remember/Know procedure. For items not assigned a Remember response, participants rated their confidence (high/low) in the Know response (for a related fMRI study, see Yonelinas, Otten, Shaw, & Rugg, 2005). For Know responses, the right-frontal old/new effect was reliably larger for those attracting the higher confidence rating. While this can be interpreted as a challenge to a number of decisions account of the right-frontal old/new effect, it has also been observed that these data points can be accommodated by such an account if it is assumed that only high confidence Know responses entail an additional decision over whether an item might be given a Remember response (Hayama et al., 2008).

Vallesi and Shallice (2006) also required participants to make confidence judgments, and in this experiment the assessment related to the accuracy of a source judgment. Participants heard words, an equal number spoken in a male/female voice. They then made source (male/female voice) judgments followed by confidence judgments (high/low) to visually presented words. Only studied words were presented at test, and the ERPs elicited by low confidence judgments were markedly more positive-going than those associated with high confidence judgments at both left- and right-frontal scalp locations. These data points certainly indicate that activity at anterior electrode locations varies according to the confidence with which source judgments are associated, but the absence of new items at test makes it difficult to make direct inferences about the right-lateralised frontal old/new effect that has been the focus in many previous studies.

The second proposal discussed by Hayama et al. (2008) is that the effect indexes processes involved in monitoring/evaluating information in service of task goals. This account is consistent with findings that the right-frontal old/new effect is larger in tasks requiring source judgments than in those requiring only old/new recognition memory judgments (Johnson, Kounios, & Nolde, 1996; Senkfor & Van Petten, 1998): it is reasonable to assume that the former requires more monitoring of the products of retrieval than the latter. Another situation in which greater monitoring might be required is when the quality of retrieved information is low, and in line with this view, support for a monitoring interpretation of the right-frontal old/new effect has been adduced from the finding that a larger right-frontal old/new effect was elicited in one of a pair of recognition memory tasks in which old/new discrimination was lower (Rugg, Allan, & Birch, 2000).

The experiment reported here was designed to provide a strong test of the decision-number account described above. In addition, the design provides a means of assessing the adequacy of a monitoring account. Towards this end, ERPs were measured during the test phases of a retrieval task in which studied words were presented in one of two colours. All words were presented in the same colour at test, and participants distinguished between old and new test words as well as the colour of the words at study. In addition, they reported their confidence (high/low) in the colour judgment.

As the numbers of decisions for old items are equated in this experiment design, changes in the magnitude of the right-frontal ERP old/new effect according to the accuracy of source judgments, and/or confidence in the source judgments, would present a strong challenge to the view that only the number of internal decisions determines when changes in the magnitude of the right-frontal old/new effect will occur. In addition, the use of confidence ratings provides a means of assessing one way in which a monitoring account can be operationalised. If greater monitoring is required when the amount or quality of retrieved information is low, and if an indicator of this is a propensity to make low rather than high confidence source judgments, a positive correlation between the magnitude of the right-frontal ERP old/new effect and the proportion of source judgments attracting low confidence responses would support the link between this electrophysiological signature and retrieval monitoring operations. This functional account has not, to our knowledge, been tested in this way before. In combination with the use of a design in which the number of decisions required for old items is constant, this experiment provides an opportunity to assess the adequacy of two functional accounts that have been offered for the right-frontal ERP old/new effect, and thereby contribute to an understanding of prefrontally mediated control processes that are engaged when retrieval from long-term memory is required.

2. Methods

2.1. Participants

Thirty-one right-handed native English speakers participated in exchange for £10 payment. Ethical approval for the study was obtained from the Cardiff University School of Psychology ethics committee. All participants had normal or corrected to normal vision, no diagnosis of dyslexia or colour blindness, and gave informed consent prior to the start of the experiment. Data from 3 participants were discarded because they did not contribute at least 16 artefact-free trials to response categories of interest (see below) due to excessive EOG artefact. Data from a further 7 participants were discarded because they were unable to make above chance judgments about study colour. Of the remaining 21 participants (mean age 21 years, range 18–27), 17 were female.

2.2. Materials

These were 360 low frequency words (MRC psycholinguistic database: frequency 1–9/million, Coltheart, 1981) presented on a black background. All were open-class and ranged between four and nine letters in length.

2.3. Design and procedure

The 360 words were divided randomly into 12 lists of 30 words which were paired at random to form 6 list pairs. One of the word lists in each pair was assigned to be the study list. All 30 words from the study list were presented again at test along with all words from the unstudied list to form one study-test block. A complete task list comprised 6 study-test blocks. An equal number of study words were shown in pink/yellow. All test words were shown in white. The order of word presentation within each list was randomised for each participant at study and at test. Four complete task lists were created by rotating the study/test status and colour of words at study.

Participants were fitted with an electrode cap prior to the experiment and were seated in a sound attenuated room 1.2 m away from a computer monitor with their fingers on response keys. A short practice session preceded the experiment and participants were able to take short breaks between study-test blocks. Participants were instructed that, in each study phase, they would see words shown in pink and yellow, and that their memories for the words and their colours would be assessed afterwards. For each study word, participants were instructed to press key pads using their index fingers to indicate word colour.

Each test phase began shortly after each study phase. Participants were informed that they would see words shown one at a time in white which were either from the immediately preceding study phase or were new to the experiment. They were asked to make an initial old/new judgment with their index fingers. For words judged old, participants were also asked to make a second response on one of four keys: *Confident-Pink*, *Think-Pink*, *Think-Yellow*, *Confident-Yellow*. Confident responses were always made with middle fingers, and Think responses with index fingers. Pink/yellow colour responses were always made with the same hand at study and at test. Participants were instructed to respond *Confident* if they were confident that they could remember the colour of the word at study, whilst they were to respond *Think* when they were less confident and only had 'a feeling' for the colour the word was presented in at study. For words judged to be new, participants were instructed to press any key after the initial old/new judgment to proceed to the next trial. The hands used to make old/new judgments at test and pink/yellow judgments at study were counterbalanced across participants.

Each study trial began with an asterisk that was displayed for 500 ms, followed by a blank screen for 200 ms, after which the word was displayed for 300 ms. The next trial began 1000 ms after a response was made. At test, 90% of trials in each block began with an asterisk that was visible for 1500 ms. The remaining 10% of test trials began with an asterisk that was visible for 500 ms. The length of asterisk presentation was varied in this way to encourage the participant to remain alert in the pre-stimulus period, during which EEG was also acquired (results not reported here). Following presentation of the asterisk, a blank screen was presented for 200 ms, and this was followed by presentation of the word for 300 ms. The screen remained blank for 1000 ms after the initial old/new response before a question mark signalling that a context judgment was required was shown for 300 ms. The screen then remained blank until 1000 ms after the participant responded, at which point the next trial started.

