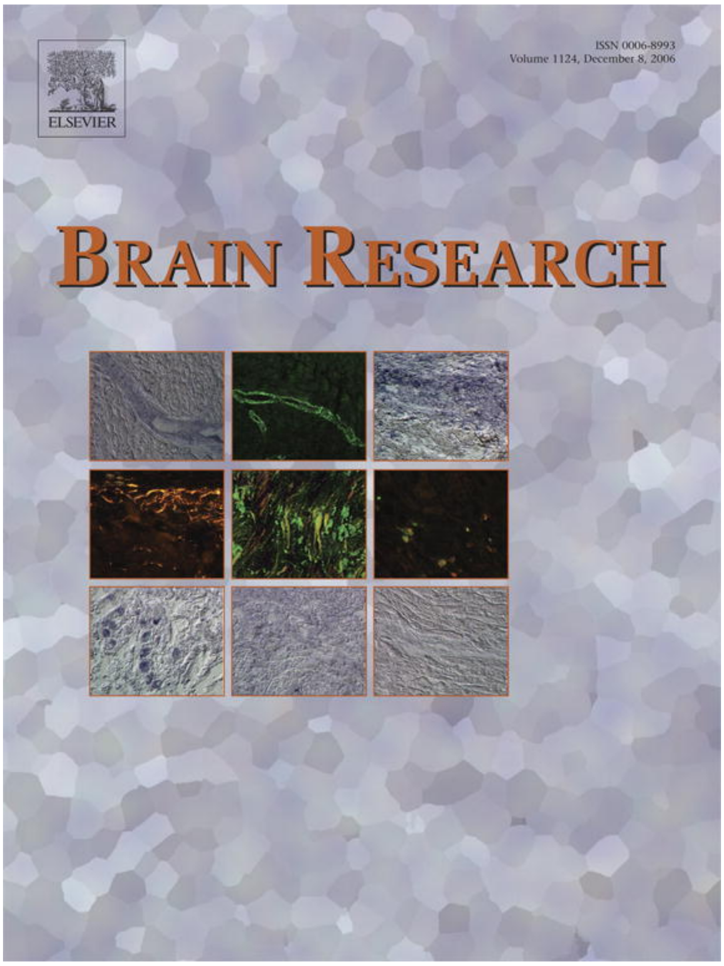
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Research Report

Prefrontal involvement in source memory: An electrophysiological investigation of accounts concerning confidence and accuracy

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ABSTRACT

Although a prefrontal involvement in the memory domain is well-documented, the specific functions the frontal lobes have in episodic memory are still unclear. This study aimed to disentangle theoretical accounts of prefrontal involvement concerning objective characteristics of the retrieval (i.e., accuracy) and accounts based on subjective features (i.e., confidence). Event-related potentials (ERPs) were recorded during the test phase of a source memory task in two experiments. The task was to retrieve the word and the voice of the speaker at study (experiment 1) or the voice of the speaker together with confidence ratings about the source judgment (experiment 2). ERPs in both experiments were not modulated by the success of the voice retrieval, discarding accounts linked to the retrieval success. A right-more-than-left late prefrontal positivity was found in both experiments. Moreover, in experiment 2, waves were more positive for low- than for high-confidence responses. This pattern was observed earlier over lateral parietal scalp regions and later, and more sustained in time, over anterior prefrontal regions. The dissociable effects found within the prefrontal scalp regions, specifically along the anterior–posterior and right–left dimensions, are interpreted as markers of qualitatively different monitoring processes.

1. Introduction

The mapping of functionally distinct processes onto different neural substrates is a central objective for memory investigation. According to a commonly accepted neuropsychological model of episodic memory (Moscovitch, 1992), medial temporal/hippocampal areas mediate modular processes like encoding, storage and retrieval processes, while frontal areas mediate higher strategic and control functions. However, the specific roles the frontal lobes play in episodic memory are still a matter of debate. The issue has been addressed by means of various approaches.

1.1. *Empirical background*

In the neuropsychological domain, it has been reported that damage to the prefrontal cortex can cause impairment in episodic memory tasks. With the exception of patients with lesions to the inferior medial regions (Gilboa and Moscovitch, 2002), the resulting impairment is usually mild and not as dramatic as that found in amnesic patients with temporal

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lesions. Patients with frontal lesions show mild deficits in item memory per se (Stuss et al., 1994), usually in the form of failures of organization at encoding (e.g., Mangels, 1997), or an increased probability of false alarms at retrieval (e.g., Curran et al., 1997; Swick and Knight, 1999), which suggests a deficit in the checking or monitoring processes (Shallice, 2002). Moreover, prefrontal patients perform poorly on tasks requiring retrieval of the memory context (source memory), such as memory for spatial position or temporal order (Janowsky et al., 1989; Shimamura et al., 2000). This may well be because these tasks greatly rely upon checking processes.

Another source of evidence comes from functional neuroimaging studies, which have consistently documented prefrontal activations during the performance of various memory tasks. In a review of PET studies, Tulving and colleagues proposed the Hemispheric Encoding/Retrieval Asymmetry (HERA) model (Tulving et al., 1994; see also Shallice et al., 1994; Rossi et al., 2006). According to this model, left and right prefrontal lobes have partially different functions in episodic memory. For verbal stimuli, left and right prefrontal cortical areas are differentially more involved in encoding and in retrieval, respectively.

In this study, we will focus on the processes involved during retrieval. A theoretical model for the retrieval processes mediated by frontal lobes, based on the theory of Norman and Bobrow (1979), has been proposed by Burgess and Shallice (1996; see also Moscovitch, 1992; Schacter et al., 1998b, for related models). This model includes two main processes. The first process specifies search parameters and cues, and updates and maintains working memory contents. The second process manipulates and monitors the products of memory search. An fMRI study by Henson et al. (1999b) brings anatomical evidence in favor of this model. In that study, the critical comparison was between two word recognition tasks that differed only in whether responses required retrieval of the spatiotemporal context of words at study (exclusion) or only an old/new judgment (inclusion). A right ventral prefrontal region (BA 47) was activated during retrieval without distinction between exclusion and inclusion conditions, consistent with the concept of search cues specification (see also Fletcher et al., 1998). The contrast between the exclusion and the inclusion conditions revealed activation in the left and right dorsolateral prefrontal cortex (BA 46). According to the authors' interpretation, these areas are associated to monitoring demands, which are particularly heavy during the exclusion condition. That work, together with many others, shows that the left prefrontal areas can also be involved during retrieval and not only during encoding, contrary to the simplest form of the HERA model (e.g., Nolde et al., 1998; Ranganath and Paller, 1999). The debate about right–left prefrontal asymmetry in episodic retrieval is far from resolved. Another open question concerns which specific products of memory search are the object of the monitoring processes associated to the prefrontal regions.

A promising line of evidence on this point comes from the electrophysiological domain. Some studies have shown a larger late prefrontal (more right) ERP positivity elicited by successful retrieval (e.g., Allan and Rugg, 1998; Donaldson and Rugg, 1998; Graham and Cabeza, 2001; Wilding and Rugg, 1996; see Rugg et al., 1996; Rugg et al., 2003, for neuroimaging related evidence) or by well-recollected test items rather than by items judged old on the basis of familiarity in the remember–know paradigm (e.g., Rugg et al., 1998). Wilding and Rugg (1996), for instance, recorded ERPs during the retrieval phase of a source memory task. Participants first made old/new judgments to visually presented words, and then for words judged old, indicated in which of two voices (male vs. female), the words had been presented at study. ERPs were more positive for words correctly judged old (hits) than for correct rejections at the left parietal sites and also at the right frontal ones (old/new effect), where they were also more sustained over time. Importantly, the right frontal component was more positive for hits followed by a correct source judgment (hit/hit) than by incorrect ones (hit/miss). Consequently, the authors proposed a relationship between right frontal ERP effect and the monitoring of the products of successful retrieval.

Nevertheless, the results achieved in this field are rather controversial as other studies fail to show any modulation of the prefrontal ERPs by successful recollection (e.g., Duzel et al., 1997; Ranganath and Paller, 1999; Senkfor and Van Petten, 1998; for related neuroimaging evidence, see Kapur et al., 1995; Buckner et al., 1998). As an example, in the study by Senkfor and Van Petten (1998), ERPs were recorded during recognition tasks for spoken words alone (items) or for both words and the voice of the speaker (sources). In both tasks, correctly recognized old words elicited more positive ERPs than new words. Only in the source task did old words also elicit a late prefrontal positivity. The prefrontal effect, however, did not differ between trials with accurate voice judgments and those with inaccurate ones. The discrepancy across studies in whether a modulation of the late prefrontal ERPs by retrieval accuracy occurs suggests that activity in these regions is not related to, or not restricted to, successful retrieval of the episodic information.

