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Research report

Neural correlates of judgments of learning – An ERP study on metacognition

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ABSTRACT

Metacognitive assessment of performance has been revealed to be one of the most powerful predictors of human learning success and academic achievement. Yet, little is known about the functional nature of cognitive processes supporting judgments of learning (JOLs). The present study investigated the neural underpinnings of JOLs, using event-related brain potentials. Participants were presented with picture pairs and instructed to learn these pairs. After each pair, participants received a task cue, which instructed them to make a JOL (the likelihood of remembering the target when only presented with the cue) or to make a control judgment. Results revealed that JOLs were accompanied by a positive slow wave over medial frontal areas and a bilateral negative slow wave over occipital areas between 350 ms and 700 ms following the task cue. The results are discussed with respect to recent accounts on the neural correlates of judgments of learning.

1. Neural correlates of judgments of learning – An ERP study on metacognition

Metacognitive skills are a powerful predictor of academic achievement (Schneider, 2008; Wang et al., 1990; Winne, 1996) and have become an integral component in theories of self-regulated learning (e.g., Zimmerman, 1986). Concerning the underlying basis, metacognition includes a variety of mechanisms that might, among others, play a role in both memory and metamemory judgments (e.g., Koriat, 1997). Therefore, neuroscientific research aims to shape psychological theory on metacognition by improving our understanding of the neural processes that underpin metacognitive components such as memory monitoring (e.g., Fleming and Frith, 2014). Metacognitive monitoring can be captured through Judgments of Learning (JOLs) in which individuals have to predict their future memory performance (Koriat, 1997; Nelson and Narens, 1990). While behavioural studies on JOLs are widely available in the literature (Koriat et al., 2014, 2006; Nelson and Dunlosky, 1991; Paulus et al., 2014; Thiede and Dunlosky, 1994), research on the underlying neural correlates of such judgments is scarce. In the present study, we used event-related potentials (ERPs) to investigate the neural signature of cognitive processes that support JOLs.

These judgments require from individuals to reflect on their own internal thoughts. Different processes have been suggested to inform these judgments. It is possible that when making a JOL, learners try to directly access their current memory and monitor the strength of the memory representation in order to make a predictive judgment about their future memory performance (e.g., Nelson and Dunlosky, 1991; Spellman and Bjork, 1992). However, increasing evidence seems to support the view that in addition to monitoring memory traces, people use inferential processes and evaluate available cues such as fluency and ease of processing to form these judgments (Koriat, 1997). For neuroscientific research, the latter finding implies that these meta-processes are dissociable from mere memory processes, and indeed, both neuropsychological studies as well as functional magnetic resonance imaging (fMRI) studies have suggested at least partially independent processes for JOLs and memory (e.g., Kennedy and Yorkston, 2000; Ries et al., 2012; Roberts et al., 2009; Vilkki et al., 1999). For example, patients with lesions to the frontal cortex tended to show impaired global JOLs but intact memory for the location of faces, while patients with lesions to the posterior cortex tended to have intact global JOLs but impaired memory for the location of faces (Roberts et al., 2009). These findings could be replicated using word list learning paradigms (Ries et al., 2012), and together suggest that the frontal

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cortex plays a critical role in JOLs. Furthermore, fMRI research demonstrates the importance of the ventro-medial and dorso-medial prefrontal cortex, orbital frontal, and anterior cingulate cortices (e.g., Do Lam et al., 2012; Kao et al., 2005; Miele et al., 2011; Schmitz et al., 2004), showing higher activation of these areas for JOLs than for memory encoding. Interestingly, these studies also demonstrate a strong task-sensitivity for JOLs. While participants in one study had to make JOLs on photographs of visual scenes (e.g., a sunset) for eventual recognition (Kao et al., 2005), participants in the second study had to make JOLs about photographs of faces for eventual cued recall of names (Do Lam et al., 2012). Whereas activity in the orbital frontal and anterior cingulate cortices was only found for the cued recall of names, the ventromedial prefrontal cortex appears to be common in both studies. Taken together, these studies indicate that JOLs related processes are distinguishable from memory processes.

Despite the extensive JOLs and memory literature using patient samples, behavioural, and fMRI measures, surprisingly only a few studies used ERPs to investigated the temporal resolution of JOLs in humans. A number of EEG studies were conducted that found JOL to be reflected in positive event-related brain potentials over frontal and central areas, sometimes accompanied by a posterior occipital negativities (Skavhaug et al., 2010, 2013; Skavhaug, 2010; Sommer et al., 1995). Interestingly, Skavhaug et al. (2010, 2013) suggested that JOLs might be distinguished from processes supporting memory encoding. Using a word-learning paradigm, they found both JOLs (high vs. low) and memory encoding (recall vs. miss) to be associated with a positive going brain potential between 550–1000 ms, while in a later time-window between 1300 and 1900 ms JOL was found to be uniquely associated with a negative-going potential over left central regions. The authors therefore proposed that especially late neural responses associated with JOLs may be distinguished from memory processes.

These findings are highly informative for our understanding of the neurocognitive correlates of metacognition. To try and further dissociate the neurocognitive processes underlying metacognition from processes supporting stimulus processing and encoding, we designed a new paradigm that differs from previous studies in several ways: Importantly, in contrast with earlier studies (e.g., Skavhaug et al., 2010), ERPs in the current study were calculated in response to a task cue instead of to the stimulus pair that needs to be remembered. With this new paradigm it is possible to explore ERP correlates of JOLs independently from electrophysiological components associated with stimulus processing and memory encoding. Furthermore, instead of contrasting high vs. low JOLs trials and/or remembered and not-remembered items, the design of the current study compared JOL with a memory control condition. More specifically, in the present study, participants studied a series of cue-target picture pairs and were asked how likely, if presented with the cue, they would be to remember the target at a later time. ERPs related to JOLs were compared to a memory related decision-making condition with similar visual input and similar response requirements as in the JOLs condition, but without the requirement to estimate one's subsequent memory performance. In the control condition participants were presented with a cue asking them to indicate if the colour yellow had been present in the picture pair. Based on the results of earlier studies (Skavhaug et al., 2010, 2013; Skavhaug, 2010; Sommer et al., 1995), we expected JOL cues to generate activation over frontal and posterior sites relative to colour cues.

