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Temporally and functionally dissociable retrieval processing operations revealed by event-related potentials

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ABSTRACT

In a pair of recent studies, frontally distributed event-related potential (ERP) indices of two distinct post-retrieval processes were identified. It has been proposed that one of these processes operates over any kinds of task relevant information in service of task demands, while the other operates selectively over recovered contextual (episodic) information. The experiment described here was designed to test this account, by requiring retrieval of different kinds of contextual information to that required in previous relevant studies. Participants heard words spoken in either a male or female voice at study and ERPs were acquired at test where all words were presented visually. Half of the test words had been spoken at study. Participants first made an old/new judgment, distinguishing via key press between studied and unstudied words. For words judged 'old', participants indicated the voice in which the word had been spoken at study, and their confidence (high/low) in the voice judgment. There was evidence for only one of the two frontal old/new effects that had been identified in the previous studies. One possibility is that the ERP effect in previous studies that was tied specifically to recollection reflects processes operating over only some kinds of contextual information. An alternative is that the index reflects processes that are engaged primarily when there are few contextual features that distinguish between studied stimuli.

1. Introduction

Damage to the prefrontal cortex (PFC) commonly results in memory impairments that are more selective than those that accompany damage to the medial temporal lobes (MTL; for reviews, see Ranganath & Knight, 2003; Stuss, Eskes, & Foster, 1994). While performance on old/new recognition memory tasks and close variants can be impaired following damage to the PFC (Alexander, Stuss, & Fansabedian, 2003; Wheeler, Stuss, & Tulving, 1995), the magnitudes of these impairments are often smaller than those observed in tasks that require judgments about specific details from prior events (Janowsky, Shimamura, & Squire, 1989; Jetter, Poser, Freeman, & Markowitsch, 1986; Simons et al., 2002; Stuss, Alexander, et al., 1994). These findings are consistent with the view that PFC supports processes that operate over recovered content in service of task goals (Moscovitch, 1992, 1994), and this broad assumption has guided several functional interpretations of the roles played by sub-regions of PFC that have been identified in brain imaging studies employing positron emission tomography (PET) as well as functional magnetic resonance imaging (fMRI) (Badre & Wagner, 2002; Henson, Hornberger, & Rugg, 2005; Ranganath, Heller, & Wilding, 2007; Ranganath, Johnson, & D'Esposito, 2003; Simons, Gilbert, Owen, Fletcher, & Burgess, 2005).

A similar perspective has guided functional interpretations of specific event-related potential (ERP) modulations that have been identified in memory retrieval tasks. One of these is the *right-frontal old/new effect* (Johnson, Kounios, & Nolde, 1996; Senkfor & Van Petten, 1998; Wilding, Doyle, & Rugg, 1995; Wilding & Rugg, 1996), which is evident in contrasts between ERPs that are elicited by studied and unstudied test items attracting correct memory judgments. The effect is largest over right-frontal scalp electrodes, and is more pronounced (positive-going relative to a correct rejection baseline) in tasks requiring the retrieval of contextual (source) information than in tasks requiring only old/new recognition memory judgments (Johansson, Stenberg, Lindberg, & Rosen, 2002; Johnson et al., 1996; Senkfor & Van Petten, 1998; Van Petten, Senkfor, & Newberg, 2000). This pattern of findings has been used to argue that the effect is generated in PFC, given the neuropsychological evidence emphasising the importance of this region for successful completion of tasks where recovery of study details is required (Cruse & Wilding, 2009; Hayama, Johnson, & Rugg, 2008; Hayama & Rugg, 2009; Kuo & Van Petten, 2006, 2008; Woodruff, Hayama, & Rugg, 2006). In addition, the time course of this effect (commencing 400–500 ms post-stimulus and lasting for up to 1500 ms) is consistent with the view that it indexes post-retrieval processes, again aligning it with

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operations supported by PFC (Donaldson & Rugg, 1998; Wilding, 1999).

The focus in this report is on recent evidence that an additional late-frontal ERP old/new effect is also observed under certain conditions. Delineating the functional properties of this second effect is important for complete descriptions of the post-retrieval processes that are engaged during retrieval tasks, and the experiment described here was designed to contribute towards this.

There are two published reports of a frontally distributed ERP old/new effect that has been linked to post-retrieval processing operations and which is separable from the right-frontal old/new effect. Woodruff et al. (2006) reported a neural and functional dissociation between two frontally distributed old/new effects in a modified Remember/Know task (Tulving, 1985; Yonelinas, Otten, Shaw, & Rugg, 2005). Following an initial study phase, participants were asked to make memory judgments to studied and unstudied words. They made 'Remember' responses when something specific about the studied word could be recollected. For words that were not recollected, they made an old/new judgment, signalling their confidence (high/low) in the decision. From 800 to 1900 ms, remember and high confidence old responses to old words were associated with right-frontal old/new effects that were of the same magnitude. A second effect had a similar time course but comprised a greater relative positivity for remember than for high confidence old judgments to old words. The ERPs associated with both of these response categories were more positive-going than those associated with new test words, and this second old/new effect was largest at fronto-central scalp locations.

The time courses of these two effects suggest that they index processes that operate after memory retrieval has occurred, and in line with this assumption, Woodruff et al. (2006), proposed a post-retrieval role for each. In keeping with one recent account (Hayama et al., 2008), they linked the right-frontal old/new effect to generic retrieval monitoring processes, since the effect did not differentiate remember from highly confident old responses. They linked the fronto-central old/new effect, by contrast, with operations working over recollected content, arguing that recollection is more likely to accompany remember responses than highly confident old responses.

A comparable functional dissociation between two late frontal old/new effects has also been reported by Cruse and Wilding (2009). ERPs were acquired in the test phases of two memory tasks, where participants first studied words presented in one of two colours (pink and yellow). At test, old words were presented intermixed with an equal number of new words to which an old/new response was required. For words judged to be old, a second four-way judgment was required for the colour in which the word had been studied (pink/yellow) and the confidence associated with the colour judgment (high/low).