1.2. *The current study*

The present study aims to investigate which variables modulate the ERPs recorded over the prefrontal areas during memory retrieval in order to understand their role in episodic memory. We chose source memory tasks for a couple of reasons. First, we aimed to compare our results with the conflicting electrophysiological literature on the role of the successful source retrieval in influencing late prefrontal ERP components (e.g., Senkfor and Van Petten, 1998; Wilding and Rugg, 1996). Second, as pointed out before, frontal activity is often held to be more related to the source memory than to item memory (e.g., Henson et al., 1999b; Janowsky et al., 1989) and this would increase the likelihood of obtaining a prefrontal engagement detectable with ERPs (e.g., Ranganath and Paller, 1999; Senkfor and Van Petten, 1998).

In experiment 1, a design similar to that used in earlier ERP studies of source memory (e.g., Senkfor and Van Petten, 1998; Wilding and Rugg, 1996) was adopted in order to further test a prediction derived from the retrieval success account by means of the ERPs. This account would predict that, in a task involving both item recognition and source judgments, hit/hit waves recorded in the right frontal sites should be more positive than hit/miss ones, since they would provide an electrophysiological correlate of the processes operating on successfully retrieved information. If this prediction is not confirmed, another explanation, not dependent on the accuracy but linked to more subjective aspects of the memory retrieval, like confidence (e.g., Henson et al., 2000), is likely to account for the frontal ERP effects usually observed in source memory retrieval tasks. This hypothesis will be tested in experiment 2.

2. Results experiment 1

2.1. Behavioral data

2.1.1. Study phase

Ninety-seven percent of the words were correctly judged according to the voice (see Experimental procedures), with no difference between items spoken in the two voices. Mean reaction time (RT) for correct voice decisions was 497 ms, again with no difference between words pronounced by the two voices. Mean RT for the stereotype judgment was 431 ms. There was no difference according to the gender of the stereotype and of the voice.

2.1.2. Test phase

2.1.2.1. Accuracy. Percentages of the various response categories for both the old/new judgment and the source one are displayed in Table 1. The old and new items were initially classified as correct, incorrect and 'don't know' according to the old/new judgment. A discrimination estimate of '$P_{hit} - (P_{false\ alarm} + P_{don't\ know/new})$' was calculated for the recognition task (see Wilding and Rugg, 1996). Discrimination was above chance for words spoken in each of the two voices [male: $t(15)=15.1$, $p<0.001$; female: $t(15)=12.7$, $p<0.001$] and the two indices for the two genders did not differ significantly. An ANOVA comparing the probabilities of incorrect responses to old male, old female and new words also revealed no significant differences.

For words spoken in each of the two voices, the probability of a correct voice judgment was reliably higher than the probability of an incorrect judgment [male: $t(15)=5.64$, $p<0.001$; female: $t(15)=2.47$, $p<0.05$]. An ANOVA comparing the probability of a 'don't know' response to correctly judged old words (male versus female voice) and to false alarms revealed a main effect of the type of initial response [$F(2,30)=6.6$, $p<0.01$]: the probability of a 'don't know' response to old words was significantly lower than the probability of a 'don't know' response to false alarms (post hoc Tukey comparisons, $p<0.05$; no difference between the two voices).

Table 1 – Percentages of response according to the accuracy of the response (correct, incorrect, and 'don't know' responses) for the old/new judgment and for the source judgment in the test phase of Experiment 1

Accuracy (%)	Voice		New
	Male	Female	
Old/New judgment			
P (correct)	77.3	74.1	73.9
P (incorrect)	15.9	18.1	15.4
P (don't know)	2.6	2.8	4.8
Source judgment (for words judged old)			
P (correct)	62.8	56.9	
P (incorrect)	29.4	34.9	13.2
P (don't know)	7.8	8.2	2.2

Note. Old words are separated according to study voice. The total percentage of old/new judgments for each voice category, collapsing accuracy, is always less than 100% because trials with no response and with reaction times out of the range 300–2000 ms have been discarded. Percentage of correct source judgment is not shown for new words because no voice had pronounced new words at study.

Table 2 – Mean reaction times (in milliseconds) of response according to the accuracy of the response (correct, incorrect, and 'don't know' responses) for the old/new judgment and for the source judgment in the test phase of experiment 1

RT (ms)	Voice		New
	Male	Female	
Old/New judgment			
RT (correct)	1154	1180	1218
RT (incorrect)	1300	1299	1296
RT (don't know)	1481	1667	1599
Source judgment			
RT (correct)	642	632	
RT (incorrect)	665	728	736
RT (don't know)	853	779	794

Note. Old words are separated according to study voice. Mean reaction time of correct source judgment is not shown for new words because no voice had pronounced new words at study.

2.1.2.2. Reaction times. The RTs for the various response categories in both the old/new judgment and the source one are presented in Table 2. Given the low number of 'don't know' responses, analysis of RTs is restricted to the correct and incorrect judgments. For the old/new judgments, an ANOVA was carried out with the factors of accuracy and word type (old male vs. old female vs. new). The only effect obtained was that RTs for correct judgments were reliably faster than RTs for incorrect judgments [$F(1,15)=26.7$, $p<0.001$].

After reclassifying old words according to the subsequent voice judgment, an ANOVA involving the factors of voice judgment accuracy (hit/hit vs. hit/miss) and word type (male vs. female voice at study) gave only a main effect of accuracy [$F(1,15)=5.1$, $p<0.05$], with RTs for later correct judgments being reliably faster than the RTs for later incorrect ones (hit/hit: 1145; hit/miss: 1174).

For the voice judgment, an ANOVA involving accuracy and word type (male vs. female) gave no significant effects (for all, $p>0.15$), probably because participants withhold responses about voice judgments until the response cue '????' appeared. At test, no effect of the congruence between the voice at study and the gender meaning of the words was found.

2.2. *Event-related potential analyses*

Only trials which resulted in hits for the old words and correct rejections for the new words were included in the ERP analyses, due to insufficient trials for adequate analyses of other categories of responses. The hits were reclassified a posteriori as hit/hit or hit/miss, depending upon the subsequent voice judgment. Only 13 participants contributed sufficient trials to permit the formation of reliable, artifact-free ERPs. As no behavioral difference had been observed between the two voices at study, the factor 'voice' was collapsed for the ERP averaging and analysis.

The mean number of trials entering into each participant's waveform analysis was 47, 24 and 77, for the hit/hit, hit/miss and correct rejection categories, respectively. ERPs concerning the test phase were averaged from 100 ms prior to the visual word onset to the occurrence of the 4 question marks, that is, they included the time interval used for the old/new judgment before the voice judgment (2300 ms). As one can see from visual inspection of the grand average (see Fig. 1) and could be expected from the literature, the ERPs related to hit/hit and hit/miss show two widespread positive-going modulations compared with the ERPs related to correct rejections: an early phasic left parietal one and a late long-lasting right frontal one. Accordingly, the subsequent analyses will focus on mean amplitudes of ERPs from the eight chosen regions in three selected latency windows: an early one (500–800 ms) and two late consecutive ones (1400–1800 and 1800–2200 ms).

2.2.1. *Early parietal effects (500–800 ms)*

In order to replicate the well-known old/new left parietal effect, a repeated measure $3\times2\times2\times2$ ANOVA was initially conducted with the following factorial analysis: response category (hit/hit, hit/miss, correct rejection) × hemisphere (left vs. right) × lobe (frontal vs. parietal) × regions (anterior vs. lateral).

This analysis yielded a significant category × hemisphere interaction [$F(2,24)=8.4$, $p<0.01$], mainly due to waves for hit/misses being more positive in the left hemisphere than in the right one ($p<0.001$); waves for the two other response categories did not differ between hemispheres. In addition, a lobe × region interaction was obtained [$F(1,12)=5$, $p<0.05$]; in view of this interaction, a $3\times2\times2$ ANOVA (response category, hemisphere, region) was conducted on the parietal regions only. The only significant effect was the response category × hemisphere interaction [$F(2,24)=11.3$, $p<0.001$]. The post hoc analysis revealed that hit/miss waves were more positive in the left than in the right parietal regions ($p<0.001$). In addition, as planned comparisons showed, the waves for hit/hit as well as those for hit/miss were more positive than those for correct rejections in the left parietal region as compared to the right one ($p<0.05$ and $p<0.01$, respectively). No hemispheric asymmetry was found for the hit/hit vs. hit/miss comparison.

2.2.2. *Middle and late frontal effects (1400–1800 and 1800–2200 ms latency windows)*

Two parallel $3\times2\times2\times2$ ANOVAs were conducted on the mean amplitudes obtained for the two middle and late subsequent latency windows of 1400–1800 and 1800–2200 ms, respectively. Each ANOVA employed the factors of response category, hemisphere, lobe and regions.