2. Results

2.1. Behavioural results

As most participants made no mistakes in the recognition phase, no statistical analysis of recognition performance was conducted.

Results of the recall condition indicated that participants correctly remembered an average of 55.26 out of 60 items (*SD*=5.58, Median=58), with 83.3% of the participants making less than 10 mistakes during this phase. Correct responses were above chance level for all participants for the recall phase.

Table 1
Distribution of means and standard deviations (SD) of JOLs scored during the learning phase.

	Very unsure	Unsure	Do not know	Sure	Very sure
Mean JOLs	2.16	7.11	10.33	19.50	21.00
SD	2.99	5.27	5.35	8.99	14.34

We used the JOLs gathered during ERP recording to determine metacognitive ability at an individual level through the construction of type II receiver operating characteristic (ROC) curves (Fleming et al., 2010). We found variation across individuals in metacognitive ability (*Aroc*=.34 to 1, *M*=.73; proportion correct: 70–100%, *M*=92.11%). See Table 1 for the distribution of the JOLs.

In the control condition, participants on average correctly indicated that the colour yellow was present in 48.94 out of 60 items (*SD*=6.55, Median=51) during the learning phase. The better participants could indicate whether the colour yellow was present in the control trials, the more likely it was that they made correct JOL judgments in the metamemory trials, Pearson's r =.662, p=.003.[1]

2.2. ERP results

2.2.1. Main analyses: JOLs versus control condition

The grand average waveforms elicited in the MC and CO conditions are depicted in Fig. 1 for frontal and posterior electrodes. The topography of the differences between MC-CO is portrayed in Fig. 2. In addition, we used current source density (CSD) to inform possible underlying sources of voltage spline maps, see Fig. 3. ERPs in the MC condition showed a positive slow wave over medial anterior-frontal sites, starting around 300 ms, relative to the CO condition. Over posterior parietal and occipital electrodes a reversed pattern was found, showing a widely distributed bilateral negative slow wave for the MC condition relative to the CO condition. CSD mapping of frontal and posterior effects supports the interpretation of separate sources in frontal and posterior regions, and argues against a single source of neural activation that is responsible for these effects.

A repeated measures ANOVA with condition (MC, CO), hemisphere (right, left) and site (frontal, fronto-central, central, centro-parietal, posterior) as within subject factors revealed a significant interaction between condition and site between 300 ms and 700 ms following the cue ($F's(1,17) > 3.27$, $p's < .047$). The interaction between site and condition was interpreted to reflect opposite effects of condition over frontal and posterior sites. A confirmatory repeated measures ANOVA with condition (MC, CO), site (frontal vs. posterior), and hemisphere (right, left) was run which revealed a significant interaction effect between condition and site between 350 ms and 700 ms following cue onset, $F's(1,17) > 5.72$, $p's < .030$. Step-down comparisons per site revealed a significant main effect of condition for frontal electrodes between 500 ms and 700 ms following cue onset, $F's(1,17) > 7.28$, $p's < .015$, reflecting the more positive ERPs over medial frontal sites in the MC condition relative to the CO condition. For posterior electrodes the effect of condition was found significant from 300 ms until 650 ms after cue onset, $F's(1,17) > 4.95$, $p's < .050$, reflecting more negative ERPs over occipital sites in the MC condition relative to the CO condition.

[1] Note: We separated the cue stimuli (ERP event) from the response stimuli to prevent motor preparation and motor artefacts in the ERP event. Therefore, Reaction times of JOL and control trials were not compared, as decisions were already made during cue presentation. Thus, interpretation of the RTs is not meaningful.

