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Metacognition of attention during tactile discrimination

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A B S T R A C T

The ability to monitor the success of cognitive processing is referred to as metacognition. Studies of metacognition typically probe post-decision judgments of *confidence*, showing that we can report on the success of wide range of cognitive processes. Much less is known about our ability to monitor and report on the degree of top-down *attention*, an ability of paramount importance in tasks requiring sustained attention. However, it has been repeatedly shown that the degree and locus of top-down attention modulates alpha (8–14 Hz) power in sensory cortices. In this study we investigated whether self-reported ratings of attention are reflected by sensory alpha power, independent from confidence and task difficulty. Subjects performed a staircased tactile discrimination task requiring sustained somatosensory attention. Each discrimination response was followed by a rating of their attention at the moment of stimulation, or their confidence in the discrimination response. MEG was used to estimate trial-by-trial alpha power preceding stimulation. Staircasing of task-difficulty successfully equalized performance between conditions. Both attention and confidence ratings reflected subsequent discrimination performance. Task difficulty specifically influenced confidence ratings. As expected, specifically attention ratings, but not confidence ratings, correlated negatively with contralateral somatosensory alpha power preceding tactile stimuli. Taken together, these results demonstrate that the degree of attention can be subjectively experienced and reported accurately, independent from task difficulty and knowledge about task performance.

1. Introduction

Many day-to-day tasks require sustained attention, such as minding the traffic ahead while driving your car. However, we are unable to sustain attention indefinitely, with spontaneous lapses in attention leading to sub-optimal performance and even causing potentially hazardous situations, e.g. when a jaywalker suddenly crosses your path (for an overview of the costs of mindwandering see e.g. Mooneyham and Schooler, 2013). We would therefor benefit from an ability to monitor our attentional performance, even in situations where external cues about its functioning are not (yet) present. Such an ability to monitor the success of cognitive processing is commonly referred to as metacognition and has experienced a recent surge of interest (Fleming et al., 2012a; Meyniel et al., 2015). However, the study of attention monitoring per-se has so far remained scant (Macdonald et al., 2011; Whitmarsh et al., 2014).

Metacognition is typically studied by means of confidence judgments, demonstrating an ability to report on the efficacy of wide range of cognitive processes, from visual discrimination and detection (Fleming et al., 2010; Baird et al., 2013; Fleming et al., 2012b; Wu, 2015), to perceptual categorization (Paul et al., 2015), memory (Yokoyama et al., 2010), mathematical calculation (Fernandez Cruz et al., 2016), visuo-motor performance (Sinanaj et al., 2015) and somatosensory discrimination (Hilgenstock et al., 2014; Baumgarten et al., 2016). Furthermore, studies show that people differ in the degree of correspondence between their subjective confidence and objective (Type-1) task performance, allowing the evaluation of metacognitive accuracy, or Type-2 performance (Fleming et al., 2010; Fleming and Lau, 2014; Maniscalco and Lau, 2012).

While both attention and confidence ratings allow researchers to determine metacognitive accuracy, attention is also neurophysiologically tractable. Specifically, extracranial electroencephalography (EEG) and magnetoencephalography (MEG) recordings of pre-stimulus activity show that top-down attention suppresses alpha (8–14 Hz) oscillations in a retinotopic (Kelly et al., 2009; Rihs et al., 2007; Thut et al., 2006; Wyart and Tallon-Baudry, 2008, 2009) somatotopic (Haegens et al., 2010; Anderson and Ding, 2011; Whitmarsh et al., 2014; van Ede et al., 2012, 2014; Haegens et al., 2011; Anderson and Ding, 2011),

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and modality-specific (Mazaheri et al., 2014; van Diepen et al., 2015) manner. The role of alpha oscillations in attention is understood in terms of its ability to selective inhibit task-irrelevant activity through pulsed inhibition, modulating cortical excitability in preparation to upcoming stimuli, as well as selecting and routing information flexibly (Klimesch et al., 2007; Jensen and Mazaheri, 2010). Indeed, fluctuations of pre-stimulus alpha in sensory areas determine subsequent performance, from tactile detection (Weisz et al., 2014) and discrimination (Haegens et al., 2011), visual detection (Thut et al., 2006) and discrimination (Kelly et al., 2009), to response inhibition (Bengson et al., 2012) and modulating partial awareness of letters versus words (Weisz et al., 2014; Magazzini et al., 2016; Levy et al., 2013). Furthermore, combined EEG-fMRI studies show that occipital and central alpha power are inversely related to visual (Scheeringa et al., 2009, 2011) and somatosensory (Ritter et al., 2009) BOLD signal, respectively. Localized alpha power can therefor function as an objective index of attentional performance in the study of metacognition. In a recent MEG study, Baumgarten et al. (2016) investigated the relationship between confidence and alpha power when subjects distinguished single from double electro-tactile stimuli. Correct trials showed a negative correlation between binned alpha power and mean confidence ratings, while incorrect trials showed a non-significant positive correlation. The relationship between confidence ratings and performance, i.e. metacognitive accuracy, was not reported, however, limiting the interpretation of these initial findings.