Analysis of the ERPs at frontal scalp locations revealed evidence for two functionally and electrophysiologically distinct effects between 800 and 1400 ms post-stimulus. From 800 to 1100 ms, ERPs associated with correct source (colour) judgments were more positive-going than those associated with incorrect source judgments. The amplitudes of these ERPs were, however, statistically equivalent from 1100 to 1400 ms. This functional separation was accompanied by evidence that different processes were engaged in the two epochs. The scalp distributions of the neural activity associated with correct and incorrect source judgments differed reliably between 800 and 1100 ms, but not between 1100 and 1400 ms. Moreover, the same pattern of reliable differences between scalp distributions was observed when the ERPs associated with high and low confidence correct source judgments were compared. These differences arose for two reasons. First, because the frontally distributed old/new effects for incorrect source judgments and low confidence correct source judgments were right-lateralised throughout the 800–1400 ms period. This was also the case for the effect associated with high confidence correct source judgments from 1100 to 1400 ms. Second, for the latter response category, the frontal effect from 800 to 1100 ms extended to a greater degree to fronto-polar and left-frontal scalp locations (contrast Figs. 1 and 2; Cruse & Wilding, 2009).

These findings are consistent with the view that the ERPs index two distinct processes between 800 and 1400 ms. One of these – indexed by the right-frontal ERP old/new effect – extends across the 800–1400 ms period. The second is engaged to the greatest degree between 800 and 1100 ms. The functional distinction between these effects that was offered by Cruse and Wilding (2009) mirrors the distinction proposed by Woodruff et al. (2006). They noted that the effect revealed only in the 800–1100 ms epoch was larger for correct than incorrect sourse judgments, and larger for high than low confidence correct source judgments. They assumed that recollection was likely to have occurred to a greater degree for correct rather than incorrect source judgments, as well as for high rather than low confidence correct judgments, and as a result suggested that this frontal ERP effect indexed processes that operated only over recollected content. In keeping with findings that the right-frontal old/new effect is not tied specifically to recollection (Woodruff et al., 2006; in particular, see Hayama et al., 2008), they proposed that this effect indexed somewhat more general retrieval monitoring operations.

The experiment described below was designed to test this account. Towards this end, the paradigm used by Cruse and Wilding (2009) was employed again, the critical change being that participants were asked to retrieve auditory information from study events rather than visual information. Half of the study words were spoken in a male voice, the remainder in a female voice. All test words were presented visually. Participants made an old/new decision followed by a four-way *confident-male*, *think-male*, *think-female*, *confident-female* decision for words judged to be old. If the account offered by Cruse and Wilding is correct, then this experiment – which is identical to theirs with the exception of the content upon which memory judgments must be made – will reveal evidence for two functionally and electrophysiologically distinct frontal old/new effects in a manner comparable to that reported in the earlier study.

2. Method

2.1. Participants

Twenty-four right-handed native English speakers took part in exchange for payment of £10. All had normal or corrected to normal vision and hearing, no diagnosis of dyslexia, and gave informed consent prior to the start of the experiment. Data from 8 participants were discarded as they did not contribute at least 16 artefact-free trials to the response categories of interest due to poor performance (5 participants) or excessive EOG artefact (3). Of the remaining 16 participants (mean age 21 years, range 19–26 years), 11 were female. Ethical approval for this study was obtained from the School of Psychology Ethics Committee, Cardiff University.

2.2. Materials

These were 360 low frequency words (MRC Psycholinguistic Database: frequency 1–9/million, Coltheart, 1981). 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. These were then grouped randomly in pairs to form 6 study-test blocks. Within each study-test block, words from one list were spoken at study, while all words from both lists were presented visually at test. Spoken words were presented via headphones. Half the words heard at study were spoken in a male voice, the remainder in a female voice (15 per voice per study list). All test words were presented in white on a black background. The order of word presentation was randomised for each participant at study and test. Four complete task lists were created by rotating the study/test status and gender of voice at study.

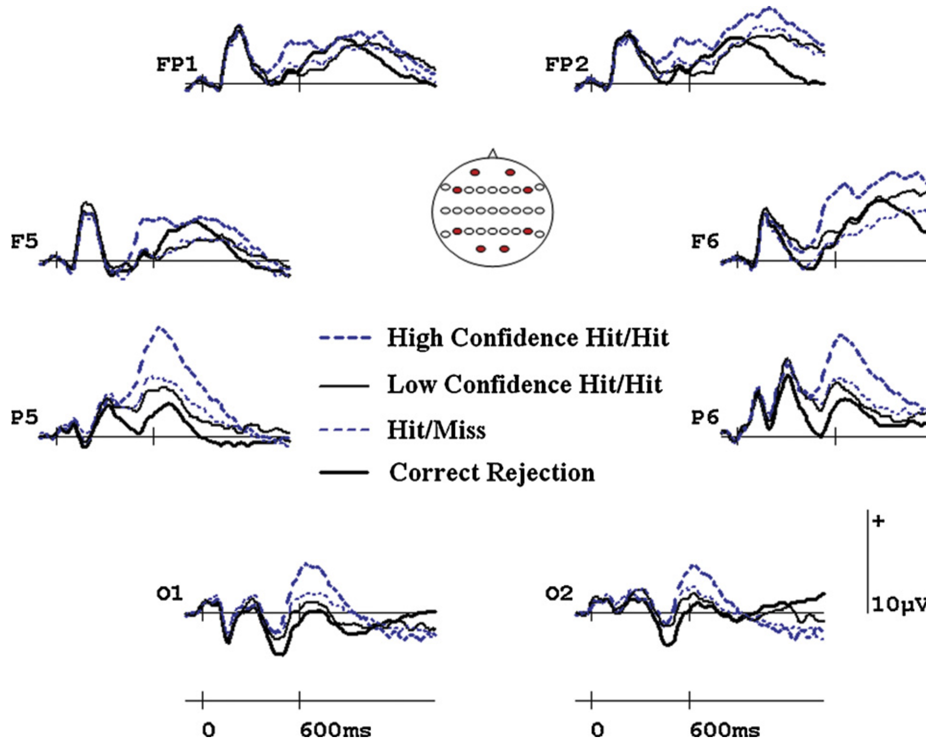

Fig. 1. Grand average ERPs associated with the high confidence hit/hit, low confidence hit/hit, hit/miss and correct rejection response categories for electrode locations FP1, FP2, F5, F6, P5, P6, O1 & O2. The waveforms are shown for epochs of 1536 ms in length, including a 102 ms baseline period.