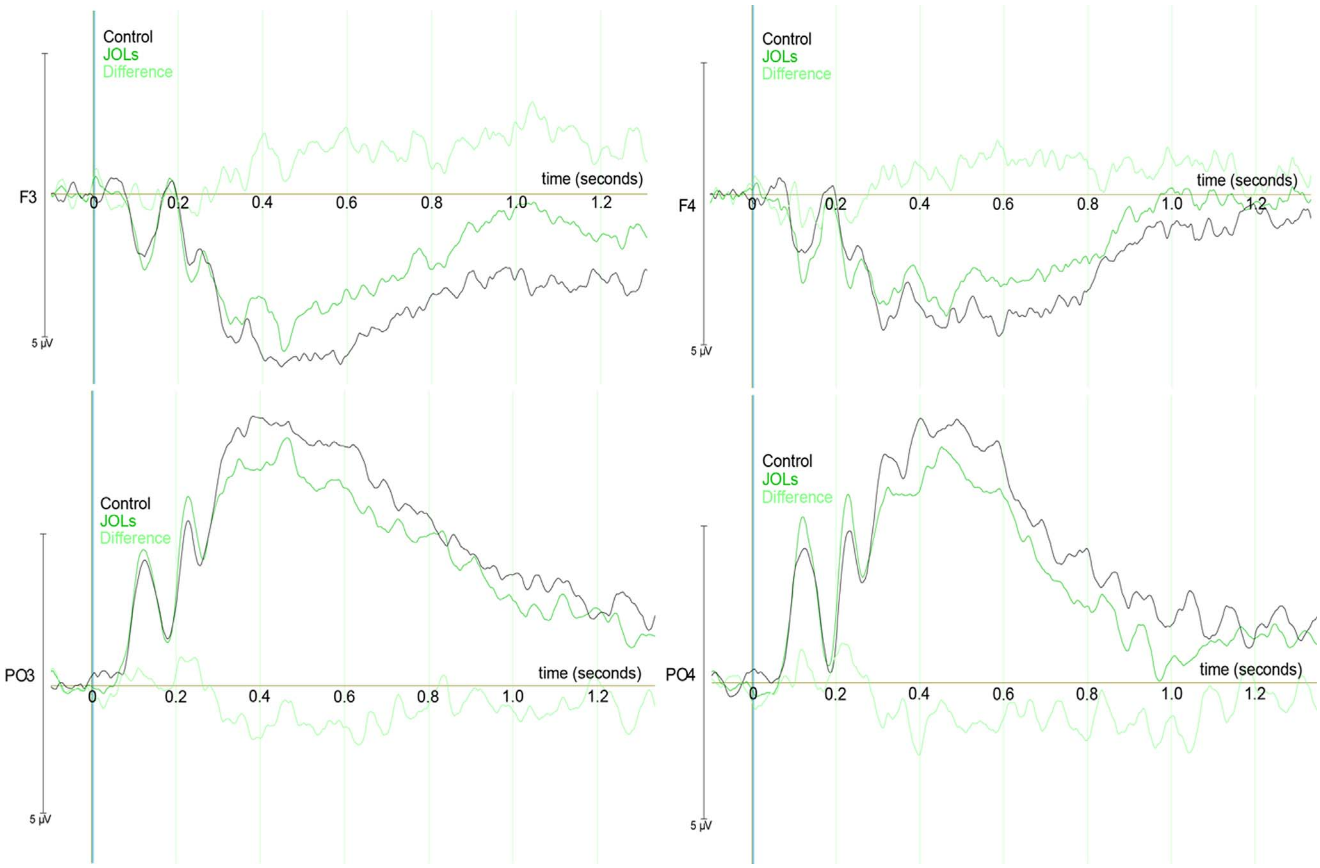

Fig. 1. Grand average ERP waveforms at selected electrodes; frontal (F3, F4) and posterior (PO3, PO4) electrodes are depicted. Positive voltage is depicted upwards. The gray line represents the control (CO) condition, the dark green line represents the JOL condition (MC) and the light green line the difference between the MC and CO conditions. A significant difference between MC and CO conditions was found between 350–700 ms.

2.2.2. Exploratory analyses: low versus high JOLs

To further explore these frontal and posterior effects during JOLs, we divided the trials of the MC condition into high JOLs (i.e., participants responded that they were sure or very sure to remember the right picture when only presented with the left picture) and low JOLs (i.e., participants responded that they did not know, were unsure, or very unsure to remember the right picture when only presented with the left picture). Participants with at least 10 artefact free trials per condition were included in the analyses (N=10). Because of the low N, we used a criterion of $p < .10$, and a minimum of three consecutive intervals significant at this level to explore differences between high and low JOL. Note that because of the requirement of having three consecutive intervals significant, any overall effect still adheres to the significance level of .05, with the chance of such an effect being .026 (i.e., $26 \times .05 \times .05 \times .05$).

The grand average waveforms elicited in the high and low JOLs are depicted in Fig. 4 for frontal and posterior electrodes. The topography of the differences between low JOL and high JOL is portrayed in Fig. 5. To confirm the functional involvement of the medial frontal positivity and posterior bilateral negativity in JOL, a repeated measures ANOVA with condition (high JOL, low JOL), hemisphere (right, left) and site (frontal, posterior) was conducted. Results revealed an interaction effect between condition and site between 550 ms and 700 ms following cue onset, $F's(1,9) > 4.49$, $p's < .063$, and between 1000 ms and 1200 ms following cue onset, $F's(1,9) > 4.72$, $p's < .058$. Step-down comparisons per site revealed a significant main effect of condition for frontal electrodes between 550 ms and 700 ms following cue onset, $F's(1,9) > 8.24$, $p's < .018$, and between 1000 ms and 1200 ms following cue onset, $F's(1,9) > 10.96$, $p's < .009$, with low JOLs eliciting significantly more positive waveforms than high JOLs. No significant effects were found for posterior electrodes, all $p's > .05$.

2.2.3. Exploratory analyses: comparing slow wave components

To explore whether the distribution of the slow wave effects of MC versus CO and low versus high JOLs differs (see van Elk et al., 2010, for a similar procedure), a repeated-measures ANOVA with site (frontal, posterior), hemisphere (right, left) and contrast (Low–High JOLs, MC-CO) was conducted, using a criterion of $p < .10$, and a minimum of three consecutive intervals significant at this level. Results revealed an main effect of site between 300 ms and 450 ms following cue onset, $F's(1,9) > 3.89$, $p's < .080$, between 550 ms and 700 ms following cue onset, $F's(1,9) > 7.98$, $p's < .020$, and between 1000 ms and 1200 ms following cue onset, $F's(1,9) > 5.09$, $p's < .051$. Most importantly, no significant interactions between contrast and site were found, indicating similar activation pattern for both contrasts.