The current study further extends the research on metacognition of attention. While it was previous shown that ratings of attention correspond to contralateral alpha power Whitmarsh et al. (2014), it has not yet been investigated whether attention ratings are able to explain variations in somatosensory discrimination. In other words, the link between neurophysiological measures of attention, subjective ratings of attention, and behavioral performance was still missing. The current study therefor set out to measure metacognitive performance in a somatosensory discrimination task. However, as argued in Whitmarsh et al. (2014), by providing a task context, confidence (about performance) might give away cues about the attentional state. We tested this alternative explanation by also measuring the correlation between confidence and alpha power. In contrast to Whitmarsh et al. (2014), subjects were not cued to attend to either their left or right hand, but were always attending to their left hand. This removed the necessity to counter-balance the response hand, further simplifying the experiment for the subject and potentially increasing spontaneous fluctuations of attention between trials. Furthermore, to increase the sensitivity of our correlation analyses, we increased the metacognitive ratings from a 4-step to a 7-step rating. A block-design allowed a within-subject comparison of metacognitive performance and neurophysiological correlates of both attention and confidence judgments.

Subjects discriminated electro-tactile stimuli, followed by either attention, confidence or control (random) ratings. On-line staircasing was used to manipulate task difficulty while equalizing performance levels between subjects and conditions. It has previously been shown that confidence in a decision increases with discriminability of the stimulus (Vickers and Packer, 1982) and decreases with task difficulty (Lund, 1926; Hertzman, 1937; Kiani et al., 2014). In rats, the probability that a trial will be aborted reflects decision confidence, which increases with reduced target discriminability on error trials (Kepecs et al., 2008; Kepecs and Mainen, 2012). Furthermore, computational models where confidence reflects target discriminability (Rolls et al., 2010b; Kepecs and Mainen, 2012; Insabato et al., 2010; King and Dehaene, 2014) are supported by BOLD studies (Rolls et al., 2010a) and intercranial recordings in monkeys (Kiani and Shadlen, 2009). We therefore hypothesized that difficulty would influence confidence ratings, but not affect attention ratings.

Metacognitive accuracy was measured independently from response bias by means of the area under the receiver operating characteristic curve (AUROC2, Fleming and Lau, 2014). We hypothesized that both attention and confidence ratings reflect discrimination performance, expressed by a mean AUROC2 greater than 0.5. We expected attention ratings, but not confidence ratings, to correlate negatively with alpha power preceding the tactile stimuli. MEG was used to source-reconstruct trial-by-trial alpha power during a three second interval preceding the tactile stimuli, an interval previously demonstrated to be associated with retrospective ratings of attention (Macdonald et al., 2011; Whitmarsh et al., 2014).

2. Materials and method

2.1. Subjects

26 healthy subjects (12 females, mean age 29 years, range 23–35) enrolled after providing written informed consent and were paid in accordance with guideline of the local ethics committee. The experiment was in compliance with national legislation and the code of ethical principles (Declaration of Helsinki). One subject was excluded from the analysis due to an implant that would make subsequent MRI scanning unsafe.

2.2. Experimental paradigm

The experiment consisted of three randomized conditions presented in three randomized triplets, for a total of nine blocks. Each block started with a display of instructions, followed by 40 trials. The onset of each trial was indicated by the disappearance of arrows flanking the fixation cross (Fig. 1). Attention was maintained during a delay of logarithmic probability, i.e. according to a flat hazard rate (3–15 s, M=5 s). A single electro-tactile stimulus was then presented, followed in 50% of cases (*ad random*) by a second stimulus. To normalize performance over subjects, the stimulus onset asynchrony (SOA) of the second stimulus adapted on-line according to a 2-up, 1-down staircasing procedure, resulting theoretically in a performance of 71% (Levitt, 1971). The minimum SOA was set at 10 ms due to the fact that during piloting shorter SOAs resulted in qualitatively stronger sensations, probably due to temporal summation. One second after stimulation, a response screen probed subjects to indicate whether the stimulus consisted of one or two shocks, followed by a 7-step rating. In the attention condition, subjects reported on their level of attention at the moment of stimulus presentation. In the confidence condition, subjects reported their confidence in the stimulus discrimination. In the control condition, subjects had only to select a point on the scale that was indicated at random (excluding starting position), c.f. Fleming et al. (2012b). The direction of scales was counterbalanced over subjects. No feedback about performance was provided.

2.3. Procedure

After digitization of head-shape and location of head-position coils, disposable ring electrodes (Nicolet, Natus Medical Inc.) were placed on the second phalanx of the thumb, at 4 mm apart, and connected to the stimulator (DeMeTech SCG 3.0) placed outside the magnetically shielded room. The stimulation current (at 200 μs) was adjusted in collaboration with the participant to a level where a clear but comfortable sensation was perceived. The level was always at a minimum of 120% of sensory threshold, and never reached motor threshold. In a workup session preceding the recording, the initial step sizes (5 or 10 ms) and SOAs (50, 100 or 200 ms) were calibrated. If during the workup the staircasing did not converge, stimulus intensity was increased and the calibration repeated. Once seated in the MEG gantry, the experiment was practiced for a minimum of 10 trials per condition until understood. A self-paced break was allowed between each block and a longer break was advised at every three blocks. The experiment lasted for a total of about 45 min, including breaks.