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The temporal dynamics of metacognition: Dissociating task-related activity from later metacognitive processes

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ABSTRACT

In recent years, neuroscience research spent much effort in revealing brain activity related to metacognition. Despite this endeavor, it remains unclear exactly when metacognitive experiences develop during task performance. To investigate this, the current study used EEG to temporally and spatially dissociate task-related activity from metacognitive activity. In a masked priming paradigm, metacognitive experiences of difficulty were induced by manipulating congruency between prime and target. As expected, participants more frequently rated incongruent trials as difficult and congruent trials as easy, while being completely unable to perceive the masked primes. Results showed that both the N2 and the P3 ERP components were modulated by congruency, but that only the P3 modulation interacted with metacognitive experiences. Single-trial analysis additionally showed that the magnitude of the P3 modulation by congruency accurately predicted the metacognitive response. Source localization indicated that the N2 task-related activity originated in the ACC, whereas the P3-interplay between task-related activation and metacognitive experiences originated from the precuneus. We conclude that task-related activity can be dissociated from later metacognitive processing.

1. Introduction

When acting upon stimuli in the environment, our actions are accompanied by metacognitive experiences. For example, when typing on a foreign keyboard, you will clearly experience that your actions do not proceed very fluently. While the neurocognitive underpinnings of metacognition have recently received a lot of attention (Fleming et al., 2014, 2010; McCurdy et al., 2013), it remains unclear how these metacognitive experiences develop in time. For example, it is highly debated whether metacognitive experiences associated with our actions are created at the same time of the decision to act, or whether they also depend on new information arriving beyond this decision point (Yeung and Summerfield, 2012). More generally, it is unknown at which point in time specific neural processes contribute to the creation of metacognitive experiences.

Metacognition, a general term used to describe the subjective experiences associated with our actions, has been studied in a variety of research fields. In the meta-memory literature, researchers have extensively investigated subjective experiences associated with memory formation, such as judgments-of-learning during acquisition (Metcalfe and Finn, 2008), and feeling-of-knowing during recall (e.g., Díaz et al., 2007). In the neurocognitive literature, most studies use low-level perceptual decision tasks, and examine the degree of confidence associated with decisions (de Gardelle and Mamassian, 2014; Fleming and Lau, 2014; Fleming et al., 2010) or the awareness of having made an error in the decision process (Boldt and Yeung, 2015; Steinhauser and Yeung, 2010). In the current study, we focus on one particular class of metacognitive experiences, namely the experience of fluency in action-selection. Several recent studies already demonstrated that participants can reliably introspect on the fluency of their action-selection, even when they are unaware of the stimuli manipulating the fluency of selection. For example, Charles et al. (2013) showed that participants could differentiate between correct and incorrect judgments in a simple decision task, even though they did not perceive the stimulus they had to decide on. In a similar vein, studies have used subliminal priming to create a conflict between two responses, and observed that task performance and perceived difficulty were jointly influenced, without participants being

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aware of the visual stimuli driving these changes (Chambon and Haggard, 2012; Desender et al., 2014; Wenke et al., 2010). That is, even though participants are completely unaware of the presence of the subliminal stimuli creating the response conflict, they nevertheless have the metacognitive experience that responding was more difficult on those trials where the subliminal stimulus interfered with response selection. A major benefit of these conflict paradigms is that a large body of research has already documented the neural components associated with the processing of response conflicts. However, while it was recently demonstrated that metacognitive experiences are critically involved in conflict processing (Desender et al., 2014), the role of metacognitive experiences in relation to these components has not been studied.

Conflict tasks are known to reliably modulate two important event-related components (ERPs) in the EEG waveform (Ullsperger et al., 2014). First, a fronto-central N2 component around 200–300 ms post-stimulus is observed, which is believed to reflect a sensitivity of the anterior cingulate cortex (ACC) to the activation of incompatible responses (Van Veen and Carter, 2002). Later in time, a central-parietal P3 component around 300–400 ms post-stimulus emerges, whose functional role is still a matter of debate. Some consider it to be an index of stimulus evaluation (Coles et al., 1985; Purmann et al., 2011), whereas others assume that the P3 reflects the engagement of attentional resources needed for improved control (Clayson and Larson, 2011; West, 2003). Interestingly, the P3 component is also considered as a signature for conscious access (Del Cul et al., 2007; Kouider et al., 2013), making it a likely neural correlate of metacognitive awareness in conflict tasks.