3. General discussion

The goal of the present ERP study was to investigate the neural correlates of cognitive processes that support JOLs. To this end, we compared JOLs with a memory based colour judgment within one paradigm. Interestingly, ERP results showed a clear pattern of slow wave effects over frontal and posterior areas, starting at 350 ms until 700 ms after stimuli onset. Over frontal regions, MC was found to be accompanied by a more positive slow wave compared to the CO condition, while over posterior areas, MC was found to be accompanied by a more negative slow wave compared to the CO condition. Thus, our findings expand the knowledge on the neural signature of cognitive

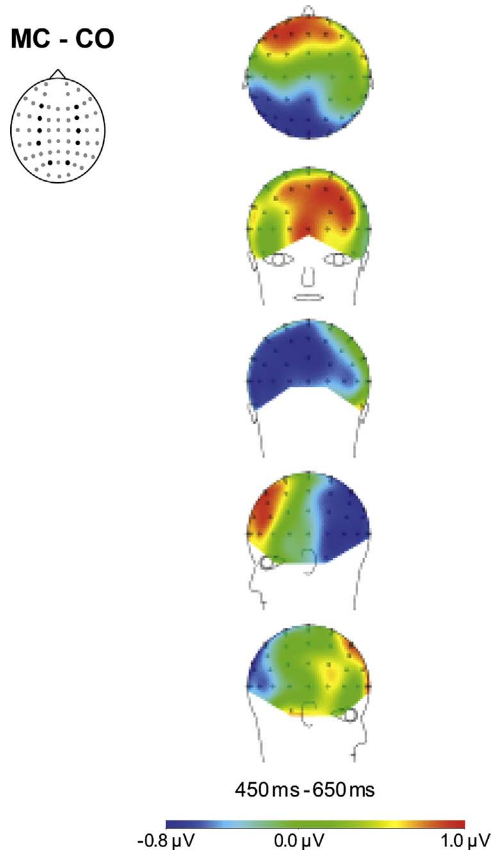

Fig. 2. Topographic voltage maps of mean amplitude differences (MC minus CO). JOLs were associated with stronger positivity over the frontal regions, and stronger negativity over the posterior regions.

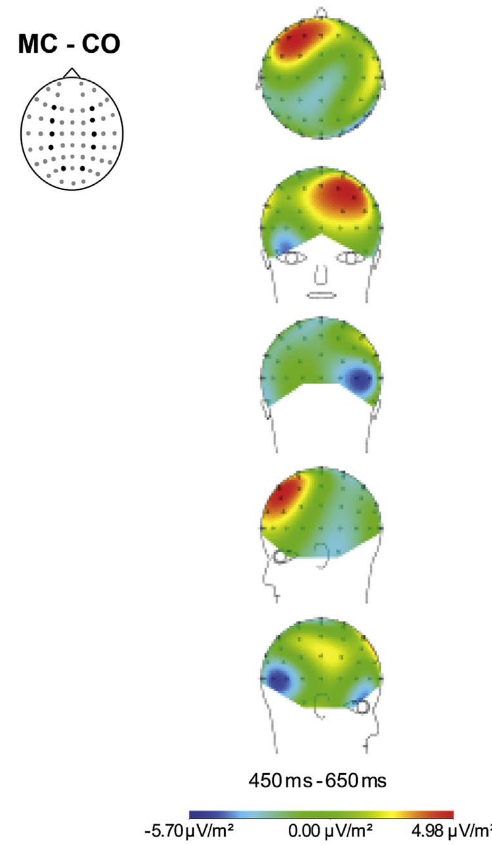

Fig. 3. Current source density (CSD) of MC minus CO. JOLs were associated with stronger positivity over the frontal regions, and stronger negativity over the posterior regions.

processes that support JOLs, showing distinct neural reactions compared to a memory-related decision judgment. This distinction was furthermore supported by comparable neural responses over prefrontal areas when contrasting high versus low JOLs. Overall, these results highlight the neural correlates of metacognitive judgments and point to the role of frontal areas in metacognition.

Comparable to previous studies that investigated the electrophysiological brain correlates of metacognition (Skavhaug, 2010; Skavhaug et al., 2010, 2013; Sommer et al., 1995), we found a distinctive pattern of effects consisting of a medial frontal positivity and bilateral posterior positivity to be associated with JOL's. Importantly, these results were obtained using a new experimental paradigm that was designed to isolate JOL from stimulus encoding and memory-related processes. Previous studies have encountered particular problems in dissociating JOL from memory encoding and stimulus processing in general. In the current paradigm we therefore aimed at separating the presentation of stimuli and the task cue signalling JOL.

The contrast between low and high JOLs revealed a similar positive slow wave effect over medial prefrontal areas, accompanied by a (non-significant) negativity over occipital cortex, that was comparable to (i.e., statistically indistinguishable from) the pattern of effects resulting from the contrast between the MC and CO cues. This finding strengthens the validity of the conclusion that the present paradigm and in particular the use of a MC and CO cues was effective in isolating JOL from initial memory encoding and stimulus processing effects. Note however that due to the low number of participants in the JOL (low - high) contrast, arguments that are based this particular contrast should be considered with caution. A replication with a higher number of subjects is required to confirm these findings. Future research could for example use a between-subjects design to increase power and provide a sufficient number of trials for confirming our analyses.

One noticeable difference between the JOL (low–high) contrast effect in the present study and JOL contrasts reported in previous studies (Skavhaug, 2010; Skavhaug et al., 2010, 2013; Sommer et al., 1995) is that effects in the current study showed a stronger frontal positivity and posterior negativity for *low* JOL trials than for *high* JOL trials, whereas in previous studies the same effects were found for the reversed contrast (high JOL–low JOL). This is a interesting finding which suggests that participants may have used the cue interval to retrieve and /or re-process picture pairs that were not yet learned adequately during S1, and that they invested less effort on re-processing picture – pairs of which they judged learning to be sufficient during S4. More generally, this interpretation fits with the notion that retrieval of studied material plays an important role in judging one's ability to remember materials at a later time (Nelson and Narens, 1990). Furthermore, this interpretation can explain the marked resemblance of the electrophysiological correlates of JOL in the current cue-based paradigm, and the ERP correlates of JOL in previous studies that focussed on stimulus encoding. That is, functional processes that assisted learning in the stimulus presentation phase may have been activated as well in response to the MC cue, allowing participants to optimize their acquisition of picture pairs and providing guidelines to participants for estimating their ability for later reproduction.