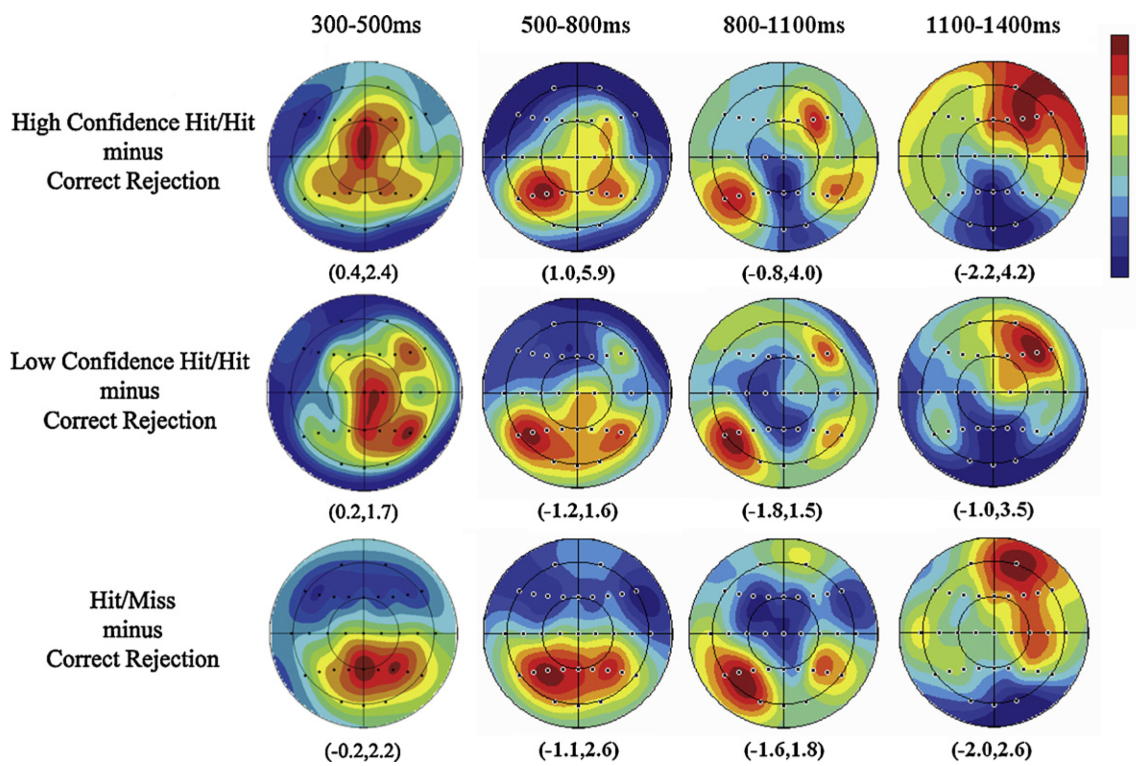

Fig. 2. Topographic maps showing the scalp distributions of the high confidence hit/hit, low confidence hit/hit, and hit/miss old/new effects over the 300–500, 500–800, 800–1100, and 1100–1400 ms time windows. The maps were calculated on the basis of difference scores obtained (for each time window) by subtracting mean amplitudes associated with correct rejections from those associated with the relevant classes of hits. The voltage minima and maxima below each map can be interpreted relative to the colour bar on the right-hand side of the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Participants were fitted with an electrode cap prior to the experiment. They were seated in a sound attenuated room 1.2 m from a computer monitor with their fingers on response keys. A short practice session preceded the experiment (5 male/5 female at study; 10 old/10 new at test) and participants were able to take short breaks between blocks. Participants were instructed that, in each study phase, they would hear words spoken in a male and female voice and that they should remember the word along with the voice in which it was spoken for a subsequent memory test. Participants were instructed to use their index fingers on their left/right hands to indicate whether study words were spoken by a male/female voice.

Test phases began 10 s after the conclusion of the preceding study phase. Participants were informed that they would see words that were either from the immediately preceding study phase or were novel to the experiment. For each word, they were asked to make an initial old/new judgment with the left/right index fingers. For words judged old, participants then responded on one of four keys, corresponding to the following judgments: *Confident-Male*, *Think-Male*, *Think-Female*, *Confident-Female*. *Confident* responses were always made with the middle finger, and *Think* responses with the index finger. *Male* and *Female* responses were always made with the same hand as at study. Participants were instructed to respond *Confident* if they were confident that they could remember the voice in which the word was spoken at study, while they were to respond *Think* when they were less confident and only had 'a feeling' of the gender of the voice 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 the old/new judgements at test and male/female judgements at study were counterbalanced across participants.

Each study trial began with an asterisk displayed for 500 ms, followed by a blank screen for 200 ms after which the word was spoken. All auditory stimuli were digitised at 16 kHz and had a mean length of 770 ms, which did not differ between voice genders. The next trial began 1000 ms after the gender response. Test trials began with an asterisk that was visible for 500 ms, following which a blank screen was presented for 200 ms before presentation of the test word for 300 ms. The screen remained blank for 1000 ms after the old/new response before a question mark appeared for 300 ms signalling that a combined voice/confidence judgment was required. Following this judgment the screen remained blank for 1000 ms before the onset of the next trial.

2.4. Electrophysiological recording

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 referenced to linked electrodes located midway between POz and PO3/PO4, respectively. The data were band-pass filtered offline (0.03–60 Hz), down-sampled to 166 Hz (6 ms/point), and re-referenced computationally 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.

2.5. ERP analyses

Contrasts were performed between those ERPs associated with correct judgments to new test words (correct rejections), correct voice judgments (hit/hits) separated by confidence, and incorrect voice judgments (hit/misses) collapsed across confidence. Low trial numbers precluded analyses of hit/misses separated by confidence. All response categories were collapsed across study voice.[1] Mean numbers of epochs per participant per response category were: correct rejections: 101 (range 38–142), high confidence hit/hit: 45 (18–81), low confidence hit/hit: 29 (16–56), hit/miss: 31 (20–54).