2.4. Electrophysiological recording procedure

EEG was recorded from 32 silver/silver chloride electrodes housed in an elastic cap. They were located at midline sites (Fz, Cz, Pz, Oz) and left/right hemisphere locations (Fp1/Fp2, F7/F8, F5/F6, F3/F4, F1/F2, T7/T8, C5/C6, C3/C4, C1/C2, T5/T6, P5/P6, P3/P4, P1/P2, O1/O2: Jasper, 1958). Additional electrodes were placed on the mastoid processes. EEG was acquired at 2048 Hz (frequency range = DC-419 Hz) referenced to linked electrodes located midway between POz and PO3/PO4 respectively, time-locked to word presentation and filtered offline between 0.03 and 40 Hz. The data were down-sampled to 166 Hz (6 ms/point), and re-referenced to the average of the mastoid signals into epochs of 1536 ms (256 data points), each including a 102 ms pre-stimulus baseline, relative to which all post-stimulus amplitudes were measured. EOG was recorded from above and below the right eye (vertical EOG: VEOG) and from the outer canthi (Horizontal: HEOG). Trials containing large EOG artefact were rejected, as were trials containing A/D saturation or baseline drift exceeding ±80 μV. Other EOG blink artefacts were corrected using a linear regression estimate (Semlitsch, Anderer, Schuster, & Presslich, 1986). The averaged ERPs for each participant and for each category of interest were subjected to a 7-point (22 Hz) binomially weighted smoothing filter prior to analysis.

3. Results

3.1. Behaviour

There were no differences at the group level in response accuracies for words presented in either pink or yellow at study, in keeping with previous findings in similar studies where colour manipulations have been employed (Cycowicz, Friedman, & Snodgrass, 2001; Wilding, Fraser, & Herron, 2005). In addition, for false alarms ($p = .15$) the probability of a pink colour judgment was 0.50, suggesting that equivalent accuracy for pink/yellow colour judgments was not in part a reflection of a bias to select one colour when uncertain. In light of these findings, the initial behavioural analyses and all ERP data reported are collapsed across study colour. Table 1 shows the probabilities of correct old/new judgments to old and new words, as well as the conditional probabilities of correct/incorrect colour judgments separated according to confidence. All of the behavioural data is collapsed across block: in an initial analysis including the factor of test block (2 levels: blocks 1–3, blocks 4–6) there were no reliable differences between the proportions of correct old/new and source judgments according to block, and this factor is not considered in any subsequent analyses. Old/new discrimination was above chance ($t(20) = 16.42$, $p < .001$), as was the conditional probability of a correct source judgment collapsed across response confidence (hereafter hit/hit responses: $t(20) = 7.57$, $p < .001$). For hit/hit responses, the probability of a high confidence response was reliably greater than a low confidence response ($t(20) = 2.40$, $p < .05$), whereas for incorrect source judgments (hit/miss responses) the reverse was true ($t(20) = -8.77$, $p < .001$).

Table 1
Mean probabilities of identifying old and new words correctly (hit and correct rejection (CR)) for all 21 participants. Also shown are the conditional probabilities of correct (hit/hit) and incorrect (hit/miss) source judgments, split according to the confidence judgments (high/low) that they attracted. Standard deviations are in brackets.

P(hit)	0.79 (0.09)
P(CR)	0.85 (0.13)
P(hit/hit: high)	0.41 (0.17)
P(hit/hit: low)	0.29 (0.07)
P(hit/miss: high)	0.08 (0.06)
P(hit/miss: low)	0.22 (0.08)

Mean reaction times for the initial old/new judgments are shown in Table 2. The middle and lower sections show the mean RTs for correct initial judgments separated according to source accuracy and response confidence. Correct rejections were made more quickly than correct responses to old words (collapsed across source accuracy: $t(20) = 2.71$, $p < .05$). A two-way ANOVA on the RTs for words judged correctly to be old with factors of source accuracy and confidence revealed main effects only: hit/hit responses were faster than hit/miss responses ($F(1,20) = 5.52$, $p < .05$), and high confidence responses were faster than low confidence responses ($F(1,20) = 4.43$, $p < .05$).

Table 2
Mean reaction times (standard deviations in brackets) for the response categories shown in Table 1.

Hit	1165 (360)
CR	985 (160)
Hit/hit: high	1065 (226)
Hit/hit: low	1202 (433)
Hit/miss: high	1140 (375)
Hit/miss: low	1252 (505)

3.2. ERP analyses

The key experiment predictions for a decision-number account can be tested by analysing the magnitudes of right-frontal ERP old/new effects in the relevant response categories. The outcomes of these analyses are described first below, and are followed by the correlation analyses that test the monitoring account of the right-frontal ERP old/new effect.

Two sets of ERP analyses were conducted in the first instance. The first ($N = 21$) was between the ERPs associated with correct rejections and the hit/hit as well as the hit/miss response categories, in keeping with the analysis strategies in previous source memory studies. The mean numbers of epochs per participant per response category were: correct rejections: 76 (range = 44–123), hit/hit: 54 (34–86), hit/miss: 24 (16–46). A second set of ERP analyses was conducted on data from 16 participants who contributed sufficient trials to the correct rejection response category, as well as to the hit/hit response category split according to whether they were associated with high or low confidence judgments. The mean numbers of epochs per participant per response category were: correct rejections: 65 (44–123), hit/hit (high confidence): 30 (18–51), hit/hit (low confidence): 20 (16–41). The pattern of behavioural data for this sub-group mirrors closely that shown for all 21 participants, and can be seen in Appendix A, Tables A.1 (accuracy) and A.2 (reaction times).

The ERPs were analysed for 3 post-stimulus time windows: 500–800, 800–1100 and 1100–1400 ms. These were selected on the basis of the time courses of ERP old/new effects identified in previous source memory studies (Allan, Wilding, & Rugg, 1998; Mecklinger, 2000). For the initial analyses, the data from twenty electrode locations were grouped to form four clusters at anterior-right (Fp2, F8, F6, F4, F2), anterior-left (Fp1, F7, F5, F3, F1), posterior-right (O2, T6, P6, P4, P2), and posterior-left (O1, T5, P5, P3, P1) locations. For each time window, initial global ANOVAs were conducted including the factors of response category, the anterior/posterior dimension, hemisphere, and electrode site.