Both showed a main effect of lobe [1400–1800 ms: $F(1,12)=27.8$, $p<0.001$; 1800–2200 ms: $F(1,12)=40$, $p<0.001$] and hemisphere [1400–1800 ms: $F(1,12)=12.2$, $p<0.01$; 1800–2200 ms: $F(1,12)=13.4$, $p<0.01$]. For the 1400–1800 ms latency window only, these main effects were better qualified by a significant lobe × hemisphere interaction [$F(1,12)=5.3$, $p<0.05$]; this interaction derived from the right regions being more positive than left ones for the frontal lobes ($p<0.001$), but not the parietal lobes ($p=0.08$). Moreover, response category modulated this effect as the category × lobe × hemisphere interaction indicated [1400–1800 ms: $F(2,24)=7.5$, $p<0.01$; 1800–2200 ms: $F(2,24)=5.7$, $p<0.01$]. Thus, the hit/miss waves were significantly more positive than correct rejection waves only in the right frontal regions (for both latency windows, $p<0.01$). No significant difference was obtained between the RAF and the RLF regions.

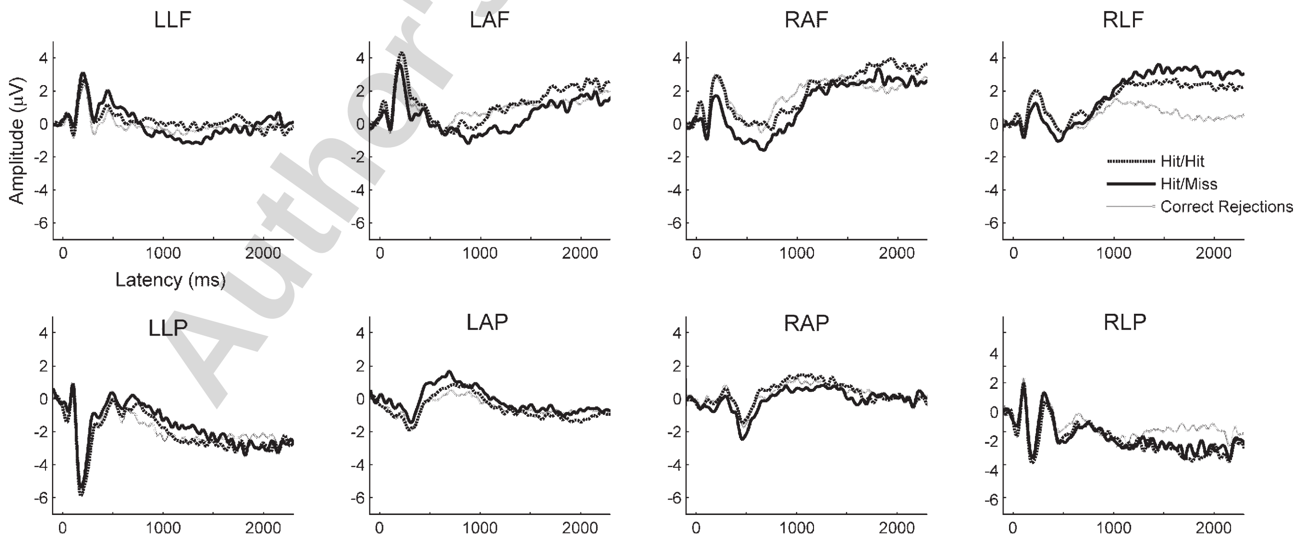

Fig. 1 – Grand average of ERPs associated with the hit/hit, hit/miss, and correct rejection response categories in Experiment 1. LLF, LAF, RAF, RLF, LLP, LAP, RAP, and RLP signify left lateral frontal, left anterior frontal, right anterior frontal, right lateral frontal, left lateral parietal, left anterior parietal, right anterior parietal, and right lateral parietal.

The hit/hit waves too were more positive than correct rejections in the right frontal regions but the post hoc Tukey test gave a significant result for the latency window of 1800–2200 ms only ($p<0.01$). No differences were observed between the different conditions in the left hemisphere.

3. Discussion experiment 1

Experiment 1 replicates the basic old/new effects known from the literature. In keeping with previous findings (e.g., Donaldson and Rugg, 1998; Wilding and Rugg, 1996), the differences between the ERPs to correct memory judgments for old and new items were characterized by an early left parietal old/new effect, consisting of waves for hits being more positive than waves for correct rejections. However, unlike some studies (e.g., Wilding and Rugg, 1996), but similar to others (Cansino et al., 2002; Senkfor and Van Petten, 1998), parietal waves were not modulated by the accuracy of the subsequent source judgment (hit/hit vs. hit/miss). Moreover, the hemispheric asymmetry (left more than right) in the old/new parietal effect was detected for the hit/miss condition only and not for the hit/hit one.

In addition, the present results replicate the late right frontal old/new effect (e.g., Donaldson and Rugg, 1998; Wilding and Rugg, 1996), with waves for hit/hit and hit/miss trials being more positive than those for correct rejections in two late latency windows. However, the hit/miss waves were slightly, although not significantly, more positive than the hit/hit ones in the right prefrontal region. Hence, in the current experiment, the late positive frontal component is independent of the successful retrieval of a full memory trace. This pattern is in conflict with the retrieval success account of the late right frontal old/new effect (e.g., Wilding and Rugg, 1996). It is noteworthy that, in this experiment, RTs for old/new judgments were significantly slower for hit/miss than for hit/hit, while in the Wilding and Rugg's (1996) study there was no difference between RTs for the two types. Moreover, the percentage of correct source judgments was higher in our study than in their experiment 2, which was more similar to our design (60% vs. 50%), probably because our study involved a deeper encoding than their lexical decision.

Similar results to ours have been usually explained as reflecting monitoring of search operations in general (e.g., Kapur et al., 1995; Senkfor and Van Petten, 1998) rather than of the products of memory retrieval. A more specific interpretation of the prefrontal role in memory retrieval, which provides a clear alternative to the retrieval success accounts, is that this area is more involved when the response is less certain and hence needs additional monitoring (Henson et al., 1999a). In order to test this hypothesis more directly, an fMRI study by Henson et al. (2000) adopted a procedure in which old/new judgments were required together with confidence ratings of these judgments. Results showed that correct low-confidence responses to old items activated dorsolateral prefrontal cortex bilaterally. There is therefore enough evidence to suppose that the evaluation or checking of the response could be a good candidate for the modulation of the prefrontal ERP effects during source memory judgments (e.g., Shallice, 2002).

The hypothesis of a possible influence of confidence on prefrontal ERPs during a source memory task will be investigated directly in experiment 2. The ERP technique is a useful tool to temporally characterize an effect of retrieval confidence on the cortical electrical activity and to possibly dissociate it from the effect of retrieval accuracy. A procedure similar to that used in the fMRI study by Henson et al. (2000) was therefore adopted in the next experiment.

Late ERP positivity is generally considered an electrophysiological hallmark of prefrontal engagement during retrieval (e.g., Wilding and Rugg, 1996). Thus, the prediction was made that late prefrontal waveforms associated with low-confidence judgments will be more positive than those associated with high-confidence ones as the former have been held to require processes typically involving the frontal lobe (e.g., monitoring processes; see Henson et al., 2000, for fMRI evidence).

4. Results experiment 2

4.1. *Behavioral data*

4.1.1. *Study phase*

The mean RTs for stereotype judgment were 622 ms, with no difference between words pronounced by the two voices (paired *t*-test: $t(16)=1.49$, $p=0.15$). There was no effect of congruence between voice and gender stereotype.

4.1.2. *Test phase*

4.1.2.1. *Accuracy*. Percentages of responses classified according to response confidence, voice at study and accuracy are shown in Table 3. A 2×2×2 ANOVA was performed with accuracy, confidence and study voice as the within-subjects

Table 3 – Mean reaction times (in milliseconds) and percentages of the source judgment classified according to the voice at study (male versus female), accuracy (hit versus miss), and confidence (high- versus low-confidence) in the test phase of experiment 2

Percentage	Voice			
	Male		Female	
	High confidence	Low confidence	High confidence	Low confidence
Hit	1375	1459	1379	1484
	31%	25%	28%	22%
Miss	1464	1485	1412	1472
	16%	20%	21%	22%

variables and the percentage of responses as the dependent variable. There were significantly more hits than misses [$F(1,16)=27.4$, $p<0.001$]. The accuracy × confidence interaction was also significant [$F(1,16)=13.9$, $p<0.01$], due to the percentage of highly confident responses being greater for hits than for misses (post hoc, $p<0.001$), while the percentage of low-confidence responses did not differ reliably between hits and misses ($p=0.36$). A voice × accuracy interaction was also observed [$F(1,16)=9.7$, $p<0.01$]. This was due to the difference between hits and misses being greater for words presented at study in the male voice than ones presented in the female voice. No other effects were significant.