Overall, we think that the findings of our study indicate that the experimental design, and in particular the contrast between the MC and CO conditions, provided a good measure of the neural processes supporting JOL. More specifically, we believe that the choice to investigate cue-related ERPs provides a promising approach in addition to paradigms that use stimulus-related ERPs. That is, cue-related

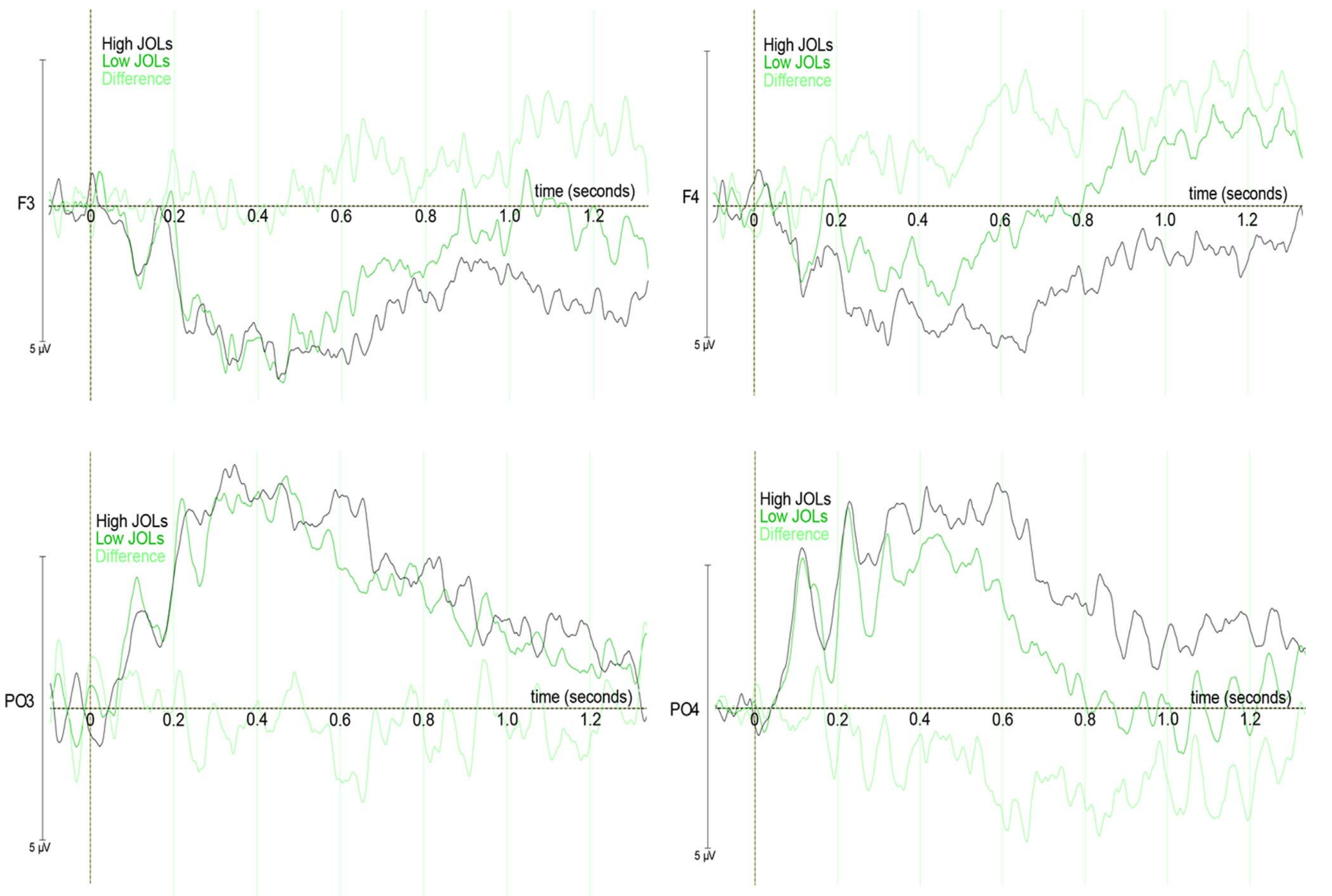

Fig. 4. Grand average ERP waveforms at selected electrodes; frontal (F3, F4) and posterior (PO3, PO4) electrodes are depicted for high and low JOLs. Positive voltage is depicted upwards. The gray line represents trials that received high JOL ratings, the dark green line represents trials with low JOL ratings and the light green line the difference between the high JOL and low JOL ERPs. A significant difference between high JOL and low JOL conditions was found in time windows between 550–700 ms and between 1000–1200 ms.