Where these ANOVAs revealed reliable effects involving response category, they were followed up by all possible paired comparisons, which were conducted separately at anterior and posterior sites when the initial analyses revealed interactions including response category and the anterior/posterior dimension. Where necessary, analyses included the Greenhouse–Geisser correction for non-sphericity (Greenhouse & Geisser, 1959). Uncorrected degrees of freedom and *F*-values are shown in the text and results tables, accompanied by their respective epsilon values when appropriate.

3.3. Hit/hit and hit/miss ERP old/new effects

Fig. 1 (upper panel) shows that the ERPs associated with the hit/hit and hit/miss response categories begin diverging from those associated with correct rejections after 400–500 ms. These positive-going old/new effects are larger for the hit/hit than the hit/miss category at left-parietal locations from 500 to 1100 ms. Positive-going frontal ERP old/new effects are broadly comparable for the two classes of hits throughout the recording epoch, as is a late posterior negativity that can be seen clearly over posterior scalp in Fig. 1.

In the three initial global analyses, mean amplitude measures for ERPs associated with correct rejections and the hit/hit as well as the hit/miss response categories were contrasted. These revealed reliable interactions between response category, the anterior/posterior dimension, and hemisphere in all epochs (500–800 ms: $F(2,40) = 3.96$, $p < .05$, $\varepsilon = 0.87$; 800–1100 ms:

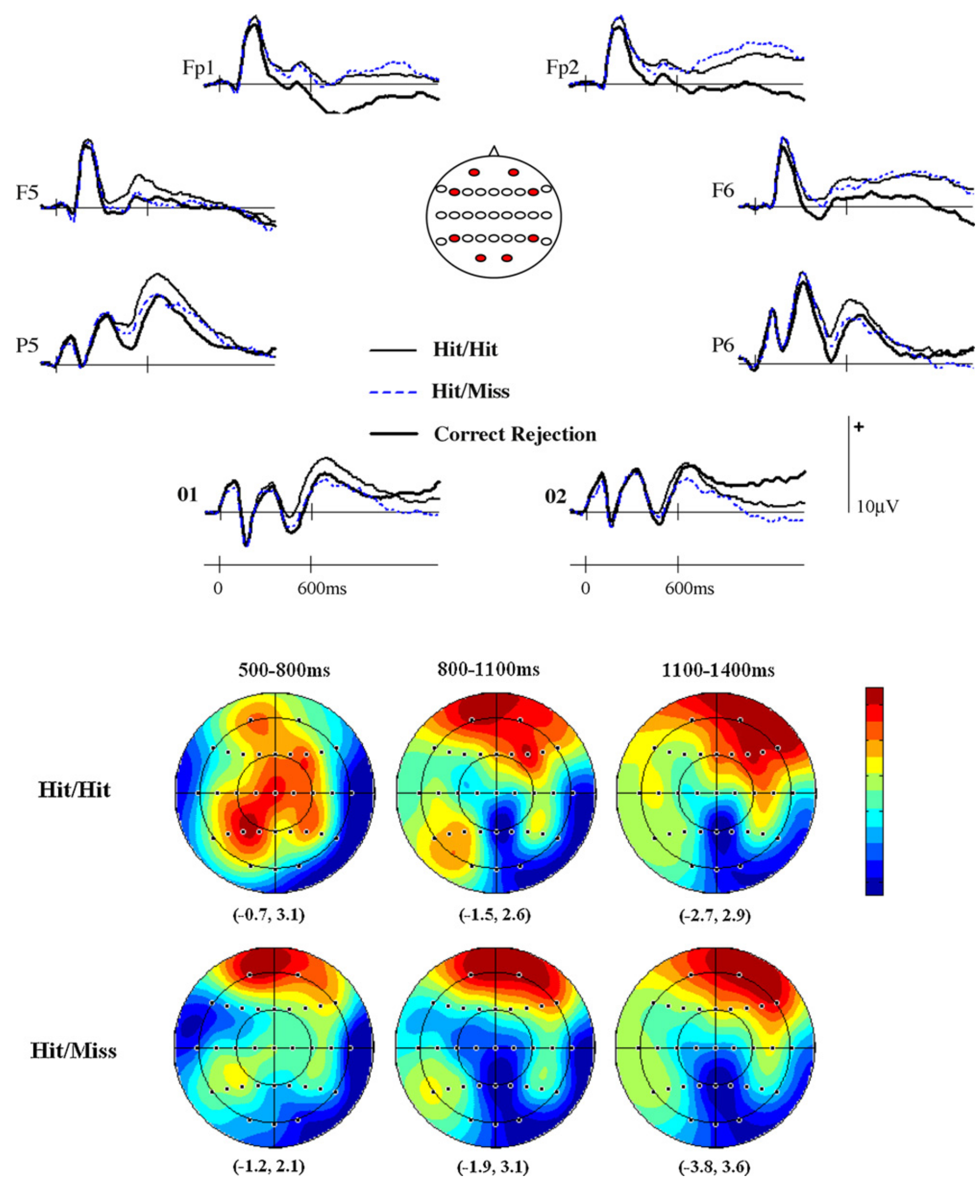

Fig. 1. *Upper Panel*: Grand average ERPs associated with the hit/hit, hit/miss and correct rejection response categories. Data are shown for 8 electrode locations at fronto-polar (Fp1/Fp2), anterior (F5/F6), posterior (P5/P6), and occipital (O1/O2) sites. *Lower Panel*: Topographic maps showing the scalp distributions of the old/new effects over the 500–800, 800–1100, and 1100–1400 ms time windows. Voltage maps were computed on the difference scores obtained by subtracting the mean amplitudes associated with correct rejections from the mean amplitudes associated with hit/hit (collapsed across high and low confidence), and hit/miss response categories. Each map is scaled proportionately between the minimum and maximum amplitude values denoted in brackets below each map.

Table 3
F-values and significance levels for the paired comparisons between the mean amplitudes associated with the hit/hit, hit/miss, and correct rejection (CR) response categories over the 500–800, 800–1100, and 1100–1400 ms epochs at anterior and posterior sites separately. Only effects involving response category that were reliable in at least one contrast are shown. RC = response category, AP = anterior/posterior dimension, HM = hemisphere, ST = site. ns. = non-significant ($p > .05$). Full dfs are shown on the left with epsilon values in brackets alongside each associated *F*-value.

