The electrophysiology of subjectively perceived memory confidence in relation to recollection and familiarity

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A B S T R A C T

Subjectively perceived confidence is critically involved in distinguishing recollection from familiarity in episodic memory retrieval. However, the extent to which recollection and familiarity share similar electrophysiological processes associated with subjectively perceived memory confidence remains an open question. In addition, the role of memory encoding in subjectively perceived confidence during retrieval has not yet been investigated. To address these issues, an EEG study was performed in thirty healthy volunteers. During a memory task, participants encoded a subset of words while rating the words on pleasantness. Memory recognition and subjectively perceived confidence concerning these ‘old’ and additional ‘new’ words was tested. Results showed that during retrieval, correctly classifying an old item with high subjectively perceived confidence was associated with a parietal ERP and parietal theta power, while frontal theta activity was related to high-confidence novelty processing. During the memory encoding phase, a parietal ERP and frontal theta oscillations were related to subsequent subjectively perceived memory confidence. Our findings provide the first evidence that subjectively perceived memory confidence is associated with distinct electrophysiological correlates during both memory encoding and retrieval.

1. Introduction

The neural processes involved in subjectively perceived confidence in episodic memories are still largely unknown. In contrast, the neural processes of two phenomena closely related to subjectively perceived memory confidence, recollection and familiarity, have been relatively well explored. Recollection is thought to be associated with an all-or-none process accompanied by high-confident recognition (e.g., Curran, 2004; Yonelinas, 2001, 2002, but see Rugg, Cox, Doyle, & Wells, 1995). Conversely, a continuous process which guides recognition with a variable level of perceived confidence is assumed to be more related to familiarity (Yonelinas, 2001; Yonelinas, Dobbins, Szymanski, Dhaliwal, & King, 1996). On the electrophysiological level, recollection and familiarity are associated with two distinct memory retrieval event-related potentials (ERPs). A posterior positive deflection peaking between 400 and 800 ms, labeled the parietal old/new effect or late positive component, is associated with recollection, and a frontal negative deflection peaking between 300 and 500 ms, labeled the FN400 effect, is related to familiarity (e.g., Curran, 2000; Curran & Cleary, 2003; Friedman & Johnson, 2000; Rugg & Curran, 2007; Tsivilis et al., 2015; Woodruff, Hayama, & Rugg, 2006).

Given the existing interrelations between subjectively perceived memory confidence, recollection, and familiarity, one could speculate that these share a common electrophysiological basis. However, this assumption has not been tested thus far. First, the parietal old/new effect related to recollection resembles the parietal positive-going deflection peaking between 500 and 800 ms that has been linked to high-confident familiarity. (Woodruff et al., 2006; Woroch & Gonsalves, 2010). However, Woodruff et al. (2006) reported that this parietal effect was dissociable from the recollection-related parietal old/new effect. Since this parietal effect was exclusively linked to familiarity judgements, it remains unclear whether the absence of recollection judgements caused the dissociation with the parietal old/new effect. Second, the FN400 related to familiarity seems to resemble the frontal negative deflection peaking between 300 and 500 ms that is associated with subjectively perceived memory confidence (Woodruff et al., 2006; Yu & Rugg, 2010). To our knowledge, no studies have yet addressed the issue whether the FN400 component is actually involved in these different processes.

Importantly, the studies conducted so far have focused mainly on the retrieval phase of memory. Since memory encoding is a crucial condition for successful consolidation and retrieval, it is important to know the extent to which encoding influences memory processes at retrieval. Electrophysiological studies on memory encoding related to
subsequent recollection and familiarity have mainly focused on ERPs and yielded inconsistent results. In a number of studies familiarity-related (Duarte, Ranganath, Winward, Hayward, & Knight, 2004; Mangels, Picton, & Craik, 2001) or recollection-related ERP effects have been demonstrated (Cansino & Trejo-Morales, 2008; Duarte et al., 2004; Friedman & Trott, 2000). Since other studies report mixed findings (Voss & Paller, 2009; Yovel & Paller, 2004) or null-effects (Guo, Duan, Li, & Paller, 2006; Smith, 1993), the role of encoding in recollection and familiarity remains unclear. Also, whether subsequent subjectively perceived memory confidence can be predicted by encoding electrophysiology remains an open question.