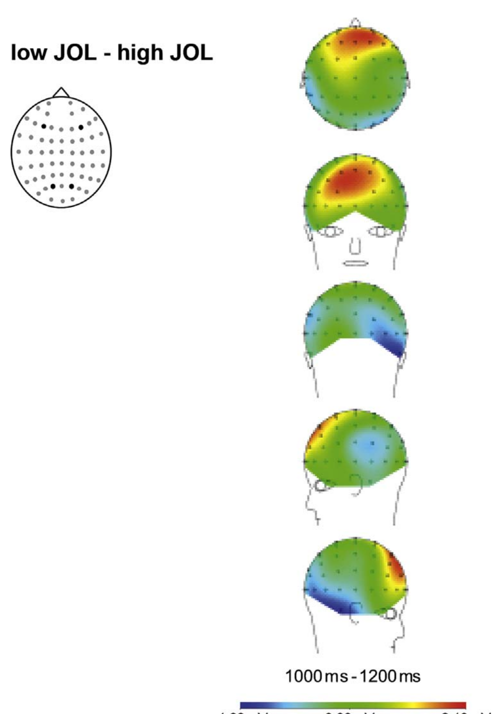

Fig. 5. Topographic voltage maps of mean amplitude differences (low JOL minus high JOLs). Low JOLs were associated with stronger positivity over the frontal regions, and stronger negativity over posterior regions.

ERPs provide a selective measure of JOLs that is not confounded by ERP effects associated with stimulus processing and memory encoding. Considering the similarity of ERP effects in stimulus- and cue-related designs and the possible functional relationship between encoding and retrieval, we think it would be interesting to combine both approaches in a single experimental design in future studies.

How to interpret the frontal and posterior slow waves that accompanied metacognitive judgments? What do these findings reveal about the nature of metacognitive processes? Here, we offer two mutually non-excluding interpretations. First, it is interesting to note similarities with the literature on visual working memory. The present results are comparable to findings that have been reported by Sommer et al. (1995) who found JOLs of faces to be reflected in similar frontal positive and posterior negative slow wave effects with similar polarities. These findings could indicate an activation of visual working memory processes (e.g., Berti et al., 2000; Ruchkin et al., 1997; Uhl et al., 1990; van Schie et al., 2005; see also Skavhaug, 2010). The timing of frontal effects was partly overlapping with effects found over posterior regions, which is in line with research on visual working memory, mental imagery, and visual attention that has reported separate activations in frontal and posterior areas during the maintenance, selection, and manipulation of visual information in memory (Kosslyn et al., 1994; Schendan and Kutas, 2002; Skavhaug, 2010; Smith and Jonides, 1997). CSD mapping additionally confirmed the involvement of separate current sources over bilateral occipital regions, and medial prefrontal sites. The possible involvement of visual working memory processes supporting JOL is in line with theoretical considerations that retrieval processes form the basis of people's JOLs (e.g., Nelson and Dunlosky, 1991; Spellman and Bjork, 1992). When performing the

JOLs task, participants might, for example, try to visualise the stimuli to estimate their ability to recall the target picture at a later point in time, thereby activating frontal and visual areas supporting working memory.

Second, and alternatively, one could argue that our results support the theoretical perspective that analytic metacognition might be based on metarepresentational processes that have been reported in the ToM literature (e.g., Kühn-Popp et al., 2013; Meinhardt et al., 2011, 2012; Sabbagh and Taylor, 2000; for review see Carrington and Bailey, 2009). For example, Sabbagh and Taylor (2000) found an enhanced positivity over frontal areas and others more specifically found a frontal slow wave (e.g., Meinhardt et al., 2012). In addition, comparable positive slow-wave components were found in research distinguishing metarepresentations (i.e., false belief reasoning) from simple mentalizing processing (i.e., true belief processing), with metarepresentation processing showing a more positive slow wave than simple mentalizing (Meinhardt et al., 2011).

Note that both interpretations of the current findings are not mutually exclusive. It could for example be that participants entertain mental simulations in visual working memory and language areas to allow metacognitive estimations of future test performance. Interestingly, recent neuroimaging research has identified different structural regions supporting metacognition of perceptual accuracy and metacognition of higher-order cognitive performance within different subsystems of a larger scale network involved in mentalising (Valk et al., 2016). Using different imaging modalities, MC on perceptual accuracy was associated with prefrontal regions, while MC on higher-order cognition was associated with parietal and posterior temporal regions. An interesting point for future investigations is to investigate the functional contribution of modality specific activations to metacognition. This could for instance be accomplished with dual-task interference paradigms (see van Elk et al., 2014, for a selective review) wherein participants engage in a secondary task that limits modality specific systems (auditory, visual, motor) in contributing to simultaneous metacognitive judgements. An alternative approach could be to present the same memory items in different modalities (e.g., as a visual stimuli and language stimuli) within a single experimental design to identify modality specific effects.

Skavhaug et al. (2010) suggested that JOL may be reflected by relatively late neural responses between 1300 ms and 1900 ms following stimulus onset. In the current study, effects of JOLs were observed much earlier, between 350 ms and 700 ms after onset of the cue. This can be explained by the fact that in the current paradigm stimulus processing and memory encoding had already taken place during the learning interval in which participants had been presented with the picture pair. That is, processing related to JOLs can onset quickly after presentation of the cue and is not delayed by stimulus identification and memorizing. More speculatively, the relative speed with which metacognitive processes were activated in the current experiment following the MC cue suggests that JOL's may at least partly depend on automated processes that support metacognitive judgements. This may point towards the involvement of subpersonal heuristics such as the fluency or vividness with which a recently presented stimulus pair is recollected (Koriat and Ackerman, 2010) as such experiences have been suggested to play a major role in metacognitive judgments (Koriat, 1997; Proust, 2013). Future research could investigate if variations in onset, duration and amplitudes of ERP components are in any way associated subpersonal heuristics such as accessibility, effort, and familiarity (cf. Proust, 2010).

