Brain Research 1695 (2018) 84–90

Contents lists available at ScienceDirect

Brain Research

journal homepage: www.elsevier.com/locate/bres

Research report

An ERP study on metacognitive monitoring processes in children

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ARTICLE INFO

Article history:
Received 7 October 2017
Received in revised form 3 April 2018
Accepted 27 May 2018
Available online 28 May 2018

Keywords:
Metacognition
Judgments of learning
ERP
Memory
Development
Children

ABSTRACT

Little is known about what exactly differentiates metacognitive processes from ordinary cognitive processes particularly early in development, and the underlying developmental aspects. To examine the time-course of metacognition, the present study investigated the neural underpinnings of judgments of learning (JoLs) and compared them with control judgments, using an event-related potentials (ERP) design. During ERP recording, children age seven to eight were presented with cue-target picture pairs and instructed to learn these pairs. After each pair, they either had to make a JoL (assess the likelihood of remembering the target when only presented with the cue) or a colour judgment (indicate whether the colour yellow had been present in one of the two pictures presented earlier). Results revealed a late slow wave divergence maximal pronounced from 550 ms to 950 ms post-stimulus that distinguished between JOLs and colour judgments. Over centro-parietal areas, JoLs showed a more negative going slow wave compared to the colour judgments, and this pattern was independent of performance. The results are in support of theories that assume a distinction between metacognitive and cognitive processes.

1. An ERP study on metacognitive monitoring processes in children

Metamemory has been defined as meta-level cognition about memory processes and involves the monitoring of one's own learning processes (Nelson and Narens, 1990). One type of metacognitive monitoring judgments are so called judgments of learning (JoL). In a typical JoL paradigm, participants are usually instructed to study picture- or word-pairs and have to predict for each pair the likelihood of remembering the target on a future memory test when only presented with the cue (e.g., Nelson and Dunlosky, 1991; Lockl and Schneider, 2003; Tsalas et al., 2017). Empirical research has shown that prediction accuracy increases over the school years (Schneider, 2008) and that accuracy can be influenced by different factors, such as the ease with which the material is memorised (Koriat, 1997) or the timing of the judgments (Nelson and Dunlosky, 1991). Consequently, cognitive research has aimed to understand the processes which underpin these monitoring judgments and which influence their accuracy. Neuroscientific research offers a unique opportunity to complement our understanding of these processes.

Recent neuroscientific evidence, for example, has been able to inform the debate of whether people have direct and privileged access to their epistemic content and that JoL are thereby a direct readout of the strength of memory traces, or whether monitoring judgments are informed indirectly from the evaluation of different cues, such as the ease with which information is being processed or recalled (Koriat, 1997). Indeed, neuropsychological studies using functional magnetic resonance imaging (fMRI), as well as recent ERP studies investigating the temporal resolution of JoL in adults, support the notion that JoL are in fact distinguishable from memory processes. This suggests, that there are at least partially independent processes involved in JoL and memory (e.g., Kennedy and Yorkston, 2000; Ries et al., 2012; Roberts et al., 2009; Vilkki et al., 1999). For example, while some of these studies demonstrated that especially late neural responses (1300–1900 ms) for JoL using a word-learning paradigm are distinguishable from memory processing (e.g., Skavhaug et al., 2010; Sommer et al., 1995), recent ERP research using a picture-learning paradigm found distinguishable neural responses during earlier processing from 350 ms to 700 ms (Müller et al., 2016).

From a developmental perspective it remains unclear, however, what the neurocognitive correlates for metacognitive judgments in