Using the same time-windows adopted by Cruse and Wilding (2009), as well as an additional earlier epoch, the ERPs were first analysed separately for 4 post-stimulus time windows: 300–500, 500–800, 800–1100 and 1100–1400 ms. For these analyses, data from 20 electrode locations were grouped to form 4 clusters over 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) scalp. Initial global ANOVAs were conducted including the factors of response category (the four described above), the anterior/posterior dimension, hemisphere, and site. The outcomes of these analyses involving all four response categories are reported in the text of the manuscript below. Reliable effects involving response category that were revealed in these analyses were followed up by all possible paired comparisons, which were conducted separately at anterior and posterior sites when the initial analyses revealed interactions including category and the anterior/posterior dimension. The outcomes of these paired contrasts are shown in Table 3, and the text below describes the reasons for the reliable effects that are shown in the table. All analyses included the Greenhouse–Geisser correction for non-sphericity when required (Greenhouse & Geisser, 1959; Winer, 1971). Uncorrected degrees of freedom and *F*-values are shown in the text and results tables, accompanied by their respective epsilon (e) values when necessary. Only effects involving the factor of response category are reported. In the following sections, 'superior' sites are those lateralised sites that are closest to the midline (FP1, FP2, F1, F2, P1, P2, O1, O2) and 'inferior' sites are those furthest from the midline (F7, F8, T5, T6). 'Mid-lateral' sites are between inferior and superior sites (F3, F4, F5, F6, P3, P4, P5, P6).

[1] The accuracy of source judgments was superior for words spoken in the male voice at study. To determine whether this behavioural difference was accompanied by differences between ERPs split according to voice, the ERPs associated with correct source judgments were separated on this dimension. Average numbers of trials per participant for these hit/hit response categories were: male: 53 (range 24–78), female: 52 (26–72). These ERPs were contrasted across the 500–800, 800–1100, and 1100–1400 ms time-windows using data from the same electrode locations and factors employed in the main analyses described above. There were no reliable effects or interactions with response category in any time-window. Low trial numbers precluded a comparable analysis on hit/miss ERPs separated by study voice.

Table 1

Mean probabilities of correct judgments to old words (Hit) and incorrect judgments to new words (false alarms: FA). Also shown are the conditional probabilities of correct (hit/hit) and incorrect (hit/miss) source judgments, split according to the confidence judgments (high/low) they attracted. Data for old words are shown separated according to the voice gender in which they were studied, as well as collapsed across this factor. Standard deviations are in brackets.

	Male	Female	Overall
p(Hit)	0.76 (0.10)	0.75 (0.10)	0.75 (0.09)
p(FA)	–	–	0.22 (0.13)
p(Hit/hit: high)	0.44 (0.14)	0.39 (0.14)	0.42 (0.13)
p(Hit/hit: low)	0.30 (0.12)	0.25 (0.09)	0.28 (0.09)
p(Hit/miss: high)	0.06 (0.04)	0.11 (0.08)	0.08 (0.05)
p(Hit/miss: low)	0.20 (0.07)	0.25 (0.08)	0.23 (0.06)

Table 2

Mean reaction times for correctly identified new words (correct rejections: CR) and old words (Hit) split according to voice but collapsed across the subsequent source judgment. Also shown are the RTs for the initial old/new judgment separated according to subsequent source accuracy (hit/hit and hit/miss) as well as confidence (high/low). Standard deviations are in brackets.

	Male	Female	Overall
Hit	1053 (200)	1085 (217)	1077 (204)
CR	–	–	1040 (257)
Hit/hit: high	1022 (195)	1022 (234)	1015 (195)
Hit/hit: low	1093 (249)	1167 (269)	1134 (250)
Hit/miss: high	1011 (220)	1004 (269)	1035 (211)
Hit/miss: low	1089 (251)	1136 (239)	1116 (273)

3. Results

3.1. Behaviour

Table 1 shows the mean probability of false alarms (p[FA]) as well as probabilities of correct judgments to old words (p[Hit]) split according to study voice but collapsed across the accuracy of the subsequent male/female (voice) judgments. Old/new discrimination was statistically equivalent for words spoken in either voice at study and was reliably above chance in both cases (both $t(17) > 19.00$, $p < 0.001$). Table 1 also shows the probabilities of correct (hit/hit) and incorrect (hit/miss) voice judgments for words judged correctly to be old, split according to study voice as well as the confidence judgments (high/low) they attracted. A $2 \times 2 \times 2$ ANOVA (factors of accuracy, confidence and voice) revealed two interactions. First, between voice and accuracy ($F(1,15) = 13.24$, $p < 0.01$), reflecting the greater probability of a correct voice judgment for words spoken in the male voice. Second, between accuracy and confidence ($F(1,15) = 44.19$, $p < 0.001$), which came about because correct voice judgments attracted more high than low confidence judgments, whereas the reverse was true for incorrect voice judgments.

Table 2 shows the mean reaction times (RTs) for correct old/new judgments split according to study voice. A paired *t*-test contrasting the RTs for correct old responses split according to voice but collapsed across accuracy and confidence revealed no reliable differences. A 2 × 2 × 2 ANOVA (factors of accuracy, confidence and voice) revealed a main effect of confidence only ($F(1,12) = 9.17$, $p < 0.05$)[2] reflecting faster high-confidence responses.

3.2. ERPs

As can be seen in Fig. 1, both the high and low confidence hit/hit ERPs begin diverging from those associated with correct rejections from around 300 ms. The positive-going old/new effects associated with each of the classes of hit/hit response category are largest at parietal electrode sites from around 500 to 800 ms, and at right-frontal sites from ~800 ms. ERPs associated with high confidence correct voice judgments are more positive-going than those associated with low confidence correct voice judgments as well as incorrect voice judgments from around 400 ms post-stimulus, although this difference according to confidence becomes less pronounced at right-frontal sites from approximately 1100 ms.

The initial analyses separated by epoch revealed reliable interactions between category, the anterior/posterior dimension and hemisphere from 300 to 500 ms ($F(3,45) = 3.70$, $p < 0.05$, $e = 0.82$), as well as category × anterior/posterior dimension × site interactions from 500 to 1100 ms (500–800 ms: $F(12,180) = 2.37$, $p < 0.05$, $e = 0.43$; 800–1100 ms: $F(12,180) = 2.87$, $p < 0.05$, $e = 0.44$) and a category × anterior/posterior dimension × hemisphere × site interaction from 1100 to 1400 ms ($F(12,180) = 2.28$, $p < 0.05$, $e = 0.53$).