In addition to the temporal course associated with the electrophysiological processes of recollection and familiarity, several studies have reported a positive association between theta power (3–8 Hz) during episodic memory retrieval, and recollection (Addante, Watrous, Yonelinas, Ekstrom, & Ranganath, 2011; Gruber, Tsivilis, Giabboni, & Muller, 2008; Guderman & Duzel, 2005; Herweg et al., 2016). These studies focused on time- and phase-locked event-related changes in evoked oscillatory power (Gruber et al., 2008), and changes in time-, but not phase-locked induced oscillatory power (Gruber et al., 2008; Guderman & Duzel, 2005). In general, it is assumed that evoked power is more closely related to bottom-up processes, while induced power is more closely related to top-down processes. (Chen et al., 2012; David, Kilner, & Friston, 2006; Tallon-Baudry & Bertrand, 1999).

Specifically, successful source memory goes accompanied by increased post-stimulus induced theta power (Gruber et al., 2008; Guderman & Duzel, 2005), while post-stimulus evoked theta power differentiated between recollection and familiarity in a remember/know paradigm (Herweg et al., 2016). In addition, pre-stimulus theta power is linked to successful source memory (Addante et al., 2011). However, it is unknown how theta power is related to subjectively perceived memory confidence and familiarity. And whether theta power during encoding is predictive of future recollection, familiarity and subjectively perceived confidence during the retrieval phase.

The present exploratory study set out to examine the electrophysiological correlates related to subjectively perceived memory confidence in the context of recollection and familiarity. Specifically, we expected to find an association between the FN400 and parietal old/new effect, and subjectively perceived memory confidence. Secondly, we anticipated to find an ERP difference during memory encoding that is associated with subsequent subjectively perceived memory confidence during memory retrieval. Thirdly, we explored possible links between theta power during encoding and retrieval, and subjectively perceived memory confidence.

2. Methods

2.1. Participants

Thirty healthy adult volunteers (19 women) with a mean age of 23 (M = 22.82, SD = 3.94) participated in this study. All had normal or corrected-to-normal vision, were right-handed, native Dutch speakers, non-smokers, and were free from any self-reported neurological or psychiatric conditions. Participants were students and former students recruited through the Radboud Research Participation System. All volunteers received ten Euros per hour for participation. The study was approved by the local ethics committee of the faculty of social sciences of the Radboud University and informed consent was obtained from all participants.

2.2. Memory task

Stimuli were presented on a personal computer screen with a 21-inch monitor, approximately 60 cm from the participant. Stimulus presentation and recording of responses were attained using PsychoPy (v1.80; Peirce, 2007). The stimulus material consisted of 900 words randomly chosen from a pool of 1106 words, selected from the MRC Psycholinguistic Database (http://websites.psychology.uwa.edu.au/school/MRCDatabase/uwa_mrc.htm) and translated into Dutch. A unique list of words for encoding and retrieval was randomly generated separately for each participant. All words in this database are scored on word frequency, familiarity, and concreteness, which combined leads to an ‘imageability’ rating between 100 and 700 (Coltheart, 1981). We included only nouns that had a rating of > 550. Words were presented in Arial, with a height of one cm, centrally, in white on a grey background.

2.3. Procedure

Upon arrival at the laboratory, all volunteers gave written informed consent and were screened for eligibility to participate in EEG studies. Participants were excluded from participation if they had a history of neurological or psychiatric disease, used psychoactive medication or substances, or were pregnant.

EEG signals were recorded and amplified with a BioSemi ActiveTwo system (BioSemi B.V., Amsterdam) from 32 Ag-AgCl-tipped electrodes, according to the International 10–20 System. Additionally, reference electrodes were placed bilateral on each mastoid, and bipolar electrooculogram (EOG) recordings were obtained from electrodes placed one cm lateral of the outer canthi, and above and below the left eye. Each active electrode was measured online with respect to a Common Mode Sense (CMS) active electrode. The combination of the CMS electrode and Driven Right Leg (DRL) passive electrode ensures that the CMS electrode stays as close as possible to the reference voltage at the analogue-to-digital converter. During acquisition, electrode offset was kept below 35 mV. The EEG signal was pre-amplified at the electrode to improve the signal-to-noise ratio, amplified with a gain of 16 ×, and digitized at a 24-bit resolution with a sampling rate of 1024 Hz.