In conclusion, the present study tested a new experimental paradigm to investigate neural correlates of judgements of learning, independently from processes supporting memory encoding and stimulus processing. ERP results corroborate findings of previous studies by revealing a similar medial frontal positivity and accompanying bilateral posterior negativities in response to a MC task-cue. Analysis of low JOL trials relative to high JOL trials resulted in a comparable but opposite pattern of ERP effects as compared to previous studies. These findings suggests that retrieval and/or reprocessing of learned materials play a prominent role in metacognitive evaluations of learning. We encourage future studies to investigate the relationship between encoding and retrieval as a mechanism informing metacognitive judgements of learning.

4. Methods

4.1. Participants

Twenty students from the Ludwig-Maximilian University of Munich (9 male; M_{age}=23.30 years, SD_{age}=3.60; age range 18–35 years) received credit points or financial compensation for their participation. All participants were right-handed and had normal or corrected-to-normal vision. No one had a history of neurological, major medical, or psychiatric disorder, as determined by self-report. After artefact detection, 2 participants who had less than 20 trials left per condition were excluded from further analyses. A remaining 18 participants (8 male; M_{age}=23.33 years, SD_{age}=3.80; age range 19–35 years) were thus used for further analysis. Ethical approval was obtained by the local ethical committee.

4.2. Materials and procedure

The experiment had a within subjects design with two conditions (Metacognition vs. Control). EEG recording took place in a sound-attenuated, electrically shielded chamber. Participants were seated in a comfortable chair 100 cm in front of a 19-in. computer monitor. After arrival in the EEG lab, EEG electrodes were attached and participants were instructed about the experiment. They were told that the study consists of four parts investigating their memory and learning abilities.

In the first part of the study – the presentation phase – participants were presented with 120 single pictures showing coloured drawings to familiarise them with the stimuli. Pictures consisted of 709×511 pixels (i.e., 6 cm×4.33 cm) and were presented on a white background, with the drawing depicted in the middle of the screen. Because of the large number of pictures, and to ensure correct identification and naming afterwards, the name of the illustrated item was written below each picture (see also Lockl and Schneider (2003) for a comparable procedure). Participants could skip through the series in a self-paced manner and each picture was presented for a maximum of 10 s. Pictures were comparable with respect to size and colouring, and depicted daily objects (e.g., a table, a bed, an oven), or common animals (e.g., a cat, a duck, a bird). For examples of the stimuli, see Fig. 6.

In the second part of the study – the learning phase – the 120 pictures that were presented in the presentation phase were combined into pairs, resulting in a total of 60 picture-pairs. These pairs were presented twice: once for the MC judgment, and once for the control judgment. In the learning phase, ERP recordings took place. For an overview of the procedure, see Fig. 7. Participants saw a picture pair,

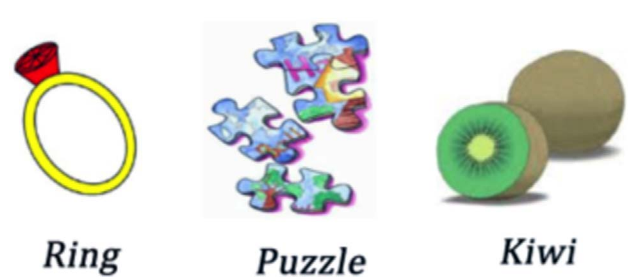

Fig. 6. Examples of the stimuli used in the presentation phase.

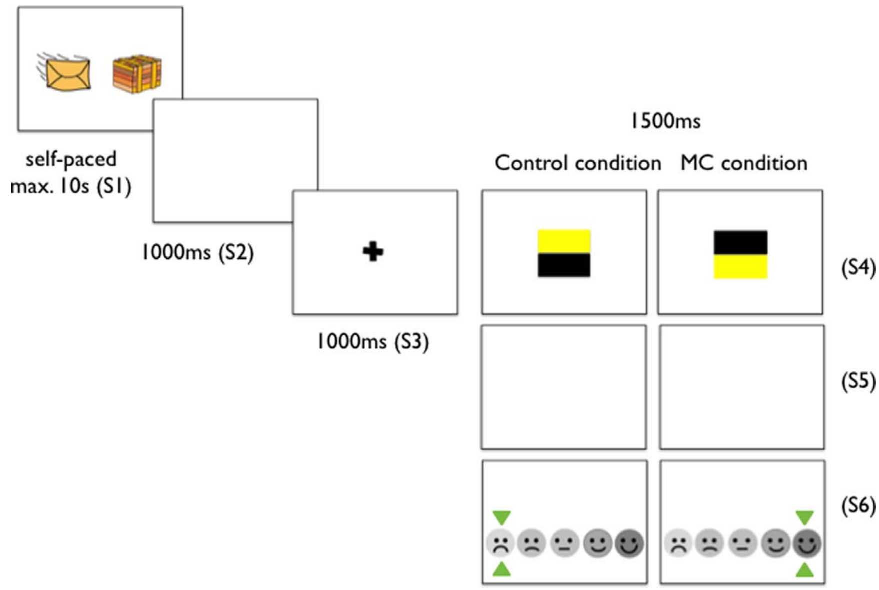

Fig. 7. Overview of the experimental procedure for the MC and CO condition. In both conditions, picture S4 was the ERP eliciting event.