The outcomes of the paired follow-up analyses are shown in Table 3, and the outcomes of the analyses at anterior sites are described first. From 300 to 1100 ms, there are reliable positive-going old/new effects only for the high confidence hit/hit response category. This effect is initially largest at superior sites (300–500 ms: category × site interaction) and then at right-mid-lateral locations (500–1100 ms: category × hemisphere × site interactions). This superior maximum old/new effect from 300 to 500 ms is reliably larger than the hit/miss effect, but not the low confidence hit/hit effect. From 500 to 1100 ms, the high confidence hit/hit effect is reliably more positive-going than both of the other effects, primarily at superior frontal sites, as indicated by the reliable category × site interactions across the 500–800 and 800–1100 ms epochs. In the 1100–1400 ms epoch, there are reliable and statistically equivalent right-lateralised frontal old/new effects for the high as well as the low confidence hit/hit response categories. There is no reliable frontal old/new effect for the hit/miss category in this epoch, and both confidence effects are reliably more positive-going, although this positivity was revealed in different terms.

At posterior scalp sites there are reliable and broadly equivalent old/new effects for each hit response category from 300 to 500 ms. For the high confidence hit/hit old/new effect, the category × site interactions from 500 to 1400 ms reflect a mid-lateral maximum from 500 to 800 ms, which changes to a greater negativity for high confidence hit/hits relative to correct rejections at superior sites in the later epochs. The category × site interactions from 800 to 1400 ms for the low confidence hit/hit old/new effect, and from 1100 to 1400 ms for the hit/miss old/new effect, also reflect this superior maximum greater relative negativity.

The most statistically robust differences between the hit response categories at posterior sites are over the 500–1100 ms period. The high confidence hit/hit ERPs are reliably more positive-going than low confidence hit/hit ERPs at mid-lateral sites from 500 to 1100 ms, as reflected by the category × site interactions. The same distribution of differences accounts for the same interaction term for the high confidence hit/hit versus hit/miss contrast in the 500–800 ms epoch. In this same epoch, the hit/miss old/new effect is reliably more positive-going than the low confidence hit/hit effect over superior sites (category × site).

3.3. Analyses of scalp distributions

These were conducted to determine whether interactions involving response category and scalp locations in the direct contrasts between the high and low confidence hit/hit categories and the hit/miss category reflect differences between the scalp distributions of the relevant effects, or simply differences between the sizes of the same effects (McCarthy & Wood, 1985). The values submitted to rescaling were the difference scores obtained by subtracting mean amplitude measures associated with correct rejections from those associated with the high and low confidence hit/hit and hit/miss categories. The max–min method of rescaling was employed (for discussion, see Urbach & Kutas, 2002, 2006; Wilding, 2006), and the analyses were conducted over the montage of electrode locations employed for the analyses on un-rescaled data described above.

For the high versus low confidence hit/hit contrast, only the data from the 800 to 1100 time window were included, because there were no reliable low confidence hit/hit old/new effects from 500 to 800 ms, and no reliable differences in the un-rescaled data between low and high confidence effects from 1100 to 1400 ms. This analysis revealed no reliable effects or interactions, suggesting that the differences between these response categories are quantitative rather than qualitative. No contrasts were performed between the low confidence hit/hit effect and the hit/miss effect since there were no time-windows in which both effects were reliable, and reliably different in the un-rescaled analyses. For the high confidence hit/hit versus hit/miss contrast, only data from 300 to 500 ms, 500 to 800 ms and 1100 to 1400 ms were analysed because there were no reliable hit/miss effects from 800 to 1100 ms. There was no reliable effect of response category in these contrasts, and the interaction between epoch and site ($F(8,120) = 5.82$, $p < 0.001$, $e = 0.40$) reflects the change in the maxima of the old/new effects across epochs, as Fig. 2 shows clearly.

3.4. Comparisons across experiments

The analyses of scalp distributions described above provided no evidence for the engagement of electrophysiologically distinct processes in the 800–1100 ms epoch when the ERP old/new effects associated with high and low confidence correct source judgments were compared. This outcome contrasts with that obtained by Cruse and Wilding (2009), who reported that the frontal scalp distributions of these old/new effects were reliably different. As outlined in the Introduction, their finding was one of the elements that motivated them to propose the existence of two electophysiologically and temporally distinct frontal old/new effects, tying one (largest between 800 and 1100 ms) to processes linked with recollection, and the other (extending over the 800–1400 ms time period) to general retrieval monitoring operations that are not restricted to the products of recollection.

The similarities and differences between the scalp distributions of the high confidence ERP old/new effects in the 800–1100 and 1100–1400 ms epochs in this experiment and in the one conducted by Cruse and Wilding (2009) are shown in Fig. 3. There is little topographic evidence for the engagement of more than one process in the current experiment, and the correspondences between these distributions were assessed formally via ANOVA.

The initial analysis included data from both epochs and experiments, with all other factors and rescaling procedures as described above. The analysis revealed a five-way interaction between epoch, experiment, the anterior/posterior dimension,

[2] Data from 3-participants were excluded from this analysis because they made no high-confidence hit/miss responses.

Table 3
Outcomes of the paired comparisons between the mean ERP amplitudes (in μV) associated with high and low confidence correct source judgments (hit/hit), incorrect source judgments collapsed across confidence (hit/miss), and correct responses to new test items (CR, correct rejections) for the 300–500, 500–800, 800–1100, and 1100–1400 ms epochs at anterior and posterior scalp sites separately. RC = response category, HM = hemisphere, ST = site, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, ns = non-significant. Full degrees of freedom are shown alongside the factor dimension abbreviations on the left-hand side of the table, and epsilon values reflecting application of the correction for non-sphericity (Winer, 1971) are shown in brackets.