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https://doi.org/10.1016/j.brainres.2018.05.041
0006-8993/

children are and whether metacognitive processes and cognitive processes are neurally distinct in children. There are two main reasons why we cannot simply extend the findings from adult populations to children: first, metacognitive processes are thought to be underpinned by the prefrontal cortex, which follows a protracted development until adolescence (Giedd et al., 1999). These structural changes are likely to be accompanied by functional changes, whereby the neural strategies and processes for metacognitive monitoring judgments might change during childhood and adolescence. Indeed, previous neurodevelopmental research has shown that this is the case in theory of mind research (Meinhardt et al., 2012). Second, there are a handful of studies on metacognitive monitoring judgments that suggest that children and adults can appear similar on a behavioural response level but seem to rely on different information in their monitoring judgments (Koriat et al., 2009, 2014; Paulus et al., 2014). Results of these studies suggest that with age, children become increasingly sensitive to more complex cues which derive from the actual engagement in a learning task rather than from an a priori, theory-based understanding of the difficulty of the learning material (Koriat et al., 2009; Tsalas et al., 2014). Accordingly, monitoring judgments in children might still be anchored more strongly in their cognitive processes, and neural responses of memory- and metamemory processes might therefore be less distinct. Taken together, these results suggest that the neurodevelopmental underpinnings of metacognitive processes in children are yet to be explored. Therefore, it was the aim of the current study to use event related potentials (ERPs) to investigate the neurocognitive basis and, more precisely, the temporal similarities and differences between neurocognitive processes that support JoL and those that are not related to JoL in children. By doing so, we can explore whether and how metacognitive processes differ from other cognitive processes.

In the present study, the same picture-learning paradigm was used as in earlier adult ERP research on metacognitive performance (Müller et al., 2016), in which JoL trials (i.e., participants were asked how likely they would be to remember the right picture, if presented with the left picture) were compared to colour judgment trials (i.e., participants were asked whether the colour yellow had been present in one of the two pictures). With this paradigm, it is possible to explore ERP correlates of JoL independently from electrophysiological components associated with stimulus processing and encoding.

We decided to test 8-year old children for two main reasons: first, because behavioural studies have shown that at this age, children can already make relatively accurate JoL and are therefore behaviourally competent in the task (Lockl and Schneider, 2003), while still showing further developmental improvements in metacognitive monitoring across late childhood and adolescence (e.g., Weil et al., 2013). Second, there are important structural changes, which take place between this age group and adolescence. Thereby it would be highly interesting whether or not in behaviourally competent children, the neural signatures of the processes under investigation might differ. Based on recent ERP research which found distinguishable neural responses during earlier processing from 350 ms to 700 ms in adults (Müller et al., 2016), we would expect different neural signatures for metacognitive and colour judgments in children, if they were to rely on different sources of information and processes in forming their JoL, for example cues inherent in the retrieval processes, such as the ease with which they retrieve a learned item. This would support theories which propose that metacognitive processes can be distinguished from memory processes (Koriat, 1997). If, however, children's monitoring judgments are still anchored more strongly in their cognitive processes, similar neural signatures for metacognitive and colour judgments could be expected. This in turn would be in line with theories that assume a privileged access to one's own memory content as a basis for metacognitive monitoring judgments.

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	11.78	8.50	17.33	8.28	14.11
SD	13.63	9.14	14.50	6.40	15.23

2. Results

2.1. Behavioural results

Results of the recall condition indicated that participants correctly remembered an average of 25.00 out of 60 items (*SD* = 11.20, *Median* = 24.50). Furthermore, we used the JoL 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* = 0.46–75, *M* = 0.58; proportion correct: 13.33–76.67%; *M* = 58.11%). Judgments of learning and Aroc were uncorrelated, Pearson's correlation = 0.25, *p* = 0.30. See Table 1 for the distribution of the JoL.

In the colour judgment condition, participants on average correctly indicated that the colour yellow was present in 26.83 out of 60 items (*SD* = 8.62, Median = 27.5) during the learning phase. Whether participants could indicate whether the colour yellow was present in the colour judgment trials and their ability to make correct JoL judgments in the metamemory trials was unrelated, Pearson's $r = 0.254$, $p = .309$[2].

2.2. ERP results

The grand average waveforms elicited in the MC and CO conditions are depicted in Fig. 1 for frontal and centro-parietal electrodes. The topography of the differences between MC-CO is portrayed in Fig. 2. ERPs in the MC condition showed a more positive going amplitude, starting around 550 ms, relative to the CO condition (see particularly the different waveform). Over centro-parietal electrodes a reversed pattern was found, showing a widely distributed negative slow wave for the MC condition relative to the CO condition. To control for possible influences, we included MC performance as indicated with the ROC curves as a covariate in the analysis to investigate a possible relationship with neural activation. As no significant main- or interaction effects were found, the ROC scores were omitted from further analyses. Additionally, further analyses revealed that mapping between cue and task instruction had no influence on the results. Therefore, both factors were omitted from further analyses.