4.1.2.2. Reaction times. Mean RTs are presented in Table 3. The same 2 × 2 × 2 ANOVA as for accuracy was performed with the mean RT as the dependent variable. The RTs for hits were faster than the RTs for misses [$F(1,16)=5.7$, $p<0.05$]. There was a main effect of confidence [$F(1,16)=7$, $p<0.05$] with RTs for high-confidence responses being faster than for low-confidence ones. There was a significant accuracy × confidence interaction [$F(1,16)=5.6$, $p<0.05$], through the RTs for highly confident judgments being faster for hits than for misses, with no such effect on RTs for low-confidence judgments. No effects involving voice were found.

4.2. Event-related potential analyses

4.2.1. Confidence analysis

ERPs elicited by the high- versus low-confidence voice judgments are displayed in Fig. 2.

4.2.1.1. Early parietal effects (500–700 ms). A 2 × 2 × 2 × 2 ANOVA (confidence, lobe, hemisphere and region) was performed with the mean amplitude of the 500–700 ms post-word onset as the dependent variable. The lobe × hemisphere interaction was significant [$F(1,16)=5.1$, $p<0.05$], due to waves being more positive in the left parietal regions than elsewhere (for all, $p<0.05$). As the confidence × lobe × region interaction was also significant [$F(1,16)=10.7$, $p<0.01$], a 2 × 2 × 2 ANOVA (confidence, hemisphere and region) was carried out limited to the four parietal regions only. This analysis produced a main effect of hemisphere [$F(1,16)=8.3$, $p<0.01$], left ERPs being more positive than right ones. More importantly, the confidence × region interaction [$F(1,16)=11$, $p<0.01$] showed waves for low-confidence responses to be more positive than waves for high-confidence ones in the lateral parietal regions only.

4.2.1.2. Middle and late anterior frontal effects (1000–1500 and 1500–2000 ms). Two 2 × 2 × 2 × 2 ANOVAs (confidence, lobe, hemisphere and region) were also performed on the mean amplitudes in the 1000–1500 and 1500–2000 ms latency windows. Significant main effects of confidence [i.e., 1000–1500 ms, $F(1,16)=5.4$, $p<0.05$], lobe [1000–1500 ms: $F(1,16)=4.9$, $p<0.05$; 1500–2000 ms: $F(1,16)=4.1$, $p=0.06$] and hemisphere [1000–1500 ms: $F(4,64)=37.2$, $p<0.001$; 1500–2000 ms: $F(4,64)=26.5$, $p<0.001$] were found. More critically, a lobe × hemisphere interaction was observed principally in the middle latency window [1000–1500 ms: $F(1,16)=7.3$, $p<0.05$; 1500–2000 ms: $F(1,16)=3.1$, $p=0.09$], due to there being more positive waves in the right frontal regions than in all the other regions (for all, $p<0.001$). However, a lobe × region interaction was also

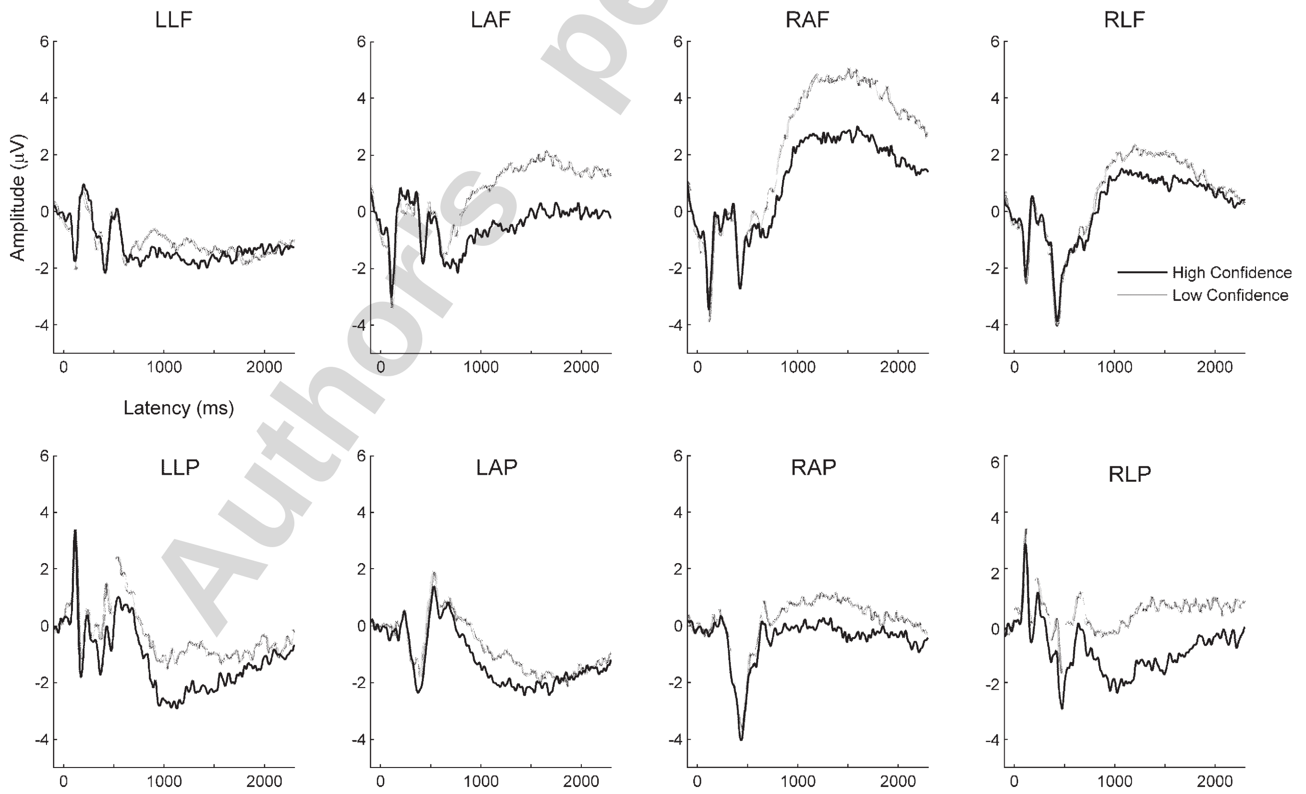

Fig. 2 – Grand average of ERPs associated with the high- and low-confidence source judgments in experiment 2. Labels of the scalp regions as for Fig. 1.

obtained for the late 1500–2000 ms latency window [$F(1,16)=5.8$, $p<0.05$], due to there being more positive waves in the anterior frontal regions than elsewhere (for all, $p<0.05$). The confidence × lobe × region interaction occurred in both time-windows [1000–1500 ms: $F(1,16)=9.5$, $p<0.01$; 1500–2000 ms: $F(1,16)=7.9$, $p<0.05$]. Post hoc comparisons indicated that low-confidence responses elicited more positive waves than high-confidence responses selectively over the anterior frontal and the lateral parietal regions during the 1000–1500 ms time-window (for both, $p<0.05$), with similar trends during the 1500–2000 ms time-window over the anterior frontal regions only (for both, $p\leq 0.07$).

Given the results of the overall ANOVA and the existing literature on late prefrontal effects, two separate 2×2×2 ANOVAs were run, for the middle and the late latency windows, respectively; they were restricted to the prefrontal regions only, involving the factors confidence (high- vs. low-confidence responses), hemisphere (left vs. right frontal) and region (anterior vs. lateral). These two analyses led to very similar findings. A main effect of hemisphere was obtained [1000–1500 ms: $F(1,16)=27.6$, $p<0.001$; 1500–2000 ms: $F(1,16)=20$, $p<0.001$], due to right frontal ERPs being more positive than left ones. The main effect of region was also significant [1000–1500 ms: $F(1,16)=4.4$, $p=0.05$; 1500–2000 ms: $F(1,16)=6$, $p<0.05$], due to there being more positive waves in the anterior prefrontal regions than in the lateral ones. The only significant interaction was the confidence × region one [1000–1500 ms: $F(1,16)=7$, $p<0.05$; 1500–2000 ms: $F(1,16)=9$, $p<0.01$]. ERPs for low-confidence judgments were more positive than those for high-confidence ones, this difference being more pronounced in the bilateral anterior frontal regions than in the lateral frontal ones, as planned comparisons demonstrated ($p<0.05$ and $p<0.01$ for the middle and late latency windows, respectively). The results of the more specific analysis therefore confirmed those from the more general one.

4.2.2. *Accuracy analysis*

Similar ANOVAs were conducted replacing the factor confidence with that of accuracy. However, no effect of accuracy was observed in the ERPs, as can be seen in Fig. 3.