	300–500 ms		500–800 ms		800–1100 ms		1100–1400 ms	
	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
High confidence Hit/hit vs. CR								
RC (1,15)	8.04*	14.86**	6.69*	53.31***	ns.	ns.	9.65**	ns.
RC × HM (1,15)	ns.	ns.	ns.	ns.	ns.	ns.	12.53**	ns.
RC × ST (4,60)	5.40* (0.41)	ns.	13.51***	9.00**(0.46)	ns.	10.35*** (0.53)	ns.	16.25*** (0.49)
RC × HM × ST (4,60)	ns.	ns.	3.09* (0.71)	ns.	2.88* (0.78)	ns.	ns.	ns.
Low confidence Hit/hit vs. CR								
RC (1,15)	ns.	7.94*	ns.	ns.	ns.	ns.	ns.	ns.
RC × HM (1,15)	ns.	ns.	ns.	ns.	ns.	ns.	8.89**	ns.
RC × ST (4,60)	ns.	ns.	ns.	ns.	ns.	5.76** (0.64)	ns.	4.89** (0.71)
Hit/miss vs. CR								
RC (1,15)	ns.	14.52**	ns.	9.16**	ns.	ns.	ns.	ns.
RC × ST (4,60)	ns.	ns.	ns.	ns.	ns.	ns.	ns.	6.09** (0.62)
High confidence Hit/hit vs. low confidence Hit/hit								
RC (1,15)	ns.	ns.	11.87**	64.48***	5.88*	15.98**	ns.	ns.
RC × ST (4,60)	ns.	ns.	16.06*** (0.55)	6.66** (0.48)	ns.	4.76** (0.63)	ns.	ns.
High confidence Hit/hit vs. Hit/miss								
RC (1,15)	5.90*	ns.	21.60***	25.31***	12.46**	ns.	5.85*	ns.
RC × HM (1,15)	ns.	5.10*	ns.	ns.	ns.	ns.	ns.	ns.
RC × ST (4,60)	3.80*	ns.	11.44***	3.27*	3.89* (0.42)	ns.	ns.	4.13* (0.45)
Low confidence Hit/hit vs. Hit/miss								
RC × ST (4,60)	ns.	ns.	ns.	4.30*	ns.	ns.	ns.	ns.
RC × HM × ST (4,60)	ns.	ns.	ns.	ns.	3.02* (0.74)	ns.	3.88* (0.80)	ns.

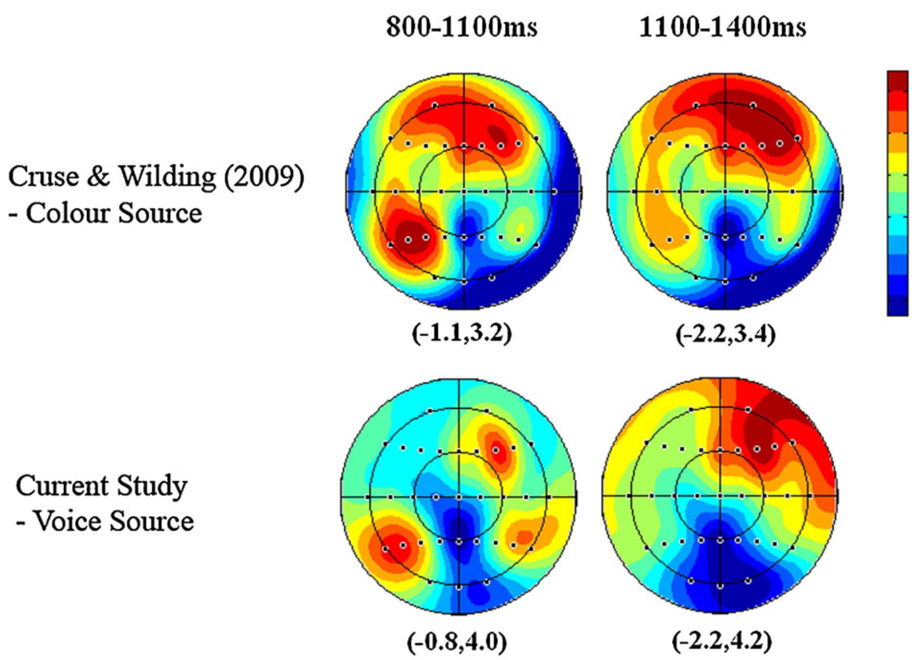

Fig. 3. Topographic maps contrasting the scalp distributions of the high confidence hit/hit old/new effects in this study, and those observed in a study reported by Cruse and Wilding (2009) in which the colour of visually presented study words was to be retrieved at test. The maps are shown for the 800–1100 and 1100–1400 ms time windows. The values employed for generating the scalp distributions were obtained in line with the approach described in the legend for Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hemisphere, and site ($F(4,120) = 22.61$, $p < 0.001$, $e = 0.79$). Analyses separated by epoch revealed an interaction involving experiment in the 800–1100 ms epoch only (experiment, the anterior/posterior dimension, hemisphere and site [$F(4,120) = 2.83$, $p < 0.05$, $e = 0.93$]). Subsequent analyses at anterior and posterior electrodes separately within this epoch revealed a reliable interaction between experiment and hemisphere at anterior electrodes only ($F(1,30) = 4.86$, $p < 0.05$), which reflects the broader frontal distribution of the high confidence hit/hit effect reported by Cruse and Wilding (2009). Critically, contrasts between response accuracies and reaction times across these two studies revealed no reliable differences (see Appendix A for details).

4. Discussion

The experiment was designed to investigate the relationships between two frontally distributed ERP old/new effects that have been reported in recent studies (Woodruff et al., 2006; Cruse &

Wilding, 2009). The outcomes of the analyses of the ERP data provide new insights into the functional significance of one of these frontal effects. We provide a detailed description of the data supporting this claim, and consider the functional implications this outcome has, after commenting on other aspects of the ERP data.