A repeated-measures ANOVA with condition (MC, CO), hemisphere (right, left), and site (frontal, centro-parietal) as within-subjects factors revealed significant interaction effects between condition, hemisphere, and site from 550 ms following onset of the stimuli until 950 after stimuli onset, $F's(1,17) > 4.592$, $p's < .047$. Step-down comparisons per site were performed and revealed no significant effects for frontal electrodes (all $p's > .10$).

[2] 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.

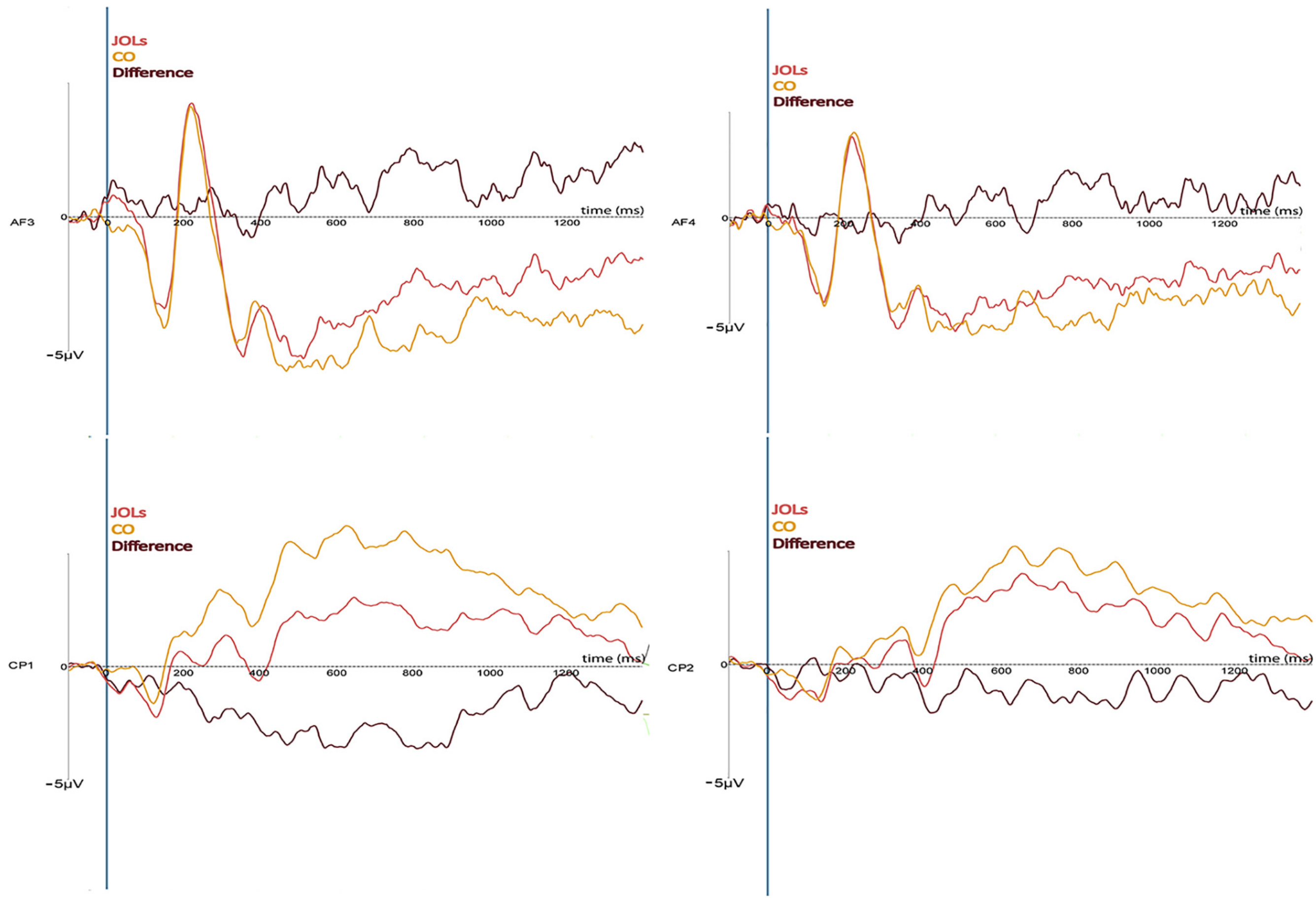

Fig. 1. Grand average ERP waveforms at selected electrodes; frontal (AF3, AF4) and centro-parietal (CP1, CP2) electrodes are depicted. Positive voltage is depicted upwards. The orange line represents the control (CO) condition, the purple line represents the JOL condition (MC) and the pink line the difference between the MC and CO conditions. A significant difference between MC and CO conditions was found between 550 and 950 ms.

For centro-parietal electrodes, significant interactions between condition and hemisphere were found from 550 ms after stimuli onset until 700 ms after stimuli onset, $F's(1,17) > 7.613$, $p's < .013$, with MC eliciting more negative waveforms than CO in the left hemisphere, $F's(1,17) > 5.203$, $p's < .036$. In addition, significant main effects for condition were found from 750 ms after stimuli onset until 950 ms after stimuli onset, $F's(1,17) > 5.324$, $p's < .034$, with MC eliciting more negative waveforms than CO. These main effects were qualified by significant interactions between condition and hemisphere were found from 750 ms after stimuli onset until 950 ms after stimuli onset, $F's(1,17) > 5.254$, $p's < .035$, with MC eliciting more negative waveforms than CO in the left hemisphere, $F's(1,17) > 9.510$, $p's < .007$.

3. General discussion