5. Discussion experiment 2

Experiment 2 confirms the general involvement of left parietal and right frontal regions in two different time-windows during a source memory task already shown in previous memory studies (e.g., Wilding and Rugg, 1996) and in experiment 1 of the present study. In particular, ERPs in the left parietal regions were the most positive in the early latency window of 500–700 ms, while ERPs in the right frontal regions were the most positive in the subsequent latency windows of 1000–1500 and 1500–2000 ms. However, the present results again do not corroborate the successful retrieval account of the prefrontal involvement during a source memory task. The accuracy of the source judgment did not influence ERPs at all (as shown in Fig. 3), confirming the results of experiment 1, even though the paradigms adopted in the two experiments were different.

The aim of experiment 2 was primarily to evaluate the role of confidence in modulating late frontal ERPs during a source

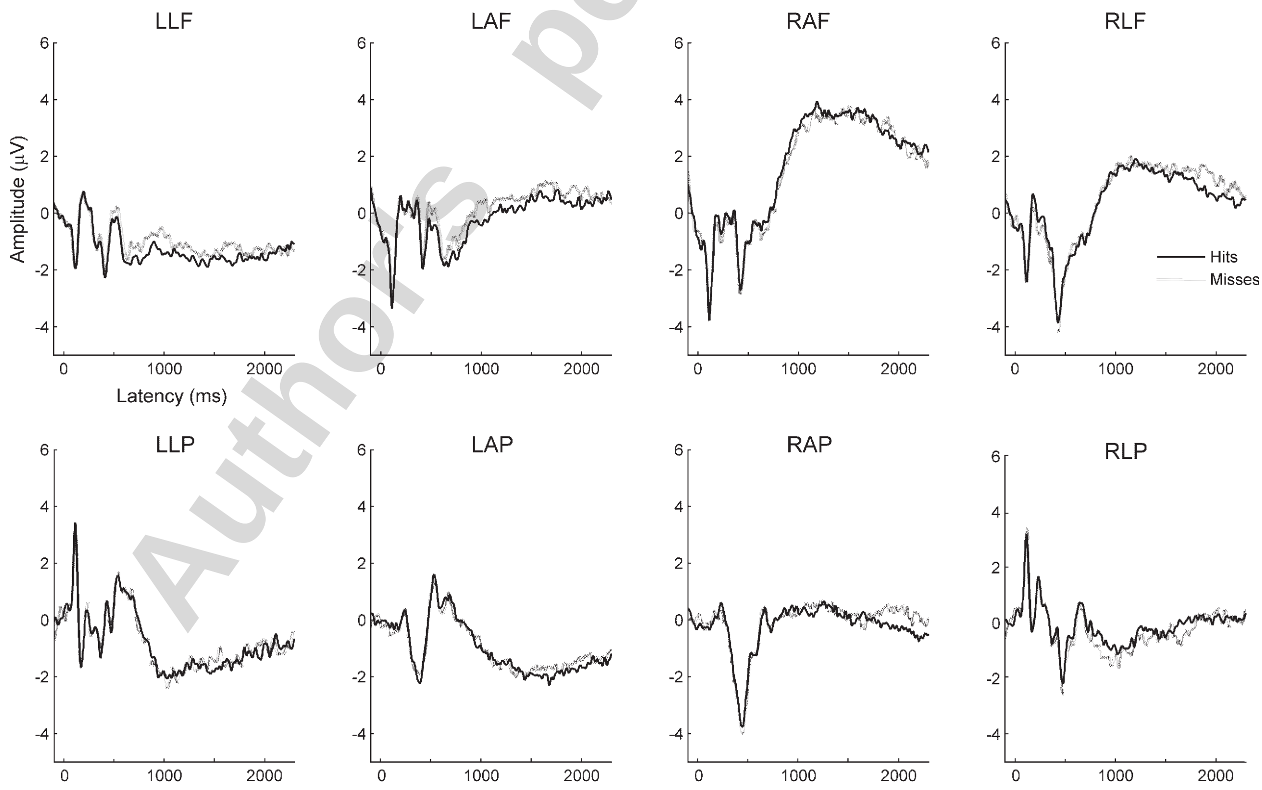

Fig. 3 – Grand average of ERPs associated with the correct versus incorrect source judgments (hits versus misses) in experiment 2. Labels of the scalp regions as for Fig. 1.

memory task. Previous ERP experiments requiring confidence rating of memory judgments did not examine late frontal effects in detail (Rugg and Doyle, 1992) and usually did not analyze low-confidence ERPs because of the low number of trials available for the averaging (Rubin et al., 1999; Rugg et al., 1995). In the current study, the production of confidence ratings by the participants influenced their ERPs in two dissociable ways. First, ERPs are more positive for low-confidence ratings than for high-confidence ones. This pattern is observed earlier over lateral parietal regions (i.e., 500–700 ms and 1000–1500 ms) and later and more sustained in time also over anterior prefrontal ones (i.e., 1000–2000 ms). This different time-course suggests a different functional role of the two regions during this task. It has been supposed that, when low-confidence responses are given, more monitoring is dedicated to the retrieval processes before a decision is made (Henson et al., 2000), consistent with the longer RTs observed in the present experiment for low-confidence judgments. Our results would fit with such a long-lasting monitoring process occurring over the anterior prefrontal regions. Conversely, the phasic effect of confidence over parietal regions, although statistically detectable, is more difficult to explain (see General discussion).

A second dissociable effect found in the present experiment consists of ERPs being specifically more positive over right prefrontal sites (i.e., anterior and lateral) than elsewhere in the middle latency window (1000–1500 ms), during which participants were performing their judgment (mean RT = 1441 ms). This effect suggests that, in the present experiment, right prefrontal positivity is associated with the online confidence evaluation of the source judgment, independently of the accuracy and confidence of such judgment (but see General discussion).

6. General discussion

The general aim of the present study was to elucidate the role of prefrontal areas in source memory retrieval and, specifically, to electrophysiologically dissociate the prefrontal ERP effects of the objective performance (viz., accuracy) from that of more subjective aspects of memory search processes (viz., confidence) during source retrieval. We tried to address these issues by means of ERPs measured with a high-density (128 channels) recording apparatus.

In particular, our first interest was to test whether accuracy of source retrieval was linked to the frontal ERP old/new effect, as suggested by some ERP studies (e.g., Graham and Cabeza, 2001; Wilding and Rugg, 1996) but not confirmed by others (e.g., Senkfor and Van Petten, 1998; Ranganath and Paller, 1999). In experiment 1, late ERPs evoked by hit/miss trials over the right frontal regions were if anything more positive, albeit not significantly, than ERPs evoked by hit/hit ones. In the light of the inconsistency of the effect of source retrieval accuracy on late frontal waves across studies (cf. Senkfor and Van Petten, 1998; Wilding and Rugg, 1996), this finding suggests that retrieval accuracy is not a critical variable influencing the late frontal ERPs. This is compatible with recent accounts ascribing the frontal contribution to memory to more general processing capacities which can be applied to non-memory tasks as well (e.g., Stuss and Alexander, 2005).

An issue then arises regarding the specific content of the monitoring processes supposed to occur during retrieval within the prefrontal areas (e.g., Burgess and Shallice, 1996). A suggestion deriving from the fMRI study by Henson et al. (2000) is that prefrontal areas are modulated by variables which are more subjective than accuracy per se, such as the confidence level of the memory judgment. Experiment 2 aimed to extend these findings, investigating the electrophysiological correlates of confidence self-ratings during a source memory task. Specifically, in the retrieval phase of the second experiment, voice judgments were embedded together with response confidence evaluation.

According to a schematic analysis of this task, the following processes should occur, among others, during any trial in order to give an appropriate response: (a) after reading the test word, attention should be focused on memory products reactivated by this cue in order to start the memory search (attentional shift towards retrieval specification); (b) attention needs to be maintained on these retrieval products so as to continue the memory search (maintenance of attention); (c) memory retrieval products elicited by the cue are possibly brought to consciousness (ecphory); (d) to perform a correct source judgment, a further process is required which scans the products of memory search for information concerning voice. Accuracy of these products is then checked especially when the voice is not confidently recollected (monitoring process); (e) finally, given the specific nature of this task, which additionally requires confidence judgments, another meta-level process is needed. This process is held to monitor the ongoing memory search itself in order to evaluate the confidence status of the current source judgment (meta-memory process).

Apart from a lack for any effect of accuracy on ERPs (process c, in our task analysis), which corroborates the results of experiment 1, the results of experiment 2 showed a number of specific ERP effects which might correspond to some of the processes already specified in the schematic task analysis. Those effects can be distinguished on the basis of their temporal and topographical distribution, on the one hand, and of their sensitivity to the confidence level, on the other hand. Each effect will be discussed in detail in the following sections.