In the intentional encoding phase of the memory task, trials began with a one-second centrally presented fixation cross, followed by a two-second presentation of a word. Each participant performed 450 encoding trials, while making a semantic classification (‘pleasant’ or ‘unpleasant’) regarding the presented word. The semantic classification of the stimuli ensured that participants kept attending to the presented stimuli and deepened encoding. When the encoding phase was completed, after a delay of approximately five minutes in which participants were instructed to the task, the retrieval phase began.

In the retrieval phase, participants performed a recognition task, including all 450 ‘old’ words presented during encoding and 450 ‘new’ words. In total, each participant performed 900 fixed-paced recognition trials, which started with a one second fixation cross, followed by a two second presentation of a word. During word presentation, participants classified the item as ‘old’ or ‘new’. Following the response, participants rated their subjectively perceived confidence of this ‘old/new’ classification on a 3-point scale (Yonelinas et al., 1996; see Fig. 1). The arrow keys were used to register the participants’ responses. During the encoding phase, the left arrow corresponded to ‘pleasant’ and the right to ‘non-pleasant’ responses. During retrieval the left and right arrows indicated ‘old’ and ‘new’ responses, respectively. For the confidence judgement the left arrow was used for ‘not sure’, the down arrow for ‘a bit sure’ and the right arrow for ‘definitely sure’ responses. Participants were instructed to use only their left or right index finger, which was determined in a randomized and counterbalanced manner.

A practice session with twenty trials preceded both the encoding and retrieval phase of the experiment, to familiarize participants with the upcoming task. Stimuli used in the practice sessions were not used in the experimental trials.

EEG recordings were made during performance of the task. Following every 150 experimental trials there was a short break of at least one minute, resulting in 25 min of encoding and 75 min of retrieval. After the memory task, volunteers were debriefed and received compensation for participation.
2.4. Data analyses

Two participants were excluded from data analyses due to technical problems with recording (n = 1) and fatigue (n = 1). Data analyses were performed with the use of MATLAB (v2015b, MathWorks Inc., Natnick MA) in combination with the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011).

2.4.1. Memory performance

Recollection and familiarity estimates were calculated using the ROC toolbox for MATLAB (Koen, Barrett, Harlow, & Yonelinas, 2016). Global memory performance was quantified by d-prime ($d'$), which was calculated using the following formula:

$$d' = Z(\text{hit rate}) - Z(\text{false alarm rate})$$

Trials in which participants indicated the highest level of subjectively perceived confidence were used as ‘high-confident’ trials, and trials in which participants indicated one of the two lowest levels of subjectively perceived confidence were combined into ‘low-confident’ trials. In order to look at subsequent memory effects, encoding trials were relabelled according to memory condition: high-confident hits, low-confident hits, and misses.

Trials in which participants failed to respond during either the encoding trial or the retrieval trial of a corresponding item were removed from further analyses (on average 9.5% of encoding trials and 8.7% of retrieval trials).

2.4.2. EEG pre-processing

EEG data were referenced off-line to the average of the mastoid electrodes and band-pass filtered between 0.1 and 30 Hz (roll off: 60 dB/oct). Stimulus-locked epochs (~1000 to 2000 ms) were extracted for encoding and retrieval trials. In addition, trials with transient muscle or electrode artifacts were rejected based on visual inspection. Ocular artifacts were removed using the default independent component analysis (ICA) in the Fieldtrip toolbox. This performs ICA on the data with the use of the logistic infomax ICA algorithm of Bell and Sejnowski (1995) supplemented by the natural gradient feature of Amari, Cichocki, and Yang (1996). With the use of this ICA, components that contained ocular artifacts were identified by inspecting the time course and spatial topography of all components. After ICA components that contained ocular artifacts were removed, remaining muscle and non-neurogenic artifacts were rejected by a second visual inspection of the data, leaving on average: 216 subsequent high-confident hit, 51 subsequent low-confident hit, 61 subsequent miss, 223 high-confident hit, 53 low-confident hit, 63 miss, 100 false alarm, 123 high-confident correct rejection, and 126 low-confident correct rejection trials. Following previous studies that found frontal and parietal activity related to subjectively perceived memory confidence, recollection, and familiarity, we examined the frontal (i.e., F3, Fz, F4) and parietal electrodes (i.e., P3, Pz, P4; Burgess & Ali, 2002; Friedman & Johnson, 2000; Gruber et al., 2008; Woodruff et al., 2006; Woroch & Gonsalves, 2010).