	Anterior			Posterior		
	500–800 ms	800–1100 ms	1100–1400 ms	500–800 ms	800–1100 ms	1100–1400 ms
Hit/hit vs. CR						
RC (1,20)	11.84**	15.77**	20.30***	23.40***	ns.	ns.
RC × ST (4,80)	6.00** (0.65)	ns.	ns.	7.72***	ns.	3.93* (0.62)
RC × HM (1,20)	ns.	ns.	11.83**	7.65*	11.84**	ns.
RC × HM × ST (4,80)	4.03* (0.75)	3.69* (0.74)	ns.	ns.	ns.	ns.
Hit/miss vs. CR						
RC (1,20)	ns.	4.95*	10.48**	ns.	ns.	6.32*
RC × ST (4,80)	4.80* (0.55)	5.72** (0.45)	4.56** (0.50)	2.83* (0.72)	6.22** (0.62)	9.25*** (0.52)
RC × HM (1,20)	ns.	5.99*	8.96**	ns.	4.66*	5.52*
RC × HM × ST (4,80)	3.37* (0.69)	ns.	ns.	ns.	ns.	ns.
Hit/hit vs. hit/miss						
RC (1,20)	ns.	ns.	ns.	14.79**	ns.	ns.
RC × ST (4,80)	4.98** (0.59)	ns.	ns.	3.85* (0.62)	ns.	ns.
RC × HM × ST (4,80)	2.69* (0.85)	3.01* (0.84)	ns.	ns.	ns.	ns.

* $p < .05$.
** $p < .01$.
*** $p < .001$.

$F(2,40) = 9.72$, $p < .001$, $\varepsilon = 0.97$; 1100–1400 ms: $F(2,40) = 12.17$, $p < .001$, $\varepsilon = 0.80$). Also common to each epoch were category by anterior/posterior dimension by site interactions (500–800 ms: $F(8,160) = 4.82$, $p < .001$, $\varepsilon = 0.54$; 800–1100 ms: $F(8,160) = 5.98$, $p < .001$, $\varepsilon = 0.52$; 1100–1400 ms: $F(8,160) = 4.86$, $p < .01$, $\varepsilon = 0.46$).

The outcomes of the subsequent separate paired contrasts at anterior and posterior sites can be seen in Table 3, which shows that there are reliable old/new effects for the hit/hit and hit/miss response categories in all time windows. The results at anterior locations are described first. For the hit/hit old/new effects, the category by hemisphere by site interactions covering the 500–1100 ms period, and the category by hemisphere interaction in the following (1100–1400 ms) epoch, reflect the transition over time of positive-going old/new effects with a left fronto-polar maximum to those with a broadly distributed right-lateralised maximum, as Fig. 1 (lower panel) shows clearly. The same two- and three-way interaction terms that were revealed in the analyses of the hit/miss old/new effects from 500 to 1400 ms came about for broadly similar reasons. The reliable differences between the hit/hit and hit/miss old/new effects at anterior sites (interactions between category, hemisphere and site) in the 500–1100 ms epoch reflect the fact that the hit/miss effect is more positive-going at right- than at left-hemisphere superior sites.

For the outcomes of the analyses at posterior locations, the category by hemisphere interactions from 500 to 1100 ms for the hit/hit old/new effect reflect the fact that this positive-going effect is larger at left- than at right-hemisphere locations. The interaction between category and site in the following (1100–1400 ms) epoch is a reflection of a negative-going old/new effect that is most pronounced at occipital sites. The contributions of these differentially lateralised positive-and negative-going old/new effects are also responsible for the interactions involving category and hemisphere and category and site, respectively, that were revealed in the analyses of the hit/miss old/new effects. Finally, the only reliable differences between the hit/hit and hit/miss old/new effects at posterior sites were obtained in the 500–800 ms epoch, where the category by site interaction reflects the fact that the larger hit/hit old/new effects are most pronounced at superior scalp sites.

3.4. High and low confidence hit/hit old/new effects

Fig. 2 (upper panel) shows that the ERPs associated with the high confidence hit/hit response category begin diverging from those associated with correct rejections across the majority of scalp locations after around 400 ms. The positive-going old/new effects move from a left-posterior to a right-frontal maximum over the course of the recording epoch. There is also a negative-going posteriorly distributed old/new effect that onsets around 800 ms post-stimulus. For the low confidence hit/hit category, a greater relative late posterior negativity in comparison to correct rejections is also evident, as is a right-lateralised frontal positivity. This frontal effect is smaller than that which is associated with the high confidence response category.

The analysis strategy for these ERPs was the same as for the analysis of the hit/hit and the hit/miss ERP old/new effects. The three initial global analyses on mean amplitude measures for ERPs associated with correct rejections as well as the high and low confidence hit/hit response categories revealed reliable interactions between category, the anterior/posterior dimension and hemisphere in all epochs (500–800 ms: $F(2,30) = 6.03$, $p < .05$, $\varepsilon = 0.71$; 800–1100 ms: $F(2,30) = 12.41$, $p < .01$, $\varepsilon = 0.74$; 1100–1400 ms: $F(2,30) = 12.47$, $p < .01$, $\varepsilon = 0.77$). Also common were interactions between category, the anterior/posterior dimension, and site (500–800 ms: $F(8,120) = 2.62$, $p < .05$, $\varepsilon = 0.53$; 800–1100 ms: $F(8,120) = 3.21$, $p < .05$, $\varepsilon = 0.47$; 1100–1400 ms: $F(8,120) = 2.93$, $p < .05$, $\varepsilon = 0.57$). These outcomes were followed up within each epoch by all possible paired contrasts at anterior and posterior sites separately, the results of which can be seen in Table 4.

At anterior locations, there were reliable positive-going high confidence hit/hit old/new effects in each epoch. The main effects were moderated by an interaction with site in the 500–800 ms epoch only, reflecting the superior maximum of these frontal effects. Reliable old/new effects for the low confidence hit/hit category were evident from 800 to 1400 ms, with the category by hemisphere interactions reflecting the right-lateralisation of the old/new effects that can be seen in Fig. 2 (lower panel). The high confidence hit/hit old/new effects were reliably more positive-going than the low confidence effects in each epoch, with the category by site interaction from 500 to 800 ms coming about for