6.1. *Parietal effects: processes (a), (b) and (c)*

As far as the ERP parietal effects during memory retrieval are concerned, recollection and retrieval quality accounts have been proposed in the literature (process c, in our task analysis, e.g., Curran, 2004; Duzel et al., 1997; Rugg et al., 1995). Such accounts originate from the hypothesis that the parietal ERP effects reflect medial temporal lobe activity (Duzel et al., 1999) or cortico-hippocampal interactions (Wilding and Rugg, 1996). Medial temporal activity, when reported in functional imaging studies, has usually been related to retrieval success (see Schacter et al., 1998a for a review). However, the present results are in conflict with these accounts as no effect of accuracy was obtained on these sites in either experiment. On the other hand, an effect of confidence was observed, with low-confident responses evoking more positive ERPs. Responses to be rated low-confidence are less likely to be vividly retrieved or recollected (as demonstrated by the behavioral results of experiment 2). Thus, given the existing evidence, the finding of low-confidence ERPs being more positive than high-confidence ones over the lateral parietal regions in experiment 2 was unexpected. However, in addition to the current study, other ERP studies also show findings somewhat in contrast with the recollection account of the parietal effects. In a face recognition task, for instance, Graham and Cabeza (2001) found similar parietal ERP amplitudes for hit/hits and hit/misses. In another ERP study of recognition (Curran et al., 2001), participants were a posteriori separated into Good and Poor performers, according to their ability to discriminate studied target words from similar lures. Surprisingly, only poor performers, despite of their inability to discriminate between old targets and lures, showed a reliable parietal old/lure difference.

The gap observed in these studies between behavioral performance and the parietal ERP effects suggests that the latter may be independent of retrieval accuracy and vivid recollection (see Rossi et al., 2006 for recent transcranial magnetic stimulation evidence). Moreover, it should be pointed out that the link between the parietal ERP effects and the medial temporal lobe activity is very indirect. Indeed, there is recent evidence showing no consistent relationship between left parietal ERP correlates of source memory retrieval and hippocampal volume and diffusion (Schiltz et al., 2006). The same study showed no correlation between accuracy in source memory retrieval and these indices of hippocampal integrity.

An alternative hypothesis, among others, is that posterior parietal ERP effects might reflect the shifting of attention to, and the maintenance of attention on, internally produced amnesic representations (processes a and b, in our task analysis; Wagner et al., 2005). This hypothesis derives from the observation that the confidence effect occurs over the lateral parietal regions in two different time-windows, a phasic early time-window and a middle tonic one, probably associated to the two abovementioned processes. Moreover, in some short-term memory models, the left inferior parietal region is thought to be the seat of the input phonological buffer (Paulesu et al., 1993; Shallice and Vallar, 1990). The maintenance of attention on memory retrieval products is therefore likely to be increased in order to achieve a source memory decision especially for weakly stored traces (low-confidence judgments), whereas it is not clear how confidence status can influence the earlier stage of attentional shift. However, these interpretations should be taken cautiously as the opposite pattern (more positive parietal ERPs for the high- than for low-confidence judgments) was reported in earlier ERP studies of confidence (e.g., Curran, 2004; Rubin et al., 1999). Differences in the task demands (source vs. old/new judgments) might help to partially account for the discrepancies with previous findings.

6.2. *Anterior frontal effects: process (d)*

An anterior-more-than-lateral prefrontal pattern was found in experiment 2 but not in experiment 1. In experiment 1, only one task at a time had to be performed, namely an old/new judgment followed by a source judgment. Conversely, in experiment 2, two different tasks had to be carried out rather simultaneously, namely a source judgment and a confidence evaluation, and the different processes underlying them had to be coordinated so as to give a response.

One possible explanation is suggested by the idea that a specific role for the anterior prefrontal region is to integrate the results of two or more separate cognitive operations in the pursuit of a more general behavioral goal (Ramnani and Owen, 2004; see also Reynolds et al., 2006). The electrophysiological dissociation between the two present experiments supports this model, if not strictly anatomically, due to the low-spatial resolution of the ERPs, at least functionally. However, in order to explain the effect of confidence on anterior prefrontal waves, this account needs to be extended by postulating further operations conceivably more engaged during a low-confidence judgment than during a high-confidence one. According to signal detection models of recognition in memory (Juola et al., 1971), low-confidence judgments are those in which the memory strength is close to the decision criterion. These situations are likely to involve more monitoring of the retrieved products, consistent with the longer RTs obtained here for low-confidence judgments. In the fMRI study by Henson et al. (2000), low-confidence responses selectively activated bilateral prefrontal cortex. In the present study, low-confidence responses evoked more positive waves on the bilateral anterior prefrontal scalp regions in a long-lasting fashion (i.e., middle and late time-windows). This ERP pattern might be considered as a marker of retrieval verification processes, which monitor the appropriateness of retrieved information, especially when the retrieval process is difficult (process d, in our task analysis; editing or mediator processes according to the model specified by Burgess and Shallice, 1996; see also Henson et al., 1999b, 2000). It would be difficult to interpret these findings from the point of view of alternative interpretations, such as the retrieval mode account (e.g., Kapur et al., 1995; Lepage et al., 2000).

An apparent inconsistency exists between the confidence effect in the study by Henson et al. (2000) and in the current experiment 2 concerning the topographical locus of the effect. In the fMRI study by Henson et al. (2000), areas which showed a confidence effect were located bilaterally in the dorsolateral prefrontal regions, while in the present study this effect is picked up more by anterior frontal electrodes than by lateral frontal ones. However, anatomical inferences based on the ERPs recorded from the scalp need to be taken cautiously because the localization of brain sources does not correspond directly to scalp potential topography. Bearing in mind this caveat, some discussion is still possible. The difference between the tasks adopted in the two studies might partially account for the discrepancy. In the Henson and colleagues' (2000) study, an old/new judgment was the object of the confidence evaluation, whereas in ours a voice retrieval was required. It could be that monitoring of source retrieval is located more anteriorly than item retrieval (e.g., Christoff and Gabrieli, 2000; Simons et al., 2005; but see Rugg et al., 2003).

6.3. *Right frontal effect: process (e)*

Finally, another clearly localized electrophysiological effect was found in experiment 2. ERPs were more positive over the right prefrontal sites (both anterior and lateral) than elsewhere, especially in the middle latency window, independently of accuracy and confidence. It is possible to interpret this asymmetry in the light of our task demands. Noteworthy, during the latency window in which the right prefrontal asymmetry is more evident (i.e., 1000–1500 ms), participants were actually performing the source-plus-confidence judgment. As pointed out in our previous task analysis, these task demands of experiment 2 explicitly require a metamemory process monitoring the state of confidence of the response (process e). The right frontal ERP effect in this interval, thus, may be accounted for by attributing a role in metamemory evaluation of retrieval processes to the right prefrontal regions. This inference about possible brain sources of the right frontal ERP effect fits with the results of neuropsychological studies showing evidence for a possible metamemory role of the right prefrontal cortex (e.g., Vilkki et al., 1998, 1999). However, the right-more-than-left effect was also found in our experiment 1 and in other ERP studies of episodic retrieval not requiring a confidence evaluation (e.g., Wilding and Rugg, 1996). This asymmetry also fits various functional imaging findings which widely document a right-more-than-left prefrontal involvement during retrieval (e.g., Lepage et al., 2000; Shallice et al., 1994; Tulving et al., 1994; but see Nolde et al., 1998). In recent fMRI studies, activity of right dorsolateral and fronto-polar prefrontal areas during retrieval has been linked to familiarity monitoring (e.g., Henson et al., 1999a; Dobbins et al., 2003, 2004). On this account, the process thought to engage the right prefrontal regions consists of monitoring a familiarity signal in order to make a decision according to an internal criterion (cf. Banks, 1970). Assuming an anatomical correspondence between scalp potentials and sources, the latter interpretation seems more appropriate to account for the right frontal ERP effect found not only in our experiment 2, but also in experiment 1 and in other studies of episodic memory which do not explicitly require metamemory processes. In our experiment 2, this familiarity monitoring could be functional not to achieve an old/new judgment (not required) but to decide how confidently one remembers the voice pronouncing the word.

6.4. Conclusions

The lack of any modulation of the ERPs throughout the scalp by accuracy of the source judgments, in both experiments of the current study, is very difficult to account for on the successful source retrieval hypothesis. The results of experiment 2 show a clear-cut dissociation among the prefrontal scalp regions of interest analyzed, along the anterior–lateral and left–right topographical dimensions, respectively. This pattern of results suggests a fractionation of memory functions within the underlying prefrontal areas. Anterior prefrontal ERPs were tonically modulated by the confidence rating of the source retrieval (i.e., more positivity for low- than for high-confidence ratings) during middle and late latency windows. This pattern brings converging evidence for the role of confidence in modulating prefrontal involvement in memory retrieval and may well be ascribed to extra monitoring demands, necessary in order to achieve a source memory judgment during uncertain situations. On the other hand, the more general right-more-than-left prefrontal ERP positivity, also found in experiment 1, could be attributed to familiarity monitoring.