2.4.3. Event-related potentials

To identify the subjectively perceived memory confidence ERP components, stimulus-locked ERPs were computed for all trial types. Encoding and retrieval ERPs were baseline-corrected by subtracting the average offset during the −200 to 0 ms pre-stimulus window. Subsequent analyses focused on mean frontal ERP amplitudes in the 300–500 ms time window and mean parietal ERP amplitudes in the 400–800 ms time window. These time windows were selected according to the time course of the FN400 and the parietal old/new effect, as found in previous studies (Curran & Cleary, 2003; Curran, 2000; Friedman & Johnson, 2000; Rugg & Curran, 2007).

2.4.4. Time-frequency analyses

Spectral power was extracted using Fourier analysis with sliding time windows (5 ms steps) and the application of the multi taper method based on Hanning tapers (Jiang, Bahramisharif, van Gerven, & Jensen, 2015; Leenders, Lozano-Soldevilla, Roberts, Jensen, & De Weerd, 2018; Mitra & Pesaran, 1999; Percival & Walden, 1993; Staudigl, Hartl, Noachtar, Doeller, & Jensen, 2017). Frequencies that were assessed ranged from 1 to 29 Hz, in 2 Hz steps, with a 500 ms time window length for each frequency. To be able to relate our findings to these previous studies, we performed separate analyses on evoked and induced oscillatory power. Specifically, we looked at evoked power by means of spectral decompositions of the averaged evoked response. Induced power was calculated by subtracting the evoked response from each trial before time-frequency analyses (Gruber et al., 2008; Roach & Mathalon, 2008) enabling us to look at the power of the averaged response (i.e., evoked power) and residual power that relates to general task-related activity (i.e., induced power; David et al., 2006). To examine the frequencies underlying the ERP effects, further analyses focused on mean frontal evoked theta (3–7 Hz) power during the 300–500 ms time window, and the mean parietal evoked theta power during the 400–800 ms time window. These time windows were selected to match the timing of the FN400 and parietal old/new effects. Regarding induced theta power, analyses focused on the stimulus presentation time window that showed effects related to recollection and familiarity (i.e., 300–800 ms).
2.5. Statistical analyses

To test for significant differences in ERPs and spectral power between conditions, general linear models (GLMs) for repeated measurements were used (two-tailed throughout). The within-subject variable was ‘condition’, with three levels for encoding (subsequent high-confident hit, subsequent low-confident hit, subsequent miss) and six levels for retrieval (high-confident hit, low-confident hit, miss, false alarm, low-confident correct rejection, high-confident correct rejection). In case the sphericity assumption was violated, Greenhouse-Geisser corrected p-values are reported. Effect sizes (partial eta-squared; $\eta^2_p$) were computed for all analyses. When the GLM was significant, post-hoc tests were performed using Fisher’s least significant difference procedure. Post-hoc tests were performed separately for ‘old’ and ‘new’ conditions. Alpha level of significance was set at 0.05 (two-tailed).

3. Results

3.1. Behavioural performance

An average d-prime of 1.29 ($SD = 0.57$), with a mean hit rate of 0.80 ($SD = 0.12$) and a false alarm rate of 0.37 ($SD = 0.14$) was found. The average estimated recollection score was 0.48 ($SD = 0.17$) and the average estimated familiarity score was 0.81 ($SD = 0.46$).

3.2. EEG: Retrieval phase

3.2.1. Parietal old/new effect

A significant main effect of condition was observed ($F(5, 135) = 4.17, p = .006, \eta^2_p = 0.13, \varepsilon = 0.69$; see Fig. 2). Post-hoc tests revealed that specifically high-confident hits resulted in higher amplitudes (see Table 1), which suggest that there is a subjectively perceived confidence effect that is specific to the successful retrieval of words.

3.2.2. Parietal oscillatory power

For evoked theta power a main effect of condition was found ($F(5, 135) = 6.19, p = .006, \eta^2_p = 0.19, \varepsilon = 0.35$). Post-hoc tests showed that theta power was strongest in high-confident hits and high-confident correct rejections (see Table 1 and Fig. 3). Induced parietal theta power showed a marginally significant difference between conditions ($F(5, 135) = 2.36, p = .063, \eta^2_p = 0.080, \varepsilon = 0.74$; see Table 1 and Fig. 4).