In the current study, we investigated the neural signatures for metacognitive JoLs compared with judgments in a colour judgment condition in eight-year-old children using ERP. By doing so, we were able to compare JoL and colour judgments within one paradigm. Our findings show a clear pattern of slow wave effects over centro-parietal areas, starting at 550 ms until 950 ms after stimuli onset: MC was found to be accompanied by a more negative slow wave compared to the CO condition. Although visually frontal areas seemed to show a reversed pattern, effects were not significant. These findings allow for several novel conclusions: Most notably, already in middle childhood – an age at which explicit metacognitive processes are about to emerge and before they consolidate in late adolescence (e.g., Paulus et al., 2014; Schneider, 2008) – metacognitive monitoring judgments appear to differently involve the cognitive system, as has also been found in previous neuroscientific research with adults (e.g., Müller et al., 2016; Skavhaug, 2010; Sommer et al., 1995).

The distinct neural patterns for metacognitive and colour judgments can be seen as support for theoretical views that metacognitive judgments are not merely based on the same retrieval processes which underpin later recall, as is implied in direct access (or trace access) accounts of metacognitive monitoring. Direct access accounts propose that learners base their judgments on privileged access to their epistemic content. Inferential models however suggest that metacognitive judgments are inferred from cues inherent in the processing of learning material itself, such as the ease with which information is being processed or retrieved for example (e.g., Koriat, 1997). Concerning the current study, if JoL were based on direct access to the memory content, then we would expect a very similar neural signature of the JoL to the colour memory judgment. If, however, the JoL is additionally based on cues which are involved in the process of retrieval, and not merely on privileged access to epistemic content, then presumably the neural signature of the two types of judgments measured in the current study should diverge. While previous neuroscientific research with adults has shown that meta processes are dissociable from mere memory processes (e.g., Müller et al., 2016; Skavhaug, 2010; Sommer et al., 1995), this study extends previous finding by showing that this is already the case in middle childhood.