Based on existing evidence, both the N2 and P3 could be involved in metacognition. First, noting that activity in the ACC is related to both cognitive (e.g., response conflict, errors) and affective (e.g., pain) factors, Spunt et al. (2012) showed that the ACC tracks changes in subjective experience, such as frustration and negative affect (for theoretical perspectives, see e.g., Hillman and Bilkey (2013) and Shackman et al. (2011)). Therefore, metacognition could be related to activity in the ACC, reflected by the N2 component. Second, research on error processing revealed that awareness of one's own errors selectively modulates the error positivity (Pe) around 300 ms post-response (Hughes and Yeung, 2011; Nieuwenhuis et al., 2001), whereas the earlier error related negativity (ERN; originating from the ACC; Yeung et al., 2004) is only modulated by objective accuracy (although this latter claim has been contested, see e.g., Scheffers and Coles, (2000), Shalgi and Deouell, (2012) and Wessel, (2012)). Given that the Pe is considered to be the error-related homolog of the P3 (Ridderinkhof et al., 2009), metacognition should be expressed in the P3 component only.

In short, while both the N2 and the P3 could theoretically be linked to metacognitive experiences, this has not been tested before. The aim of the current study is to investigate this and to dissociate task-related activity from activity related to metacognitive experiences.

2. Materials and methods

2.1. Participants

Thirty-one participants, 17 female and 14 male, participated in return for a monetary compensation (£15). Mean age of the sample was 24.3 years ($SD=5.2$, range 19–42). All participants were right-handed, had normal or corrected-to-normal vision, had no history of epilepsy and were not taking psychoactive drugs. The study was approved by the Ethics Committee of the University of Essex and written informed consent was obtained from each participant prior to the experimental session. Because of intense sweating, caused by extreme hot weather conditions, and resulting noise on the EEG recordings, the data of six participants were unfit for analyses. The data of one additional participant were excluded because of technical problems with the EEG recording.

2.2. Experimental procedure

Participants were seated in a dimly lit room for the duration of the experimental session. Participants completed a masked priming experiment in which they additionally were asked to report about the metacognitive experience associated with their response (see Fig. 1). Each experimental trial started with a fixation cross for 1000 ms. Subsequently, a prime arrow (1.5° wide and 0.7° high) pointing to the left or right was presented for 34 ms followed by a blank screen for 34 ms. Then, a target arrow (3.3° wide and 1.4° high) pointing to the left or right was presented for 116 ms followed by a blank screen. Because the prime arrows fitted perfectly within the contours of the target arrow (i.e., metacontrast masking; Vorberg et al., 2003), primes were rendered invisible. This has the major advantage that task performance and metacognitive experiences are influenced without participants being aware of the visual stimuli driving these changes (Chambon and Haggard, 2012; Desender et al., 2014; Wenke et al., 2010). Participants were asked to respond as fast and accurate as possible to the direction of the target. They were instructed to press “d” in response to a left pointing target arrow and “k” in response to a right pointing target arrow with the middle finger of each hand on a qwerty keyboard. If a response to the target was registered within 3000 ms, a blank screen was presented for 516 ms, followed by a screen asking participants a metacognitive question: “How much difficulty did you experience when responding to the arrow?”. They could answer either by pressing the “o” key with the ring finger of their right hand (“Rather more difficulty”) or by pressing the “m” key with the index finger of their right hand (“Rather less difficulty”). The wordings ‘rather more’ and ‘rather less’ were used in order to stress that the difference between both metacognitive experiences is small, a subtlety that is potentially lost when using the terms ‘easy’ versus ‘difficult’. There was no time limit to answer this question. The inter-trial interval was 800 ms.

Each participant started with 20 practice trials in which the metacognitive question was omitted. Subsequently, the experimenter explained that participants had to rate their experience associated with a trial after each response. The experimenter motivated participants to use all information available to them (i.e., difficulty, error-tendency, response fluency) to answer this question. Participants were informed that there would be an equal amount of “more difficult” and “less difficult” trials, and they were motivated to keep a balance between these responses. Participants received 20 additional practice trials with the metacognitive question. After these two training phases, each participant performed eight blocks of 80 trials each. In each block, half of the trials were congruent (i.e., prime and target pointing in the same direction), and half were incongruent (i.e., prime and target pointing in opposite directions) creating a response conflict.

Only after the main experiment, participants were informed about the presence of the primes, and participated in a subsequent detection task. In this task, participants were instructed to categorize the direction of the prime arrows, instead of the target arrows. During the detection task, targets were neutral with heads pointing in both directions to ensure that participants were not accidentally responding to the target. The detection task comprised of 100 trials.