7. Experimental procedures

7.1. Experiment 1

7.1.1. Participants

Sixteen volunteer participants took part in experiment 1. They were 25.4 years old on average (range=20–33); 8 were males and 8 females; all of them were right-handed. All had normal or corrected-to-normal vision, no auditory impairment, and had no history of neurological problems. Each participant gave written informed consent prior to participation in the study and received 10 euros at the end of the experimental session. Approval from the local ethical committee was obtained for the study.

7.1.2. Material

Stimuli at study consisted of 320 Italian words (low/middle frequency, length=4–10 letters, mean=7). The list contained words with either male or female semantic associations (50% of each), as indicated by a prior pilot study. For example, words with a male semantic meaning were 'soccer' and 'plumber'; words with a female semantic meaning were 'skirt' and 'jewel'. These 320 words were divided into two paired sub-lists of 160 different words, with comparable frequency, length and meanings.

At study, words from one of the two sub-lists were presented, half pronounced by a male voice and half by a female voice. Of the words pronounced by each one of the voices, half had a congruent male meaning and half a congruent female meaning. Study words were presented in 4 blocks of 40 items, with a pause of a few minutes between blocks. The order of presentation of items within each block was determined randomly.

The test list was formed by merging all 320 words of the initial database. This means that half of the test items were old, in that they had already been auditorily presented at study, and half were new. Of the 160 old words composing each test list, 80 had been spoken in the male voice and 80 in the female voice at study. Test words were presented in 5 sub-lists of 64 items each. The assignment of words to sub-list and the order of presentation of items within each block were determined randomly.

Test stimuli were presented visually on the center of a 17″ monitor. Test words (12-point Courier New font) subtended approximate visual angles of 1.4° to 2.5° (horizontally) and 0.6° (vertically) from a viewing distance of 45 cm. Stimuli were exposed in white letters on a black background. The auditory study words were digitally recorded in two voices, male and female, at 22 kHz, 16-bit resolution, stereo mode. They were edited so that the beginning of the stored sound segment corresponded to the onset of the spoken word. The mean duration of these stimuli was 815 ms and did not differ significantly according to the gender of the voice. Auditory stimuli were presented binaurally at a comfortable hearing level through two earphones. Stimulus presentation was controlled by a PC. Responses were collected from an external four-button response box connected to the PC.

7.1.3. Procedure and task

Participants were tested individually in a silent room. Each 1-hour experimental session began with instructions about the general aim of the experiment and some advice on how to avoid producing artefacts during the EEG recording. Participants were asked to relax and to avoid muscular and eye movements and blinks as much as possible, with the exception of when the fixation point was present on the screen. Following channel placement (see below), participants were seated in front of the stimulus presentation monitor. The index and middle fingers of their hands rested on each of the 4 buttons of a response box. The task in the study phase consisted of a gender voice judgment followed by a gender stereotype judgment in order to increase the depth of the encoding. In this first phase, a fixation point (an asterisk) appeared for 400 ms at the beginning of each trial and was removed from the screen 100 ms prior to stimulus presentation. The word was auditorily presented with a blank screen appearing at the same time and lasting 1100 ms. A visually presented question 'Voice?' (in Italian: 'Voce?') lasting 1500 ms indicated to the participants the period in which they had to perform the decision on the gender of the voice. Another blank screen subsequently appeared for 400 ms. Then, a second question 'Stereotype?' (in Italian: 'Stereotipo?') lasting 1500 ms indicated to the participants when to perform the judgment of the gender stereotype. A final blank of 400 ms separated the current trial from a new one. Each participant was instructed to press one of the two external buttons on which her/his index fingers rested, which depending upon whether the item was spoken in the male or the female voice. They then had to indicate, using the same buttons, whether its meaning was associated with the male or the female sphere. The finger to be used associated to the gender of the voice and of the stereotype was kept constant for each participant. The correspondence between hand and voice gender was counterbalanced across participants. Accuracy and speed were equally stressed for the voice judgment. Participants were instructed that there was no absolutely correct response for the stereotype judgment. Participants were aware that the subsequent task would be a memory task for the voice. A practice session consisting of 4 items preceded the study phase per se. The total duration of a study trial was 5400 ms. Responses faster than 200 ms or slower than 2000 ms were treated as errors.

After a short pause of 5 min, during which the status of the net was checked and readjusted if needed, the test phase began. An asterisk lasting for 400 ms again preceded presentation of each word; it was removed 100 ms prior to stimulus onset. A test word appeared in the center of the screen for 300 ms followed by the fixation point (asterisk) for 1700 ms. The onset of the word served as the cue for the first decision. This consisted of an old/new judgment. Participants had to press an external button with their left or right middle finger according to whether they remembered hearing the word at study or not. One index finger could be used to press a middle button when the participants were not sure about the old/new status of the word. The index finger used for the 'don't know' response was the right one for half of the participants and the left one for the other half. This additional response alternative was introduced in order to obtain a cleaner separation between hits and misses (e.g., Wilding and Rugg, 1996), thereby reducing the possibility that some trials contributing to the hit ERPs could have been lucky guesses. Accuracy and speed were equally emphasized for this first decision. After a blank interval of 400 ms, a row of four question marks appeared on the screen for 2000 ms. For words judged old only, the question marks present during the 2000 ms interval were a cue to report the voice in which the word had been presented at study. The voice judgment was also made using the two external buttons on which the participants' middle fingers rested, with the option of pressing the 'don't know' middle button with one of the two index fingers (again counterbalanced across participants) in order to further separate trials on which study voice was successfully recollected and those on which it was not, by also reducing the number of lucky guesses for the source judgment. The association between hand and response for the two judgments was also counterbalanced across participants. A further blank interval of 400 ms separated the current trial from the following one. The total duration of a test trial was 5300 ms. A practice session consisting of 8 items preceded the test phase per se. Four of those practice items had already been auditorily presented at study and 4 were new. Initial old/new judgments quicker than 300 ms or slower than 2000 ms were discarded from the analyses. Subsequent voice judgments slower than 2000 ms were also discarded.

7.1.4. EEG recording

Scalp voltages were collected with a 128-channel Geodesic Sensor Net™ (Tucker, 1993) connected to an AC-coupled, high input impedance amplifier (200 MΩ, Net Amps, Electrical Geodesics, Eugene, OR). Amplified analog voltages were filtered online (0.1–100 Hz band-pass) and digitalized at 250 Hz. Individual channels were adjusted until impedances were below 50 KΩ. Recording voltages were referenced online to a vertex channel but re-referenced after ERP extraction to the average voltage of all channels (see next section).

7.1.5. EEG data reduction and analysis

The EEG was continuously recorded during the test phase. The ERPs were extracted off-line triggered by the test word onset and segmented for a temporal period extending from 100 ms pre-stimulus to 2200 ms post-stimulus. Trials were dropped from the analyses (i.e., automatically rejected prior to averaging) if they contained eye movements (eye channel differences greater than 50 μV) or more than 40% bad channels (fast average amplitude >150 μV between samples, differential average amplitude >150 μV, zero channel variance). Data from individual channels which were consistently bad for a given participant were replaced using a spherical interpolation algorithm if bad channels were less than 20% (Srinivasan et al., 1996). The ERP data from 3 participants (out of 16) were discarded because of an insufficient number of artefact-free trials per condition (<15).

The ERPs were baseline-corrected with respect to the 100 ms interval prior to word presentation and digitally band-pass filtered at 0.3–30 Hz. An average reference transformation was used to minimize the effects of reference-site activity and to estimate accurately the scalp topography of the measured electrical fields (Dien, 1998; Picton et al., 1995). A spherical spline interpolation was also used to estimate the voltages of the scalp surface that was not covered by channels and to correct the polar average reference effect (Junghofer et al., 1999).

On the basis of the literature and of preliminary analyses, eight regions were selected from the measured head space for analysis of the spatial scalp topography of the ERP effects (see Fig. 4). The selected regions can be classified according to their topographical coordinates as follows: 2 hemisphere (left vs. right) × 2 lobe (frontal vs. parietal) × 2 regions within each lobe (anterior, lateral). Waveforms were obtained averaging ERPs from a pool of four adjacent channels for each region (see Curran et al., 2001 for a similar approach). Thus, the selected regions were the following: left anterior frontal (LAF, channels: 23, 24, 26, 27), right anterior frontal (RAF: 2, 3, 8, 9), left lateral frontal (LLF: 28, 29, 34, 35), right lateral frontal (RLF: 117, 118, 122, 123), left anterior parietal (LAP: 42, 43, 47, 48), right anterior parietal (RAP: 94, 99, 103, 104), left lateral parietal (LLP: 59, 60, 65, 66), right lateral parietal (RLP: 85, 86, 91, 92). The outcomes of analyses performed including the midline channel sites are not described unless they clearly conflict with the conclusions derived from analyses of the data concerning the lateral regions. In addition, ANOVAs focusing on a sub-set of regions are reported to corroborate and extend results from the overall ANOVAs. Main effects of ERP analyses for both experiments are only briefly presented as they are not relevant for the purposes of the study. All the significant behavioral and electrophysiological effects were analyzed further through post hoc comparisons if necessary (i.e., Tukey Honestly Significant Difference).