3.2.3. FN400

The main effect of condition was significant ($F(5, 135) = 6.40, p < .001, \eta^2_p = 19, \varepsilon = 0.67$; see Fig. 2). Post-hoc tests revealed that specifically high-confident correct rejections resulted in more negative amplitudes (see Table 2). Additionally, a larger negative amplitude for high-confident hits as compared to low-confident hits was found (see Table 2). These results suggest a subjectively perceived confidence effect independent of retrieval of stored memories.

3.2.4. Frontal oscillatory power

Evoked theta power differed significantly between conditions ($F(5,
Table 1
Post-hoc comparisons regarding the retrieval phase and parietal electrodes. Statistical significant comparisons are indicated in bold.

| Comparison                                | Mean difference [95% CI] | P-value |
|-------------------------------------------|--------------------------|---------|
| **Event-related potentials**              |                          |         |
| High-confident hits − low-confident hits | 0.81 [0.009 1.62]        | 0.048   |
| High-confident hits − misses              | 0.91 [0.041 1.41]        | 0.004   |
| Low-confident hits − misses               | 0.094 [−0.65 0.84]       | 0.80    |
| High-confident correct rejections − low- | −0.11 [−0.63 0.41]       | 0.67    |
| High-confident correct rejections − false alarms | −0.35 [−0.97 0.28]     | 0.27    |
| Low-confident correct rejections − false alarms | −0.24 [−0.70 0.23]     | 0.31    |
| **Evoked power**                          |                          |         |
| High-confident hits − low-confident hits | 0.23 [0.019 0.44]        | 0.034   |
| High-confident hits − misses              | 0.22 [0.040 0.39]        | 0.018   |
| Low-confident hits − misses               | −0.011 [−0.11 0.82]      | 0.088   |
| High-confident correct rejections − low- | 0.47 [0.09 0.85]         | 0.018   |
| High-confident correct rejections − false alarms | 0.58 [0.21 0.95]       | 0.004   |
| Low-confident correct rejections − false alarms | 0.11 [−0.002 0.23]     | 0.055   |
| **Induced power**                         |                          |         |
| High-confident hits − low-confident hits | 0.78 [0.36 1.21]         | 0.001   |
| High-confident hits − misses              | 0.21 [−0.24 0.66]        | 0.34    |
| Low-confident hits − misses               | −0.57 [−1.14 0.50]       | 0.050   |
| High-confident correct rejections − low- | 0.21 [−0.38 0.81]        | 0.47    |
| High-confident correct rejections − false alarms | −0.047 [−0.60 0.50]     | 0.86    |
| Low-confident correct rejections − false alarms | −0.26 [−0.88 0.36]     | 0.39    |

Fig. 3. Evoked power changes during retrieval. (A) Evoked parietal theta power during 400–800 ms post stimulus onset. The topographical distribution represents the difference in power between high- and low-confident hits. (B) Evoked frontal theta power during 300–500 ms post stimulus onset. The topographical distribution represents the difference in power between high- and low-confident correct rejections. HitHC = high-confident hit, HitLC = low-confident hit, FA = false alarm, Miss = miss, CRLC, low-confident correct rejection, CRHC = high-confident correct rejection.

Fig. 4. Induced power changes during retrieval. (A) Induced parietal theta power during 300–800 ms post stimulus onset. The topographical distribution represents the difference in power between high- and low-confident hits. (B) Induced frontal theta power during 300–800 ms post stimulus onset. The topographical distribution represents the difference in power between high- and low-confident correct rejections. HitHC = high-confident hit, HitLC = low-confident hit, FA = false alarm, Miss = miss, CRLC, low-confident correct rejection, CRHC = high-confident correct rejection.

135) = 4.99, $p = .008$, $\eta^2_p = 0.16$, $\xi = 0.44$. Post-hoc tests revealed that high-confident correct rejections showed the highest evoked theta power (see Table 2 and Fig. 3), indicative for a subjectively perceived novelty confidence effect. No main effect of condition on induced frontal theta power was found ($F(2, 135) = 1.22, p = .31$, $\eta^2_p = 0.043$, $\xi = 0.68$; see Table 2 and Fig. 4).