A closer inspection of the differences in the neural pattern between the metacognitive and the non-metacognitive condition shows a difference in the amplitudes of the slow waves for the

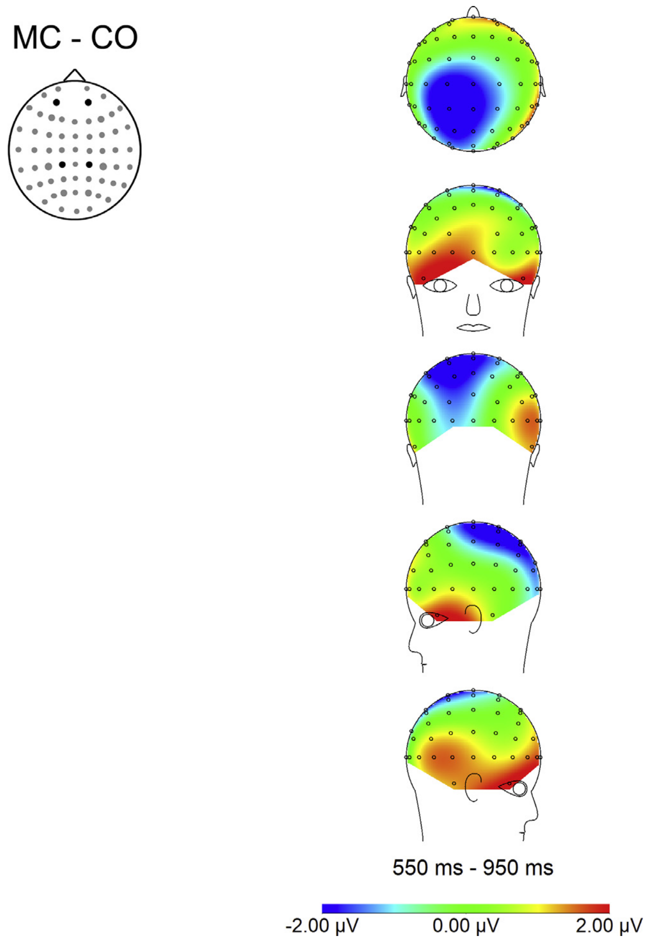

Fig. 2. Topographic voltage maps of mean amplitude differences (MC minus CO). JoLs were associated with stronger negativity over the centro-parietal regions.

metacognitive judgments and the colour judgments over parietal regions. The colour judgments for children were accompanied by a more positive slow wave amplitude in parietal regions compared to the metacognitive judgments. We offer several explanations for this difference in amplitude: First, this pattern, showing differences in intensity between metacognitive and control processes, has been previously related to increasing cognitive load for memory judgments (Ruchkin et al., 1990). Therefore, it is possible that in the current study, colour judgments placed a higher demand on retrieval processes than the metacognitive judgments.

Second, the lower amplitude for metacognitive judgments might be a result of the different processing demands that the two types of judgments placed on children. In the colour judgment condition, the judgments of whether the colour yellow had been present in one of the two pictures would have been based on retrieval processes. However, in order to make a metacognitive judgment, children might have first retrieved the items and then had to engage in a second process by making a judgment about this memory contents. If both of these processes placed demand on the same components, then there would be less capacity for each of the processes, and, as a result, the amplitude would be smaller (Kok, 2001; Wijers et al., 1989).

Third, it is interesting to note that the parietal slow wave effect resembles a pattern previously found in theory of mind research (Kühn-Popp et al., 2013; Meinhardt et al., 2012) where participants had to shift their attention from external information to an inner representation. In the current study, participants had to make a judgment of whether the colour yellow had been present or not in the previously seen pictures when prompted with a cue picture. Therefore, it is likely that upon seeing the cue picture, participants tried to retrieve a mental representation of the previously seen pictures, thereby shifting their attentional focus from an external cue to an internal mental representation of the to-be-remembered items. In summary, considering these three explanations, one could speculate that the different neural signatures for monitoring and colour judgments are due to the fact that there are retrieval processes involved in metacognitive judgments. Whether this is, however, due to the fact that children's monitoring is informed by different cues, leading to different processing of the information, or whether higher or different processing demands lead to the divergence in the neural signature, is a matter which needs to be more systematically explored in future research.

In the present study, no correlation was found between JoL accuracy (as indicated by AROC) and the ERP components, which is in line with earlier with adults (e.g., Müller et al., 2016). Thus, it can be argued that AROC can be mainly seen as a measure of accuracy of JoL, not engagement in metacognition per se: a low AROC value does not reflect no engagement in metacognitive processes, but more an engagement which resulted in an incorrect judgment, thus can be seen as less efficient. On the other side, a high AROC value might reflect a similar engagement in metacognitive processes as a low AROC value, with the distinction that it results in a correct judgment.