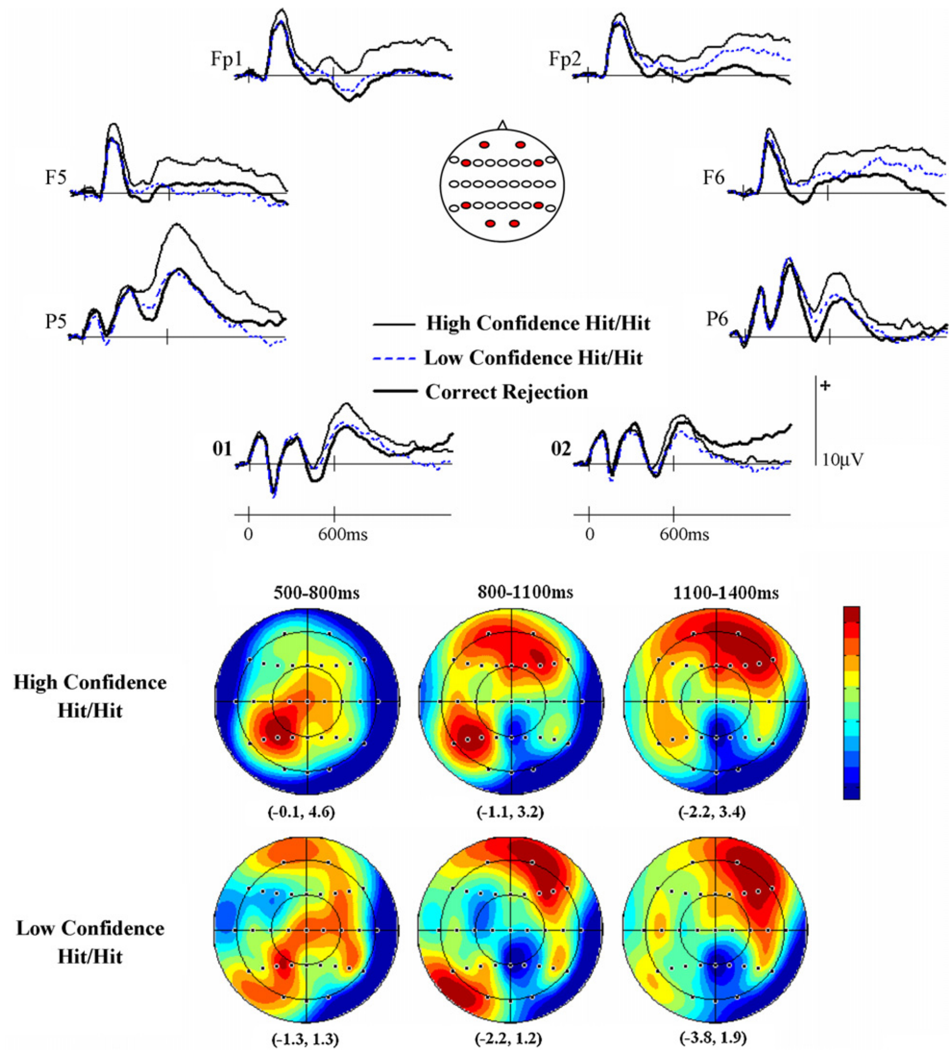

Fig. 2. *Upper Panel*: Grand average ERPs associated with the high confidence hit/hit, low confidence hit/hit and correct rejection response categories. All other figure details as for Fig. 1. *Lower Panel*: Topographic maps showing the scalp distributions of the old/new effects over the 500–800, 800–1100, and 1100–1400 ms time windows. Voltage maps were computed on the difference scores obtained by subtracting the mean amplitudes associated with correct rejections from the mean amplitudes associated with the confident hit/hit and think hit/hit response categories.

the same reason as that outlined for this term in the report of the outcomes of the analysis of the high confidence hit/hit old/new effects. The category by hemisphere interaction in the 800–1100 ms epoch reflects the fact that the greater relative positivity is most pronounced at left frontal sites (see frontal sites in upper panel of Fig. 2).

At posterior locations, the category by hemisphere and category by site interactions from 500 to 1400 ms for the high

Table 4

Outcomes of the paired comparisons between the mean amplitudes associated with the high confidence hit/hit, low confidence hit/hit, and correct rejection (CR) response categories for the 500–800, 800–1100, and 1100–1400 ms epochs at anterior and posterior sites separately. Reporting criteria and nomenclature are as for Table 3.

	Anterior			Posterior		
	500–800 ms	800–1100 ms	1100–1400 ms	500–800 ms	800–1100 ms	1100–1400 ms
High confidence hit/hit vs. CR						
RC (1,15)	11.61^{**}	16.84^{**}	20.33^{***}	31.03^{***}	ns.	ns.
RC × ST (4,60)	7.88^{***} (0.71)	ns.	ns.	10.24^{***} (0.49)	ns.	3.79^{*} (0.42)
RC × HM (1,15)	ns.	ns.	ns.	13.98^{**}	14.03^{**}	6.23^{*}
Low confidence hit/hit vs. CR						
RC (1,15)	ns.	ns.	ns.	ns.	ns.	6.16^{*}
RC × HM (1,15)	ns.	9.49^{**}	15.33^{***}	ns.	6.54^{*}	ns.
RC × HM × ST (4,60)	ns.	ns.	ns.	ns.	3.33^{*} (0.66)	ns.
High confidence hit/hit vs. low confidence hit/hit						
RC (1,15)	11.85^{**}	10.51^{**}	9.08^{**}	10.24^{**}	8.13^{*}	6.81^{*}
RC × ST (4,60)	5.41^{*} (0.44)	ns.	ns.	8.46^{***} (0.65)	6.02^{**} (0.77)	ns.
RC × HM (1,15)	ns.	6.57^{*}	ns.	7.84^{*}	5.48^{*}	ns.
RC × HM × ST (4,60)	ns.	ns.	ns.	4.23^{*} (0.59)	ns.	ns.

confidence hit/hit old/new effect reflect the contributions from two old/new effects. First, a positive-going left-lateralised old/new effect that decreases in magnitude over time. Second, a negative-going right-lateralised effect that increases in magnitude over time. The interaction terms revealed in the analyses of the low confidence hit/hit effect reflect almost wholly the contribution of the negative-going modulation only. The high confidence hit/hit old/new effect is reliably larger (more positive-going) than the low confidence effect in all epochs, with the category by site and category by hemisphere interaction terms from 500 to 1100 ms reflecting the tendency for these differences to be largest at left-hemisphere and superior electrode locations, respectively. The interaction involving category, hemisphere and site in the 500–800 ms epoch comes about for similar reasons.

3.5. Topographic analyses

The analyses of frontal ERP old/new effects described above revealed reliable interactions between response category and factors involving scalp locations from 500 to 1100 ms for the hit/hit versus hit/miss contrast. In order to determine whether these interactions came about because of differences between the scalp distributions of these frontal old/new effects, or simply differences between the magnitudes of the effects, analyses on data re-scaled using the max–min method were conducted. Rescaling removes overall amplitude differences between conditions, thereby licensing claims about differences between scalp distributions when interactions involving scalp locations remain when rescaled data are analysed (McCarthy & Wood, 1985; Urbach & Kutas, 2002; Wilding, 2006).

