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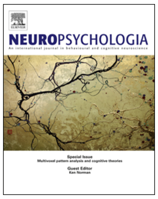

Decreased beta-band activity is correlated with disambiguation of hidden figures

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ABSTRACT

Insight is commonly described as sudden comprehension, sometimes called an “Aha! moment.” In everyday life, we apply the process of insight to problems that are difficult to solve at first glance or that we perceive as ambiguous; however the brain dynamics underlying the disambiguation process remains elusive. Beta-band oscillatory brain activity has been hypothesized to reflect the transition of cognitive states. To elucidate the neural mechanism of insight, we recorded electroencephalograms while subjects were presented with hidden figures followed by unambiguous, gray images. We identified oscillatory activity to detect temporal changes, and compared brain activity that occurred during a perceptual transition with activity that occurred when no perceptual transition occurred. Statistical comparison confirmed stronger beta-power decrease during perceptual transition. Source analysis indicated that the beta-power decrease was around the parietal–posterior regions, mainly in the precuneus. We propose that beta-band desynchronization in the parietal–posterior regions reflects the disambiguation process, and our findings provide additional support for the theory that beta-band activity is related to the transition of cognitive state.

1. Introduction

In our daily lives, perceptual ambiguity resulting from interference by factors such as masking or shading can lead to failures in immediately or accurately perceiving objects. However, once objects have been perceived, they can usually be recognized easily. A process of sudden discovery and rapid learning (Dolan et al., 1997) occurs as one transition from ambiguous to clear states. This phenomenon has been labeled the “Eureka effect,” or the “aha moment,” and has been studied previously using degraded or distorted pictures in laboratory settings. Several studies have reported that multiple brain regions, including the temporal lobe and the medial parietal cortex, are involved in this phenomenon (Andrews & Schluppeck, 2004; Dolan et al., 1997; Hegde & Kersten, 2010; Hsieh, Vul, & Kanwisher, 2010; McKeeff & Tong, 2007; Moore & Engel, 2001). However, the temporal dynamics of disambiguation remain unclear, partially due to the low temporal resolution of fMRI. Magnetoencephalographic/electroencephalographic (MEG/EEG) techniques have a higher temporal resolution, and are therefore potentially more useful than fMRI for studying the temporal characteristics of disambiguation processing.

Several MEG/EEG studies using 2-tone (black and white) images have shown that gamma-band activity is related to object representation (Goffaux, 2004; Grützner et al., 2010; Latinus & Taylor, 2005; Rodriguez et al., 1999; Trujillo, Peterson, Kaszniak, & Allen, 2005). Indeed, perception of upright 2-tone faces is associated with an increase in induced gamma power (Rodriguez et al., 1999), and gamma oscillations might differ between detected and undetected faces (Grützner et al., 2010). Additionally, gamma oscillations in the visual cortex have been shown to underlie experience-based perception of visual scenes (Goffaux, 2004). However, although these studies focused on the difference in brain states associated with detected and undetected objects, they did not examine the process of disambiguation itself.

In contrast, beta-band oscillations are thought to decrease when the current cognitive set is disrupted by incoming sensory information (Engel & Fries, 2010). Recent reports indicate that beta oscillations are related to complex cognitive processes (Basile et al., 2010; Iversen, Repp, & Patel, 2009; Okazaki, Kaneko, Yumoto, & Arima, 2008; Pesonen, Hämäläinen, & Krause, 2007; Sheth, Sandkühler, & Bhattacharya, 2009). For instance, Sheth et al. (2009) suggested that decreased beta oscillation is related to complex perceptual transitions such as transformative reasoning during cognitive insight. Thus, beta-band activity seems related to the transition of cognitive states.

We therefore hypothesize that beta-band oscillations are related to the process of disambiguation, and here we investigated

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oscillatory activity during the disambiguation process of 2-tone images using EEG. We compared three perceptual conditions derived from our task before and after disambiguation, and report significant differences in the oscillatory activity during disambiguation. In particular, we aimed to monitor the temporal dynamics of the disambiguation process and to identify the cortical regions responsible.