7.2. *Experiment 2*

7.2.1. *Participants*

Eighteen participants volunteered for experiment 2, all different from those who carried out experiment 1. They were 27 years old on average (range = 22–40); 12 were females and 6 males. All were right-handed, had normal or corrected-to-normal vision, no auditory impairment, and no history of neurological problems. Each participant gave written informed consent prior to participation in the study and received 10 euros at the end of the experimental session. One female participant was discarded from the analyses as she did not use some response categories at all (i.e., no 'high-confidence' responses).

7.2.2. *Material*

The stimuli were the same as in experiment 1. The only difference was that the same 160 words auditorily presented

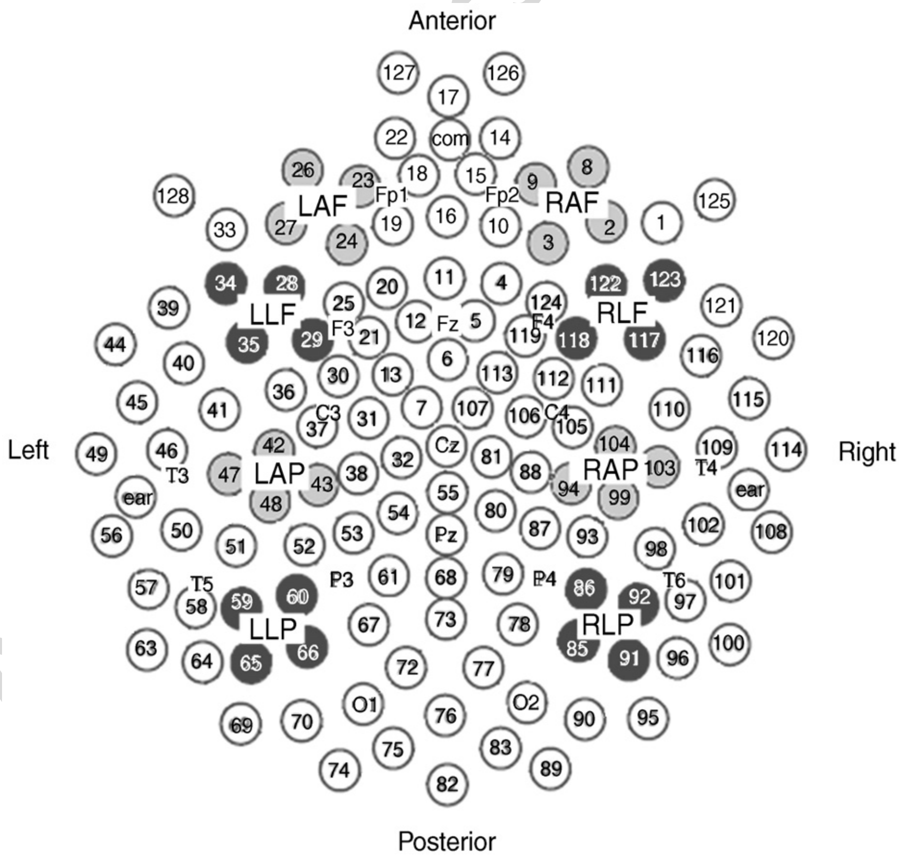

Fig. 4 – Approximate locations of the 128 channels in the geodesic sensor net. Sets of channels within anterior and lateral regions of the frontal and parietal lobes used in ANOVAs are shown in black and gray, respectively. Labels of the scalp regions as for Fig. 1. For purposes of comparison, also the approximate electrode location in the 10/20 system is shown.

at study were subsequently visually displayed at test, without new words. The 160 words presented were different for half of the participants.

7.2.3. Procedure and task

The procedure was basically the same as in experiment 1, apart from the following changes. Each experimental session lasted roughly 35–40 min. During the study phase, the task was limited to the gender stereotype judgment only, and so the time used for encoding of each word was decreased (a study trial lasted 4300 ms instead of 5400 ms). These manipulations were designed to increase the number of low-confidence judgments in order to have enough trials per condition (i.e., >15) to allow effective averaging of waves.

Following net placement, participants were seated in front of the stimulus presentation screen with the index fingers of each hand resting on a button. They wore earphones through which the auditory stimuli were presented binaurally. As a considerable number of trials had been discarded in experiment 1 because of ocular artefacts, a different procedure was adopted here. At study, an explicit request 'Blink!' (in Italian: 'Ammicca!') instead of the fixation asterisk appeared for 400 ms at the beginning of each trial and was removed from the screen 400 ms prior to stimulus presentation. During that period, participants had to blink if necessary. This procedure was adopted following guidelines by Picton et al. (2000). Participants were required to maintain their gaze fixed on the center of the screen and to avoid blinks for the rest of the trial. They were asked to relax and to avoid muscular movements as far as possible. Each word was auditorily presented, and a blank screen appeared at the same time and lasted 1400 ms. Following the blank screen period, a question 'Stereotype?' (in Italian: 'Stereotipo?') appeared for 2000 ms. This question prompted the participants to perform the gender stereotype judgment. The instruction for this task was the same as in experiment 1. After a further blank of 100 ms, a new trial began. Participants were aware that all the test visual words would have already been presented auditorily at study. A practice session consisting of 8 items preceded the study phase per se. A short pause was given after each block of 40 trials both during the study phase and during the test phase.

After a short pause of 5 min, during which the status of the net was checked and readjusted if needed, the test phase began. The request 'Blink!' lasting for 400 ms preceded presentation of each word and was removed 400 ms prior to stimulus onset. A test word appeared in the center of the screen for 300 ms followed by the four letters 'MmfF' for 2000 ms. The onset of the word served as the cue for 'voice retrieval', namely the retrieval of the voice in which the word had been presented at study. The voice retrieval responses had to be made on a four-point confidence scale. If the participants were highly confident about their decision, they had to press one of the two external buttons with a middle finger. Instead, if participants were less confident, they had to press one of the two inner buttons using an index finger. In both cases, which button they should press depended on the voice in which they thought the word had been presented. The order of the responses associated with each of the four buttons from leftmost to rightmost was male/high-confidence, male/low-confidence, female/low-confidence, female/high-confidence (reversed for half of the participants). A further blank of 100 ms separated the current trial from the next one. A practice session consisting of 8 items (all old) preceded the test phase per se. The total duration of a test trial was 3200 ms. Voice judgments quicker than 300 ms or slower than 2200 ms were excluded from analyses.

7.2.4. EEG recording

The same settings were used as in experiment 1 for the online recording of the EEG during task execution.

7.2.5. EEG data reduction and analysis

The same criteria were adopted for the data reduction and analyses of the ERPs as in experiment 1. Five participants did not reach the minimal criterion of 15 trials per category when 4 categories were created for a full 2 (confidence) × 2 (accuracy) factorial design. Moreover, the variability in the waveforms across the remaining 12 participants was considerably high[1]. ERPs were therefore averaged twice, dividing trials according to confidence (high- vs. low-confidence) one time, and according to accuracy (hits vs. misses) the other time. The mean numbers of trials used for the analyses of each subject's waveforms were 55, 58, 63, and 50, for the high-confidence responses, low-confidence responses, hits, and misses, respectively. The ERP latency windows analyzed in experiment 2 were different from those analyzed in experiment 1 as the procedure and task adopted were changed.

Acknowledgments

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[1] ERPs of the 12 participants with enough artefact-free trials per category were averaged according to a 2 confidence × 2 accuracy full factorial design. Five-way ANOVAs were conducted on these ERPs, with accuracy (hit vs. miss), confidence (high vs. low), lobe (frontal vs. parietal), side (left vs. right), and region (anterior vs. lateral) as the independent variables, and mean amplitude on selected time-windows (i.e., 500–700, 1000–1500, and 1500–2000 ms) as the dependent variable. These ANOVAs were more conservative than those conducted on ERPs of all the 17 participants averaged separately for confidence and accuracy and reported in the text (see Results experiment 2), as some of the effects detected with the latter analyses were not significant with the full factorial ANOVAs. Critically, the full factorial ANOVAs did not produce any additional interactions between confidence and accuracy. For these reasons, results of these ANOVAs will not be reported.

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