The values submitted to rescaling were the difference scores obtained by subtracting mean amplitude measures associated with correct rejections from those associated with the hit/hit and hit/miss categories. The analyses were conducted separately for each epoch and included the factors of category (hit/hit versus hit/miss) and the scalp location dimensions as described previously. The three interactions that were revealed in the analyses of the unrescaled data were also reliable after rescaling (500–800 ms: category by site: $F(4,80) = 4.91$, $p < .01$, $\varepsilon = 0.60$; category by hemisphere by site: $F(4,80) = 2.70$, $p < .05$, $\varepsilon = 0.83$; 800–1100 ms: category by hemisphere by site: $F(4,80) = 3.46$, $p < .05$, $\varepsilon = 0.86$). These interactions reflect the somewhat more focal left-frontal distribution of the hit/hit than the hit/miss old/new effect.

For the rescaled analyses of data separated according to confidence, points from the 800–1100 ms epoch alone were submitted to analysis, because only in this epoch were there reliable old/new effects for both the high and low confidence hit/hit response categories. The reliable interaction between category and hemisphere survived rescaling ($F(1,15) = 10.87$, $p < .01$), reflecting the fact that the low confidence hit/hit frontal old/new effect is right-lateralised to a greater degree than is the high confidence effect.

3.6. Correlation analyses

These analyses were conducted to investigate the relationship between the magnitudes of the right-frontal ERP old/new effect and the proportions of items judged correctly to be old that attracted either high or low confidence source judgments. Low trial numbers precluded correlation analyses for incorrect source judgments separated according to confidence, so two correlations were plotted. In both cases, the behavioural index generated for each participant was the proportion of low confidence responses given to old items for which the subsequent source judgment was correct. This measure was plotted against the magnitude of the right-frontal ERP old/new effect for two classes of ERPs—those formed for items judged correctly to be old that attracted correct source judgments and either high or low confidence responses. The composite measure of the magnitude of the right-frontal ERP old/new effect for each participant and response category was computed as the mean amplitude (averaged across sites Fp2, F2, F4, F6 and F8) of the difference between the ERPs elicited by correct rejections and correct source judgments over the 1100–1400 ms period. There was a positive correlation between this behavioural measure and the magnitude of the effects in both contrasts, but the correlation was larger and only reliable for the old/new effect associated with correct high confidence source judgments (high confidence: Pearson's $r = .531$, $p < .05$; low confidence, Pearson's $r = .101$).

4. Discussion

The experiment was designed to clarify the functional significance of the right-frontal ERP old/new effect. One possibility (see Section 1) is that the effect is sensitive to the number of internal decisions that are required for a given judgment (Dobbins & Han, 2006; Hayama et al., 2008). A second possibility is that the effect indexes monitoring operations that are engaged when material is assessed in service of task goals (Allan et al., 1998).

4.1. A decision-number account

Participants made an initial old/new judgment to visually presented words, and for words judged to be old, a second four-way judgment. They indicated the colour in which the word had been presented at study, and their confidence (high/low) in the colour judgment. ERPs were formed and averaged for new items attracting correct judgments, and for old items attracting correct old judgments that were then separated according to the accuracy of the colour judgment, as well as the confidence with which the colour judgment was made. In this design, correct and incorrect source judgments, as well as high and low confidence decisions, should be associated with the same number of internal decisions. As a result, reliable differences between the old/new effects for old words separated according to colour judgment accuracy and/or confidence would be inconsistent with a decision-number account of the right-frontal ERP old/new effect. There were two findings germane to this issue. First, right-frontal ERP old/new effects were statistically equivalent for words attracting correct old judgments and then either correct (hit/hit) or incorrect (hit/miss) colour judgments. We return to this finding later in Section 4. Second, right-frontal effects were reliably larger for words attracting high rather than low confidence correct colour judgments. While the findings for the hit/hit and hit/miss old/new effects do not challenge a decision-number account, the frontal old/new effects for correct colour judgments separated according to confidence certainly do.

Woodruff et al. (2006) also reported right-frontal old/new effects that were larger for items attracting high rather than low confidence memory judgments. In their experiment, items judged to be old were assigned either a 'Remember' response, or a high/low confidence 'Know' response. Remember/Know responses are associated respectively with items for which participants report that they either did or did not recover contextual information about study presentation (Gardiner & Java, 1993; Tulving, 1985). Hayama et al. (2008) noted, however, that their findings challenged a decision-number account only if it was reasonable to discount the possibility that an extra internal decision (whether or not to assign a 'Remember' response) was required only for items attracting high confidence judgments. It is difficult to envision how the response requirements in the experiment reported here suffer from a comparable concern, and as a result the findings provide a strong challenge to a decision-number account of the right-frontal ERP old/new effect.

The possibility that the right-frontal ERP old/new effect is sensitive to the number of internal decisions people make was generated on the basis of a proposal that right-DLPFC is sensitive to this variable. Consequently, if there were strong evidence linking this ERP effect with activity in right-DLPFC and to no other regions of prefrontal cortex, these findings would also present a challenge to the account of DLPFC function offered by Dobbins and Han (2006; Han et al., 2009). The neural generators of the right-frontal old/new effect are not, however, well-established. In light of this, and when coupled with our view that the data reported by Dobbins and colleagues make a compelling argument for the antecedents of activation changes in DLPFC, the neuroanatomical conclusion to be drawn for the right-frontal ERP old/new effect is that the generators of the effect are not restricted to the right-DLPFC.

This is not to say, however, that right-DLPFC plays no role in the generation of right-frontal old/new effects in source retrieval tasks, since a good case for its involvement can be made. For instance, the right-frontal ERP old/new effect is the difference between the neural activity elicited by correct judgments to old and to new items, and is pronounced when source judgments are required. In tasks where an old/new judgment precedes a source judgment that is made only for items judged to be old, the number of decisions required is greater for old than for new items. If neural activity in right-DLPFC is sensitive to this parameter then it is a candidate contributor to the right-frontal ERP old/new effect. Similarly, in tasks where a three-way task judgment is required (new/old context A/old context B), the presence of right-frontal old/new effects is consistent with the view that the effect receives a contribution from right-DLPFC if, as has been claimed, an internal decision that an item is old typically precedes the source judgment despite the presence of a three-way response requirement (Senkfor & Van Petten, 1998).