The ERP analyses focused on three old/new effects: those associated with high and low confidence correct voice judgments, and those associated with test words that attracted a correct old judgment but an incorrect voice judgment. There were reliable old/new effects at posterior sites from 300 ms onwards, and these effects did not vary substantively with confidence or with the accuracy of the voice judgment. At frontal sites in this epoch, the pattern is a little more ambiguous. There were reliable old/new effects only for high confidence correct voice judgments, but the ERPs elicited by high and low confidence correct judgments did not differ reliably. This was not the case in the following (500–800 ms) epoch, where high confidence correct voice judgments were associated with reliably more positive-going ERPs at anterior and at posterior sites than both of the other hit categories. For the data at posterior sites, the pattern across these epochs is consistent with the view that information sufficient to make an old/new judgment is available prior to that necessary to make a source judgment (Senkfor & Van Petten, 1998; Van Petten et al., 2000). One way of articulating this in process terms is to argue that the process of familiarity is somewhat faster than the process of recollection (Atkinson & Juola, 1974; Mandler & Boeck, 1974; Yonelinas, 1997), and the former supports old/new judgments while the latter supports source judgments. An alternative is that one graded source of information accumulates over time, with the amount required to make an old/new judgment being somewhat less than that required to make a source judgment (Johnson, Hashtroudi, & Lindsay, 1993). These possibilities are not mutually exclusive, in so far as recollection can be characterised as a graded process and memory decisions might be based upon a combined assessment of recollection and familiarity strengths (Squire, Wixted, & Clark, 2007; Wixted, 2007), but the data in this experiment do not point strongly to the accuracy or otherwise of any of these possibilities. The ambiguous pattern of reliable differences across frontal scalp locations in the 300–500 ms epoch makes a confident interpretation difficult.

For the data from the 500 to 800 ms epoch, the greater relative positivity associated with correct than with incorrect voice judgments replicates previous findings (Wilding et al., 1995; Wilding & Rugg, 1996), as does the fact that there is a greater relative positivity for high than for low confidence correct source judgments (Cruse & Wilding, 2009). The left-parietal ERP old/new effect is typically analysed in this time period (Rugg, 1995), and the effect has been linked to the process of recollection (for reviews, see Friedman & Johnson, 2000; Rugg & Allan, 2000; Wilding & Sharpe, 2003). The current findings at posterior sites are consistent with this functional account, in so far as recollection is likely to have contributed to a greater degree to high confidence correct voice judgments than to low confidence correct voice judgments as well as incorrect voice judgments. A surprising outcome, however, is the greater superior maximum positivity at posterior sites in this epoch for incorrect voice judgments in comparison to low confidence correct voice judgments. If recollection is conceived of as an all or none process, then both of these response categories reflect voice judgments based upon little veridical information and the ERPs should be comparable. Alternatively, if recollection is a graded process and low confidence correct source judgments are based upon recovery of some relevant content, then a larger left-parietal old/new effect should be observed for this response category than for incorrect voice judgments. The data are clearly not consistent with the latter account, but neither do they cohere entirely with the former. There is no immediately obvious explanation for this pattern, and in light of this we analysed the data in the same time period for these response categories at posterior sites (O1, O2, T5, T6, P5, P6, P3, P4, P1, P2) in our previous experiment where the same separation into response categories could be made (Cruse & Wilding, 2009). The magnitudes of the old/new effects were 0.03 and 0.69 μV for incorrect and low confidence correct source judgments, respectively, and these two effects were not reliably different (all $p > 0.20$). Woroch and Gonsalves (2010) reported their findings in a study where their participants made high/low confidence judgments for old/new as well as subsequent source judgments in a memory paradigm where the stimuli were images of objects. The source judgment required was the nature of the encoding task performed for each item (meaningfulness/complexity). They observed a reliable left-parietal ERP old/new effect for high confidence correct old judgments followed by incorrect source judgments, but not for low confidence correct old judgments that were followed by an incorrect source judgment. This might be seen as a surprising finding given that in neither case was veridical source information retrieved. They argued that the left-parietal effect indexes the retrieval of contextual information, but that this information need not necessarily be restricted to task-relevant content. This 'non-criterial recollection' interpretation (Yonelinas & Jacoby, 1996) could account for the current results, if it is assumed that hit/misses and low confidence hit/hits were associated with recovery of differing levels of task-irrelevant content, but why this should be the case is not entirely clear.

The key new finding in this experiment is that the outcomes of the analyses of some of the ERP old/new effects did not replicate those reported recently in a very similar study (Cruse & Wilding, 2009). In the previous experiment, two functionally and topographically distinct frontally distributed old/new effects were revealed in analyses over the 800–1100 and 1100–1400 ms time-periods. In the experiment reported here, there was no evidence for differences between scalp distributions over these time periods that would be consistent with the presence of two distinct processes. In order to quantify the correspondences between the frontal effects that were obtained in these two experiments over these time periods, a direct comparison was made. This comparison was restricted to the old/new effects for high confidence correct source judgments, as this response category was associated with the two separate effects in Cruse and Wilding's (2009) study. There were reliable differences between the distributions of the effects in the 800–1100 ms epoch but not in the 1100–1400 ms epoch. These findings across experiments, when coupled with the absence of topographic evidence for the engagement of more than one process in this experiment, are consistent with the view that one common frontal old/new effect was engaged in the two experiments, while a distinct effect was engaged in Cruse and Wilding's earlier study.

The common effect is likely to be the right-frontal ERP old/new effect. The functional significance of this effect has been the subject of considerable debate since it was first described nearly 15 years ago (Johnson et al., 1996; Senkfor & Van Petten, 1998; Wilding & Rugg, 1996). Recent evidence suggests that it indexes processes that involve part of a general assessment of task-relevant information, which is not restricted to either certain kinds of episodic memory content (Cruse & Wilding, 2009), or indeed to episodic information *per se* (Hayama et al., 2008).

This effect is clearly evident in the current study in the 1100–1400 ms scalp maps shown in Fig. 2, and in keeping with the findings in some previous experiments in which information about speaker voice has been recovered (Wilding, 1999; Wilding & Rugg, 1996), the effect was larger here for the ERPs associated with correct rather than with incorrect voice judgments. The sensitivity of this effect to the accuracy of source judgments has not been uniformly reported, however, for auditory material as well as for other kinds of content, and the reasons for the differences across studies remain unclear (Senkfor & Van Petten, 1998; Van Petten, Senkfor, & Newberg, 2000).