3.3. EEG: Encoding phase

3.3.1. Parietal ERP
Analysis showed a significant main effect of condition ($F(2, 54) = 3.23, p = .047$, $\eta^2 = 0.11$, $\xi = 0.90$; see Fig. 2). Post-hoc tests revealed that there was a higher amplitude in high-confident hits, as compared to both low-confident hits ($M_{diff} = 0.58$, 95CI = 0.044–1.11, $p = .035$) and misses ($M_{diff} = 0.53$, 95CI = 0.10–0.96, $p = .017$). No difference was observed between low-confident hits and misses ($M_{diff} = 0.043$, 95CI = −0.62 – 0.54, $p = .88$). The results show that this encoding parietal old/new is sensitive to subsequent memory (DM) effects (Paller, Kutas, & Mayes, 1987) related to subjectively perceived confidence.

3.3.2. Parietal oscillatory power
Both evoked ($F(2, 54) = 1.42, p = .25$, $\eta^2_p = 0.050$, $\xi = 0.89$) and induced ($F(2, 54) = 3.45, p = .054$, $\eta^2_p = 0.11$, $\xi = 0.75$) theta power were not significantly influenced by memory condition.

3.3.3. Frontal ERP
No effects were found on the amplitudes ($F(2, 54) = 0.20, p = .82$, $\eta^2_p = 0.007$, $\xi = 0.88$; see Fig. 2).

3.3.4. Frontal oscillatory power
No main effect of condition on evoked frontal theta power was observed ($F(2, 54) = 0.58, p = .56$, $\eta^2_p = 0.021$, $\xi = 0.84$). Induced
frontal theta power showed a significant main effect of condition ($F(2, 54) = 4.29, p = .019, \eta_p^2 = 0.14, \, \varepsilon = 0.94$). Post hoc tests revealed that induced theta power was stronger in high- as compared to low-confident hits ($M_{AGG} = 1.00, 95\% CI = 0.26–1.75, p = .001$) and misses ($M_{AGG} = 1.10, 95\% CI = 0.17–2.02, p = .022$). Induced frontal theta power was thus positively related to subsequent subjectively perceived memory confidence. This indicates that already at the encoding phase, high-confidence trials show a distinct electrophysiological pattern as compared to low-confidence hits. Induced theta power did not differentiate between low-confidence hits and misses ($M_{AGG} = 0.090, 95\% CI = −0.78–0.97, p = .83$). Finally, the frequency specificity of the theta power effects was confirmed by analyses showing that no effects were found for alpha (9–13 Hz) power (all $p$-values > .19).

4. Discussion

4.1. Retrieval

4.1.1. Parietal ERP

In line with previous studies (Woodruff et al., 2006; Woroch & Gonsalves, 2010), our results show that in particular high-confidence hits are associated with a positive wave over the parietal electrodes between 400 and 800 ms after stimulus onset. Since recollection often is accompanied by higher levels of confidence, this effect could be due to recollection-related processes. However, since Woodruff et al. (2006) showed a similar parietal effect with familiarity-based responses only, we speculate that subjectively perceived confidence plays a large role in parietal effects, irrespective of recollection and familiarity judgements.

4.1.2. Frontal ERP

Additionally, the largest frontal negative deflection in the 300–500 ms time window was seen in high-confidence correct rejections and replicates previous studies (Woodruff et al., 2006; Yu & Rugg, 2010). However, in contrast to reports of greater negativity for low-confidence familiarity as compared to high-confidence familiarity (Woodruff et al., 2006; Yu & Rugg, 2010), we found greater negativity for high-confidence hits as compared to low-confidence hits. Since our participants were not explicitly asked to differentiate between recollection and familiarity in their high-confidence responses, their responses could rely on both recollection and familiarity processes. This may also account for the discrepancy between the previous and our present results. The larger negativity for high-confidence ‘old’ and ‘new’ responses, as compared to the low-confidence responses, is in support of the view that the FN400 reflects subjectively perceived confidence. In addition, although not formally tested, the items classified as new seem to elicit greater brain responses than items classified as old. This might indicate that the FN400 effect represents an interaction between a memory effect and a confidence effect, and could perhaps explain why the amplitude for high-confidence hits does not appear to exceed that of low-confidence correct rejections.