These arguments link activity within right-DLPFC to the right-frontal ERP old/new effect, and recent findings by Hayama and Rugg (in press) also support this view. In a fMRI study comprising the same design they employed in an earlier ERP study (Hayama et al., 2008: see Section 1), a comparable increase in right-DLPFC activity relative to baseline was observed when tasks required either semantic or episodic (source) retrieval. These observations, in combination, suggest that there will be circumstances under which the right-frontal ERP old/new effect will vary according to the number of internal decisions that are made. The foregoing arguments also make it clear, however, that this ERP effect does not only receive contributions from this region of the prefrontal cortex.

4.2. A retrieval monitoring account

This experiment also provided the opportunity to assess whether the behaviour of the right-frontal ERP old/new effect is consistent with a functional account cast in terms of post-retrieval monitoring of information in service of task demands. If a monitoring account is correct, and if greater monitoring is required as the quality of recovered information decreases, then there should be a positive correlation between the magnitude of the right-frontal ERP old/new effect and the proportion of items that attract low confidence source judgments, in so far as this behavioural measure indexes the amount or quality of recovered source information. This possibility was assessed in two analyses. At the level of individual participants, the proportions of low confidence correct source judgments were plotted against the ERP old/new effects that attracted correct source judgments and then either high or low confidence judgments. A positive correlation was reliable only for the relationship involving the ERPs associated with high confidence responses.

The findings therefore provide some support for a monitoring account, and they do so for the first time at the level of individual participants. None the less, the reason why the correlations were not reliable in both cases is not entirely clear. If the right-frontal old/new effect indexes monitoring operations engaged in order to make the confidence judgment, and the proportion of items that attract low confidence source judgments provides an index of the extent to which these processes are required, then one might anticipate reliable positive correlations regardless of the high/low confidence judgment that is eventually given. It may be the case, however, that this disparity arises at least in part because signal:noise is markedly superior in the analysis where the correlation was significant. On average there were 50% more trials per participant contributing to the high than to the low confidence correct source judgment response category.

A related question that arises from the perspective of a monitoring account stems from the finding that, at the group level, the right-frontal ERP old/new effect was larger for items attracting high rather than low confidence correct source judgments. If a monitoring account is correct, then this finding indicates that the monitoring to which the items were subjected was greater on average for items attracting high rather than low confidence decisions. This finding replicates that reported by Woodruff et al. (2006) described earlier, who acknowledged that reconciling this finding with a monitoring account is challenging.

One avenue that may be fruitful to explore in this regard is how right-frontal old/new effects vary with criterion placement in source tasks. If monitoring requirements increase as distance from a task-relevant decision criterion decreases (in this case the criterion for separating high and low confidence source judgments), then in averaged ERP measures the effects will be larger for conditions in which the mean distance from criterion across the items contributing to the average is smaller. For example, for a roughly Gaussian distribution, placement of a criterion to the far right will ensure that the average distance to criterion for items falling to the right of criterion will be smaller than that for items falling to the left. The shape of the distribution will also be important, and the form that this takes for recollection remains unclear (for relevant perspectives, see Rotello, Macmillan, Hicks, & Hautus, 2006; Yonelinas, 2002). The principle, however, is that, across samples of items that fall either side of a criterion, monitoring processes may on the average be engaged to greater or lesser degrees, or indeed to the same degree, for items attracting high or low confidence judgments. It is not possible to test this account for the present data set, but the account is testable in other circumstances, most notably when encoding conditions are constant and the criterion that is adopted at test is changed via test format or instructions. In so far as the shape of an underlying distribution will be constant in this design, changes in the magnitude of the right-frontal old/new effect for high and for low confidence responses with changes in criterion placement would be interpretable in terms of the account given above.

For one of two reasons, this possibility cannot be assessed adequately on the basis of published ERP data in studies in which test manipulations of this kind were employed. First, because the test manipulations did not result in statistically significant changes in response criterion (Herron, Henson, & Rugg, 2004; see also Herron, Quayle, & Rugg, 2003). Second, because in those studies in which reliable changes in criterion were obtained, focused analyses of right-frontal old/new effects were not reported (Azimian-Faridani & Wilding, 2006; Curran, DeBuse, & Leynes, 2007).

4.3. Hit/hit and hit/miss right-frontal ERP old/new effects

The contrast between right-frontal ERP old/new effects for these response categories (collapsed across confidence) revealed no reliable differences. As noted in Section 1, the insensitivity of this effect to the accuracy of source judgments is consistent with only some previous findings (cf. Senkfor & Van Petten, 1998; Van Petten et al., 2000; Wilding, 1999; Wilding & Rugg, 1996), but the design of the current experiment permits two claims.

This is, to our knowledge, the first report of an insensitivity of the right-frontal old/new effect to source accuracy when an old/new decision preceded the source judgment, and when no test items were copy-cues (verbatim re-presentations of study items). In previous reports of a comparable insensitivity, copy-cues have been present at test, and a single three-way (old/source1/source2) judgment has been required. By contrast, in all previous reports where the right-frontal old/new effect predicted source accuracy, the old/new judgment preceded the source judgment, and no copy-cues were present at test. As a result, the absence of reliable differences between the hit/hit and hit/miss right-frontal effects in this experiment suggests that neither of these design elements are critical antecedents for the conditions under which the right-frontal ERP old/new effect will predict the accuracy of source judgments.

These observations do not, however, provide an obvious starting point for reconciling the disparities in the published literature. Inspection of differences between the accuracy of old/new and source judgments across experiments provides little incentive to consider this factor in any explanation. Similarly, although the kinds of contextual information that have been retrieved have varied across studies, there is no immediately obvious criterion which would permit a principled separation between the contents that do and do not result in right-frontal old/new effects predicting the accuracy of source judgments. Neither of these possibilities have been tested directly, however, and thus represent starting points that may contribute to an understanding of the existing disparities.

4.4. Dissociable frontally distributed ERP old/new effects

Another candidate explanation for some of the divergences across experiments is that these have come about because not entirely the same frontal ERP old/new effects were elicited. Informal inspection of variations in the locations of scalp maxima and degrees of laterality of late frontal old/new effects across studies provide general support for this view (compare, for example, Johansson & Mecklinger, 2003; Senkfor & Van Petten, 1998; Tendolkar & Rugg, 1998; Trott, Friedman, Ritter, & Fabiani, 1997; Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999). Moreover, it would arguably be unsurprising were separable late frontal ERP old/new effects to exist, given the neuroanatomical and functional heterogeneity of the PFC that has been documented in lesion and in haemodynamic imaging studies in numerous cognitive domains (Fletcher & Henson, 2001; Ranganath, 2004; Ranganath & Knight, 2003; Stuss, Eskes, & Foster, 1994).