Interestingly, from a developmental perspective, children appeared to show a comparable slow wave effect as adults (Müller et al., 2016); however, a closer inspection suggests that the frontal effects in children were not as strong as in adults. This could be interpreted in two ways: first, it could be that children were not able to process the cues in a similar way and to use the same neural strategies as adults, because of a developmental lag in the development of their prefrontal cortex (e.g., Giedd et al., 1999). Second, it could be that while children engaged in the same task as adults did, they used a different strategy to make their JoL judgments. For example, they could have relied on different cues that informed their judgments, or they could have processed cues differently than adults. Indeed, this would be plausible, as previous behavioural research suggests that there are developmental differences in the type of cues that children and adults rely on when making their judgments (e.g., Koriat et al., 2009, 2014; Paulus et al., 2014). These two explanations are not mutually exclusive. It should be noted, however, that the non-significant effects in children could be due to a lack of power, given the rather small sample in the final analysis. Therefore, both explanations should be used with caution. In future research, a higher number of participants and trials in both conditions might also allow for comparing correct versus incorrect JOL to further explore the underlying processes of JOLs.

In conclusion, the current study explored the neural underpinnings of metacognitive judgments in children. Moreover, we examined whether and how these neural correlates differ from those underpinning cognitive processes in colour judgments. The present study demonstrates that at least partially independent processes for JoL and memory in middle childhood. It provides direct electrophysiological evidence that a late centro-parietal slow wave distinguishes between explicit metacognitive and object-level cognitive processes in eight-year old children, informing the theoretical debate on how meta-memory processes differ from other cognitive processes.

4. Methods

4.1. Participants

The final sample consisted of 26 children (9 female; M_{age} = 8 years, age range 7;5–8;6 years). All children were right-handed and had normal or corrected-to-normal vision. No child had a history of neurological, major medical, or psychiatric disorder. All parents gave written consent after they and their children were informed about the procedure. Families received a travel compensation and children received a small present for participating in the experiment. The institutional ethics committee approved the experimental methods. After artefact detection, 8 participants who had less than 20 trials left per condition were excluded from further analyses (see Müller et al., 2016). A remaining 18 participants (4 female; M_{age} = 7.92 years, age range 7;5–8;6 years) were used for data analysis.

4.2. Materials & procedure

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 and their parents were instructed about the experiment. They were told that the study consists of four parts and that their children's memory and learning abilities were investigated.

Similar materials and procedure was used as previously used in Müller et al. (2016). During the first part – the presentation phase – participants were familiarised with the stimuli by presenting them with 120 single coloured drawings. Pictures consisted of 709 × 511 pixels (i.e., 6 cm × 4.33 cm) presented on a white background, with the drawing depicted in the middle of the screen. to ensure correct identification and naming afterwards, and because of the large number of pictures, the name of the illustrated item was printed below each picture (see also Lockl and Schneider, 2003 for a comparable procedure). Children could skip through the series in a self-paced manner, and the maximum presentation time for each picture was 10 s. Size and colouring of the pictures was comparable, and pictures depicted daily objects (e.g., a sofa, a ball, a violin), or common animals (e.g., a bird, a dog, a mouse).

In the second part – the learning phase – the 120 pictures from the presentation phase were combined into pairs, resulting in a total of 60 picture-pairs. These pairs were presented twice: once for the metacognitive condition, in which participants had to make a JoL judgement (MC condition), and once for the colour judgement condition, in which participants had to make a colour judgment (CO condition). In the second part ERP recordings took place. For an overview of the procedure, see Fig. 3. Participants saw a picture pair, 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, a white screen was presented for 1000 ms, followed by a 1000 ms black fixation cross. Subsequently, a task square was presented for 1500 ms, instructing participants to give a 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 colour judgment asked participants to indicate whether the colour yellow was part of 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 colour judgment task was done by filling the top or lower half of the square in black. For half of the participants, black on the lower part indicated the JoL task and yellow on the lower part indicated the colour judgment task. For the other half of the participants, black on top indicated the JoL task and yellow on top indicated the colour judgment task. Importantly, the presentation of the cue was the trigger for calculating time-locked ERPs. After the offset of the square and a delay of 1500 ms during which a white screen was presented, 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 colour judgment 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 could use the mouse to move a cursor to choose a smiley, and confirmed their choice by clicking the left mouse button. To facilitate task understanding, a block of ten practice trials including five practice trials for each condition was presented. 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 judgments in the colour judgment condition.