4.1.3. Parietal oscillatory power

As for effects in the frequency domain, the expected relation between theta power and subjectively perceived memory confidence was found. Parietal evoked theta power was strongest during high-confidence hits and high-confidence correct rejections. This finding suggest that parietal evoked theta power is more closely related to subjectively perceived memory confidence and less to the retrieval of stored memories. In a previous study it was suggested that the increase in theta power during recognition is related to processes involved in making memory decisions which are independent of the retrieval success of stored memories (Klimesch et al., 2001). In agreement, the study by Herweg et al. (2016) also showed no difference in theta-alpha (4–13 Hz) power range between recollected trials and confident correct rejection trials. In sum, these studies suggest that theta power is related to decision-making processes, which has been shown before in other cognitive domains (Cohen et al., 2009; Rawle, Miall, & Praamstra, 2012; Womelsdorf, Vinck, Leung, & Everling, 2010).

In contrast, our results show that parietal induced theta power seems to be more closely related to memory retrieval processes, given the difference in parietal induced theta power between high- and low-confidence hits. These results concur with previous studies that have shown a link between induced theta power, and accurate source memory (Gruber et al., 2008) and the temporal order of episodic memory representations (Nyhus & Curran, 2010).

In sum, the functional role of evoked and induced parietal theta power appear to be dissociable, with evoked theta being related to subjectively perceived confidence and induced theta being related to memory retrieval processes.

4.1.4. Frontal oscillatory power

While parietal evoked theta power was related to subjectively perceived confidence for both old and new items, frontal evoked theta
power was exclusively associated with subjectively perceived confidence related to novel items, as evidenced by an increased frontal evoked theta power during high-confident correct rejections. This adds to the previously reported link between novelty-related processes and frontal evoked theta power (Demiralp, Ademoglu, Comerchero, & Polich, 2001; Fallah-Ellis et al., 2010).

4.2. Encoding

In addition to the processes underlying the electrophysiological correlates of subjectively perceived confidence during memory retrieval, the electrophysiological processing during the memory encoding phase contributes to the subsequent subjectively perceived memory confidence. Subsequent high-confident hits were linked to a higher parietal ERP amplitude in the 400–800 ms time window and higher induced frontal theta power during encoding. Prior studies have demonstrated associations between parietal ERP amplitude and frontal theta power during encoding, and subsequent memory performance (Dockree, Brennan, O’Sullivan, Robertson, & O’Connell, 2015; Friedman & Johnson, 2000; Friese et al., 2013; Klimesch, Doppelmayr, Schimke, & Ripper, 1997; Osipova et al., 2006; White et al., 2013). Our results add to these findings and suggest that subjectively perceived confidence plays a significant role during the encoding and retrieval phase. We speculate that the encoding parietal old/new effect might be more closely related to subjectively perceived memory confidence, rather than recollection per se. This may possibly also explain the mixed literature regarding encoding ERPs and subsequent recollection (Cansino & Trejo-Morales, 2008; Duarte et al., 2004; Friedman & Trotz, 2000; Guo et al., 2006; Mangels et al., 2001; Smith, 1993; Voss & Paller, 2009; Yovel & Paller, 2004).

4.3. Limitations

Several limitations of this study need to be considered. First, due to the exploratory nature of our analyses no corrections for multiple comparisons were applied, therefore observed effects should be interpreted with caution. However, we adopted a theory-driven and hierarchical approach by first doing an omnibus analysis before interpreting subsequent post-hoc tests relevant for our research questions. Second, we utilized a time-limited response window for the participants of two seconds for the ‘old/new’ decision and 1.5 s for the subjectively perceived confidence judgement. Even though, this time-pressure could have influenced the strategy used by the participants, our results are in line with results from previous studies. Third, we did not correct for guessing by having a separate guess response option. However, participants had a ‘not sure’ option in the subjectively perceived confidence judgement. Given the low rate of ‘not sure’ and ‘a bit sure’ responses, we chose to collapse these two response categories into the low-confident hit condition.

4.4. Conclusion

In conclusion, our study provides evidence that subjectively perceived memory confidence is associated with dissociable neural processes during both memory encoding and retrieval.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandc.2018.07.003.

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