either for a maximum of 10 s, or they could skip through to the next part of the trial if they thought they had learned the pair. After each picture presentation, a white screen was presented for 1000 ms, followed by a 1000 ms black fixation cross on a white background. Subsequently, a task square was presented for 1500 ms, which either asked participants to give a judgment of learning (JOL) or to give a colour judgment. The judgment of learning task required participants to estimate how likely it would be that they would recall the target picture that had been presented on the right side when presented, at a later point in time, with the picture that had been presented on the left side of this target picture (MC condition). The control task asked participants whether the colour yellow had been present in one of the two pictures (CO condition). The task cue consisted of a black square outline separated by a black horizontal line at the centre of the square, on top of a white background. Cueing of the JOL task or the control task was done by filling the top or lower half of the square in black. For half of the participants, black on top indicated the JOL task and yellow on top indicated the control task. For the other half of the participants, black on the lower part indicated the JOL task and yellow on the lower part indicated the control task. The presentation of the cue was used as a trigger for calculating time-locked ERPs. After the offset of the square and a delay of 1500 ms (white screen), judgments could be given on a five-point smiley scale ranging from a sad smiley on the most left side to a happy smiley on the most right side of the scale. In the metacognition condition, a sad looking smiley meant that participants were unsure about remembering the right picture when only presented with the left one, while the happy looking smiley meant that participants were sure that they would remember the right picture when only presented with the left one. In the control condition, a sad smiley meant that yellow had not been present in either of the two pictures, while the happy smiley meant that yellow had been present. In both conditions, the neutral smiley in the middle meant that participants did not know the answer. Participants used the mouse to move a cursor on the screen to choose a smiley, and confirmed their choice by clicking on the left mouse button. To facilitate task understanding, a block of 10 practice trials was presented with 5 practice trials for each condition. Trials were presented in a pseudorandom order. By doing so, it could be guaranteed that approximately half of the pairs were presented first for the JOL judgments, and half for the control judgments.

The third part of the study was a recall phase in which participants were presented with the left items of the picture-pairs they had previously studied in the learning phase. The recall phase enabled us to calculate metacognitive accuracy. The item was presented on the left side of the screen while the right side of the screen, where the target picture had previously been presented, was empty. Participants' task was to name the corresponding missing item. The experimenter registered correct and incorrect responses on a printed form. Pictures were presented until participants gave an answer, or for a maximum of 10 s. No EEG recording took place in this phase.

Subsequently, in the fourth part of the study – the recognition phase – participants were presented with the left object of the pair presented at the top middle of the screen and in which they had to make a forced choice. Below were two objects, one on the left and one on the right side of the screen: the correct corresponding item of the pair, and a new, non-corresponding item. Participants could use the left or right mouse button to indicate which of the two objects was the matching object of the pair. Pictures were presented until participants gave an answer, or for a maximum of 10 s. No EEG recording took place in this phase. After finishing the fourth part, participants were debriefed, paid, and thanked for their participation.

4.3. EEG/ERP recording and analysis

The electroencephalogram (EEG) was acquired using BrainAmp amplifiers (Brain Products, Gilching, Germany) with 64 active electrodes (ActiCap System, Brain Products, Gilching, Germany) placed on standard positions according to the extended International 10–20 System. All electrodes were referenced to position Cz. Electrodes below the right eye and near the outer canthi of the left and right eyes (F9, F10) were used to monitor the vertical and horizontal eye movements. The ground electrode was positioned at AFz. Impedances of all electrodes were kept below 10 kΩ. Signals were recorded with a band-pass filter of .016–100 Hz and were continuously sampled to a hard disk at a rate of 500 Hz.

For all offline analyses, Vision Analyzer software (Brain Products, Germany) was used.

Offline all electrodes were re-referenced to an average reference and a digital band pass filter of 0.1–20 Hz/−12 dB was applied. EEG data was inspected for artefacts using an automated procedure. Intervals where EEG amplitude of a channel exceeded ± 50 μV were excluded. In addition, the EEG data was visually inspected for artefacts that were missed by the automated procedure and excluded from analysis. The remaining data was corrected for ocular artefacts (blinks and eye-movements) using the algorithm. Segments time-locked to the condition cue were extracted. The segments were 1500 ms long (−100–1400 ms). The 100 ms interval before picture onset was defined as a pre-cue baseline. Segments were baseline corrected (−100–0 ms) and artefact-free segments for all responses were averaged separately for each participant and each experimental condition (MC, CO). ERPs were exported as mean amplitudes per electrode within specific time windows for statistical analysis, as described below. All participants who had at least 20 artefact free trials per condition were included in the analyses (N=18). The average number of useable segments after artefact rejection was comparable in the MC condition (M=43.6, SD=10.99) and in the CO condition (M=45.4, SD=10.30).

4.4. Statistical analysis

Average ERPs to MC and CO trials were binned in intervals of 50 ms that were exported and tested for significance using ANOVA repeated measures analysis. Statistical analyses were performed for bilateral frontal pairs (F3/F4), fronto-central pairs (FC3/FC4), central electrodes (C3/C4), centro-parietal pairs (CP3/CP4), and posterior electrode pairs (PO3/PO4). The data for each time bin were analysed with condition (MC vs. CO), hemisphere (left vs. right), and site (frontal vs. fronto-central vs. central vs. centro-parietal vs. posterior) as within-subjects factors. All factors were subjected to repeated-measures ANOVAs and, where appropriate, Greenhouse–Geisser corrections for non-sphericity were applied. The corrected p-values and the original degrees of freedom are reported. Significant results ($p < .05$) are reported only when the factor condition is involved, and were followed by post-hoc tests if appropriate. To correct for chance capitalisation (i.e., correcting for the number of tests of significance being performed) a minimum of three consecutive significant intervals ($\alpha < .05$) of 50 ms were accepted as truly significant (see also Gomarus et al., 2009).[2] If significant effects in successive time segments were found, we reported the largest p-value and the smallest F-value.

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[2] Using a criterion of three consecutive significant intervals in the analyses, the number of significant intervals by chance would reduce to .003 (i.e., 26×.05×.05×.05), which is well below the significance criterion of .05.

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