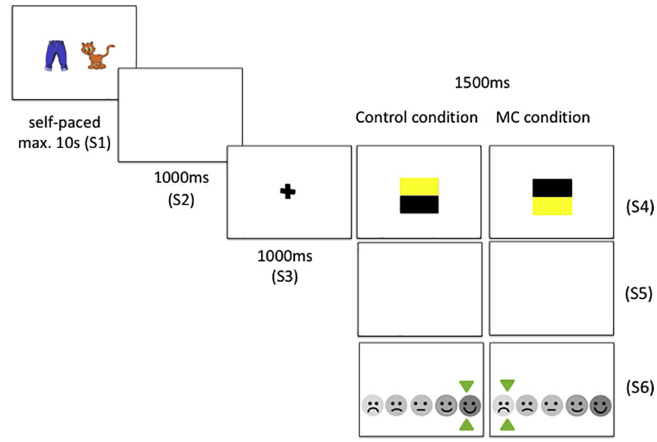

Fig. 3. Overview of the experimental procedure for the MC and CO condition. In both conditions, picture S4 was the ERP eliciting event.

In the third part – the recall phase – participants were presented with the left items of the picture-pairs they had previously studied in the learning phase and was used to calculate metacognitive accuracy. The item was presented on the left side of the screen while the right side of the screen was empty. Participants' task was to name the corresponding missing item presented before on the right side of the screen. 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 without recording EEG signals.

Finally, in the fourth part - the recognition phase - participants were presented with the left object of the pair presented at the top middle of the screen, and below two objects. One item 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. Children were asked to make a forced choice. They 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 without recording EEG signals. 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 0.016–100 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 of Gratton et al. (1983). Segments time-locked to the condition cue were extracted. The segments were 1500 ms long (−100 to 1400 ms). The 100 ms interval before picture onset was defined as the pre-stimulus baseline. Segments were baseline corrected (−100 ms to 0 ms) and artefacts-free segments for correct responses were averaged separately for each participant and each experimental condition (MC, CO). ERPs were exported as mean area amplitudes within specific time windows for statistical analysis, as described below. All participants who had at least 20 correct 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 $M = 32.94$ ($SD = 11.71$) and in the CO condition $M = 34.67$ ($SD = 10.67$), $p > .14$.

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 measurements analysis. Consistent with existing ERP research on JoL and object working memory (Müller et al., 2016; Sommer et al., 1995; van Schie et al., 2005), ERP components and differences between conditions were maximal over frontal and centro-parietal sites. Therefore, statistical analysis was limited to electrodes from these two regions, and the positive mean amplitudes were measured at frontal electrodes (AF3, AF4) and centro-parietal electrodes (CP1, CP2). Statistical analyses of the ERP data were conducted on ERP mean amplitude measures obtained within the time windows relative to a 100 ms pre-stimulus baseline. The resulting data for each interval were analysed with condition (MC vs. CO), hemisphere (left vs. right), and site (frontal vs. centro-parietal) 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 ($p < .05$) were reported only when the factor condition is included 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)[3]. If significant effects in successive time segments were found, we reported the largest p-value and the smallest F-value.

[3] Using a criterion of three consecutive significant intervals in the analyses, the number of significant intervals by chance would reduce to 0.003 (i.e., $26 \times 0.05 \times 0.05 \times 0.05$), which is well below the significance criterion of 0.05.

Acknowledgements

We thank Ruth Hofrichter, Sara Murphy, and the whole developmental psychology EEG lab at the University of Munich for their help in collecting the EEG data. This study was supported by a European Research Council (ERC) advanced grant, "Dividnorm" (project 269616) awarded to Joëlle Proust.

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