Cruse and Wilding (2009) considered several factors that might be determinants of the circumstances under which right-frontal old/new effects predict the accuracy of source judgments, including whether or not old/new judgments precede or are made in conjunction with source decisions, and the kinds of content that are to be recovered. Another consideration is levels of response accuracy across tasks. In a number of the experiments where right-frontal effects have not predicted source accuracy, the likelihood of a correct old/new judgment was close to ceiling. In the experiments where the effect has predicted source accuracy, this has typically not been the case. For the latter, it is possible that some words attracting correct old judgments are associated with weak memory, and these items are also likely to attract incorrect source judgments. One possibility, therefore, is that this frontal effect reflects operations engaged only when there is a sufficiently strong memory for the word itself to warrant the initiation of operations that might assist in recovery of source information. Operations involved in retrieval search are one example of this kind, as suggested by Senkfor and Van Petten (1998; see also Van Petten et al., 2000). This account accommodates the majority of the published data points in retrieval tasks, with the possible exception of the findings of Cruse and Wilding (2009). In that experiment old/new discrimination was far from ceiling but right-frontal old/new effects did not predict the accuracy of source judgments. It may be the case that the strength of memories is only one of the antecedents for when the processes indexed by the right-frontal old/new effect will be engaged.

As noted above, a key aspect of the findings in this experiment, as well as in the contrasts between this experiment and an earlier one conducted by Cruse and Wilding (2009), was that the right-frontal old/new effect was not accompanied by an additional topographically distinct frontally distributed old/new effect, and that the processes engaged between 800 and 1100 ms post-stimulus were not comparable to those identified in Cruse and Wilding's previous study. There was, however, some evidence consistent with the view that not entirely the same processes were engaged across the 800–1100 and 1100–1400 ms epochs in this experiment, since old/new effects varied with confidence (being larger for high confidence correct source decisions) in the earlier period only.

In the absence of evidence for different scalp distributions, it is difficult to make strong claims about the presence or absence of two effects in this experiment. Irrespective of whether this is the case, a stronger assertion that can be made is that an effect observed in the previous study by Cruse & Wilding was not evident here. Woodruff et al. (2006) as well as Cruse and Wilding (2009) identified an additional old/new effect that was less lateralised than the right-frontal effect. In both of these previous experiments, moreover, the effect responded to task manipulations in a way that meant it could be aligned with the process of recollection. In the experiment reported by Woodruff et al. (2006) the effect was larger (more positive-going) for test items attracting a remember judgment rather than a highly confident judgment that an item had (in the absence of remembering) been encountered in a prior study phase. In the experiment reported by Cruse and Wilding (2009), the effect was larger for correct judgments about study context (colour) that were accompanied by high rather than low confidence, and larger for correct than for incorrect source judgments.

This pattern of sensitivities prompted both sets of authors to propose that the effect reflected post-retrieval operations that acted specifically over recollected content. The marked absence of this frontal effect in the experiment reported here, however, represents a strong challenge to this view. Fig. 3 emphasises the differences between the scalp distributions of the effects associated with high confidence correct context judgments (voice and colour, respectively) in this experiment and in our earlier experiment (Cruse & Wilding, 2009). The differences between the scalp distributions of the frontal ERP old/new effects were reliable in the 800–1100 ms time window, despite the absence of reliable differences in response accuracies and reaction times across the two experiments.

One interpretation of these outcomes is that the effect indexes processes that operate over only some kinds of recollected content. In the study of Woodruff et al. (2006), participants made an inanimate/animate decision at study to visually presented words, while those in the study of Cruse & Wilding make a binary response indicating the colour in which visually presented words were displayed. The absence of the ERP effect of interest in this study, where study items were spoken words requiring a binary male/female judgment, suggests a link between this effect and the recovery of modality-specific information.

An alternative, however, is that the effect is linked less directly to the modality in which studied items were presented, and more to the degree to which study items share features with other study items. While a binary judgment was required in each of the three studies under consideration, it is reasonable to assume that the number of distinctive elements along which study items might be separated was greater in the current experiment, because of variations in auditory components across words including intonation, emphasis and speech rate. There are fewer immediately obvious dimensions along which stimuli in the other two relevant studies might have varied, and the greater proportion of distinctive elements might have reduced the need (relative to the requirements imposed in the other studies: Cruse & Wilding, 2009; Woodruff et al., 2006) for the operation of processes that assist in distinguishing between competing and relatively similar memory representations.

This alternative account is appealing, because it moves away from the alignment of processes with only certain kinds of recovered content. It also provides a straightforward testable prediction: if the effect is not content-specific then under appropriate circumstances – where there is sufficient heterogeneity across encoded content – the effect will be evident when the study material comprises visually presented words. One means of implementing this would be to contrast the effects of interest under conditions where the number of colours associated with a set of study items is varied systematically. According to the foregoing account, the ERP effect will be attenuated as the heterogeneity of a given study set increases.

Another consideration that follows from this kind of account is that, in line with recent evidence for the right-frontal old/new effect (Hayama et al., 2008), this additional frontal old/new effect reflects operations that will not be engaged only in tasks requiring recovery of information from episodic memory. This remains to be determined, but it is a possibility that fits with conceptualisations of PFC function that emphasise operational demands that are shared by a range of different cognitive challenges, of which episodic memory judgments are simply one kind (Duncan & Owen, 2000; Fuster, 2008).

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Appendix A.

Tables A.1 and A.2 show the behavioural data from the study reported by Cruse and Wilding (2009). A three-way mixed models ANOVA conducted on the probabilities of high/low confidence

Table A.1
Mean probabilities of correct old/new judgments to old (Hit) and new words (CR, correct rejection) in the study reported by Cruse and Wilding (2009; $n = 21$). 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)

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

judgments to hit/hit and hit/miss responses in the current experiment ($n = 16$) and those reported by Cruse and Wilding (2009; $n = 21$), with a between-subjects factor of source content (2 levels: colour, voice) and within-subjects factors of confidence and source accuracy, revealed no main effect of, or interactions with, source content. A two-way mixed-models ANOVA conducted on the mean RTs for correct responses to old and new items with a within-subjects factor of old/new status and a between-subjects factor of source content (colour/voice) revealed no main effects or interactions. A further three-way ANOVA on the mean RTs for words correctly judged to be old (factors as the for the first analysis of accuracy) also revealed no reliable effects or interactions with content. In summary, the patterns of behaviour are markedly similar across experiments, in contrast to the findings for the frontally-distributed ERPs.

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