Evidence that separable late frontal ERP old/new effects can be elicited was obtained in the current experiment. The evidence comprised the reliable interactions between location and response category that were obtained in the analyses of the rescaled hit/hit and hit/miss old/new effects, as well as the analyses of the rescaled high and low confidence hit/hit effects. The scalp maps in Figs. 1 and 2 show that frontal old/new effects generally become progressively more right-lateralised over time, but the degree to which they do so is greater for the hit/miss than the hit/hit category, and greater for the low confidence than for the high confidence hit/hit category. These differences can be seen clearly in the scalp maps in Fig. 2 for the 800–1100 ms post-stimulus period.

One possibility is that these differences are simply a consequence of the propagation over anterior scalp of the left-parietal old/new effect, which is larger for hit/hit than for hit/miss responses, and markedly larger for high than for low confidence hit/hit responses. The lesser degrees of right-lateralisation for the hit/hit response categories in the two critical contrasts described above might therefore reflect the greater extent to which neural activity associated with the parietal ERP old/new effect projects

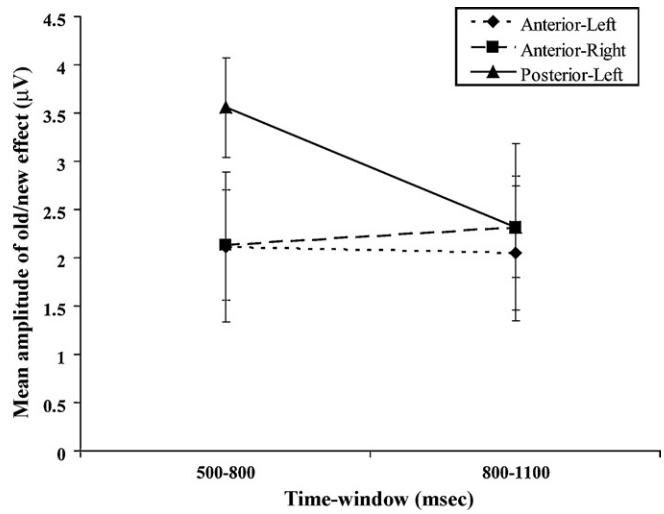

Fig. 3. Mean amplitudes of the high confidence hit/hit old/new effect averaged across anterior-left (Fp1, F7, F5, F3, F1), anterior-right (Fp2, F8, F6, F4, F2), and posterior-left (O1, P7, P5, P3, P1) electrode clusters in the 500–800 ms and 800–1100 ms time-windows. Error bars show ±1 standard error.

to left-frontal sites for those categories. The pattern of mean amplitude measures plotted in Fig. 3 argues against this account, however. The figure shows changes over time in the mean amplitudes of the high confidence hit/hit old/new effects at left- and right-frontal sites, as well as at left-parietal sites. In addition, the figure also shows that the magnitude of the old/new effects at left- and right-frontal sites remains constant alongside a diminution over time for the left-parietal effect. These data points argue strongly for the view that two electrophysiologically dissociable old/new effects were observed in this study: low confidence correct source judgments elicited a right-frontal old/new effect only, whilst high confidence correct source judgments also elicited a left-lateralised effect with an earlier onset. It seems reasonable to assume that this distinction also explains the evidence for qualitative differences in neural activity obtained in the hit/hit versus hit/miss contrast.

Given that the left-frontal old/new effect was extracted via a contrast between correct source judgments separated according to confidence, one possibility is that the effect is tied specifically to processes related to recollection of task-relevant content. The basis for this claim is the possibility that averaged ERPs for items attracting confident source judgments will be associated with recollection to a greater degree than will items attracting low confidence judgments. The same argument can be applied to the hit/hit versus hit/miss comparison.

A functionally similar effect has been described by Woodruff et al. (2006). In their experiment, items assigned a Remember response diverged from those assigned high confidence Know responses at frontal and fronto-polar scalp sites in the same time frame as the left-lateralised effect described here (in particular, see Fig. 9, p. 132 of Woodruff et al. (2006)). It will be important in subsequent experiments to investigate the correspondence between this effect and the somewhat more left-lateralised effect described in this experiment, especially in light of their apparent functional similarities. Whether they are in fact electrophysiologically distinct effects remains to be determined.

Irrespective of the outcome of this issue, the current findings substantiate the view that at least two neurally and functionally distinct late frontal effects can be observed in ERP studies where episodic retrieval is required (Woodruff et al., 2006). It has been argued above that it is reasonable to assume the right-DLPFC contributes to the right-frontal ERP old/new effect, but the fact that the effect also differentiated between high and low confidence correct source judgments suggests that other generators located in PFC also contribute. These additional generators of the effect do not necessarily have to be located in right PFC, as generators located on the medial walls would produce a scalp field with a contralateral maximum (see Barrett, Blumhardt, Halliday, Halliday, & Kriss, 1976; Brunia & Vingerhoets, 1981; Woodruff et al., 2006). For the same reason, for the left-frontal old/new effect described here, aligning the effect with generators located solely in the left hemisphere is probably premature.

In summary, in addition to these neuroanatomical considerations, the larger right-frontal ERP old/new effect for high than for low confidence correct source judgments suggests that a functional account of the effect that is couched in terms of the number of internal decisions required is at best incomplete. A strong push towards incorporating an element of retrieval monitoring into the account comes from the reliable correlation that was described above, and it has also been argued that the larger old/new effect for high than for low confidence judgments can be accommodated within this framework. Further progress in delineating the functional significances of late-frontal ERP old/new effect is a necessary element in the development of dynamic functional and neural characterisations of control processes that are engaged during memory retrieval.

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Appendix A.

Table A.1
Mean probabilities of identifying old and new words correctly (hit and correct rejection (CR)) for the 16 participants contributing sufficient trials to the analyses separated according to confidence. Also shown are the conditional probabilities of correct and incorrect source judgments, split according to the confidence judgments (high/low) that they attracted.

P(hit)	0.80 (0.08)
P(CR)	0.82 (0.14)
P(hit/hit: high)	0.41 (0.14)
P(hit/hit: low)	0.29 (0.05)
P(hit/miss: high)	0.09 (0.06)
P(hit/miss: low)	0.21 (0.07)

Table A.2
Mean reaction times and standard deviations for the response categories shown in Table A.1.

Hit	1126 (297)
CR	976 (127)
Hit/hit: high	1045 (202)
Hit/hit: low	1167 (374)
Hit/miss: high	1061 (243)
Hit/miss: low	1231 (482)

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