2. Methods

2.1. Participants

Fourteen volunteers (12 men and 2 women; mean age 24.6 years) participated in the experiments. One male participant was excluded from analysis because of movement artifacts. Informed consent was obtained from all participants after details of the procedure had been explained to them. Experimental procedures were approved by the Committee for Human Research at Toyohashi University of Technology.

2.2. Stimuli and task

Stimuli were based on natural images that include an object (Sozaijiten, Datacraft Co., Ltd. and GuMantan, DesignEXchange Co., Ltd.). The images were converted into gray-scale and 2-tone images (Fig. 1). A pool of 300 paired gray and 2-tone images (GI and TI, respectively) was used for the experimental task. Experiments were performed in a dark shielded room, and stimuli were displayed on a TOTOKU CV921X CRT monitor with a spatial resolution of 800 × 600 pixels, a refresh rate of 100 Hz, and driven by a VSG2/5 graphics card (Cambridge Research Systems). The participants were seated 55 cm in front of a computer screen. The experiment consisted of 5 blocks, with each block containing 60 trials and lasting approximately 8 min. The stimuli were presented in a specific order in each trial (first-TI→ GI→ second-TI). The first-TI was presented for 500 ms, and subjects were asked to respond by pressing one button to indicate they saw the image (recognition), and another if they did not (no-recognition). First-TI offset was followed by a 1000-ms blank screen. Next, a gray-scale image (either the gray image of first-TI, or an unrelated image) was presented for 500 ms. After a 1500-ms blank screen, the second-TI was presented for 500 ms, and subjects were again asked to respond when they saw it. As a result, we had three possible perceptual outcomes (first-TI: no-recognition, second-TI: no-recognition (NN); first-TI: no-recognition, second-TI: recognition (NR); and first-TI: recognition, second-TI: recognition (RR)) (Fig. 2). In this study, we focused on the subjective process of disambiguation. So the present analyses are based on the responses given by the participants on whether they did or not see the image and there is no control about if this response is correct or not. To keep the number of trials in each condition equal, we performed a pre-test for selecting images. Three volunteers (2 men and 1 woman; mean age 21.7 years) participated in the pre-test, with the procedure being the same as for the main experiment. Based on the average results of the pre-experiment, we selected the 100 most easily perceived images and the 200 that were most difficult. For half of the 200 difficult images, the gray images were unrelated to the 2-tone ones to obtain the sufficient number of NN responses. As a result, NN responses included two cases in which the gray-scale image was related and unrelated to the 2-tone image. However, we focused on whether the perceptual state changed and in the NN condition, the minimum requirements is the situation in which ‘aha moment’ is not triggered. For EEG analysis, we focused our analysis on the EEG signals from the onset of GI.

2.3. Data acquisition

EEGs were recorded using a 64-channel system (Electrical Geodesics, EGI), and all signals recorded were referenced to a Cz electrode, sampled at 500 Hz using the Netstation acquisition software and an EGI NetAmps 300 amplifier. Impedance was checked online before recording, and considered acceptable when below 50 kΩ. We used all EEG data for analysis except channels 61–64, which were attached to the face area. The data were re-referenced to the average of all non-excluded channels.

2.4. ERP (event-related potential) analysis

Butterworth band-pass filter with tenth order (1–30 Hz) was applied offline to the continuous EEG data using the EEGLAB toolbox (Delorme & Makeig, 2004). The continuous EEG data were epoched into 900-ms data (from −100 to 800 ms from stimulus onset) and baseline corrected (−100 to 0 ms). Epochs containing activity greater than the absolute value of 70 μV in amplitude were defined as artifact epochs and rejected from further analysis. Epochs containing extreme values (limits = ±70 μV), abnormal trends (max slope = 50; R^2 limit = 0.3), improbable data (single-channel limit = 5; all channel limit = 5), and abnormally distributed data (single-channel limit = 5; all channel limit = 5) were also rejected. Differences between both conditions were tested for statistical significance by using a cluster-level randomization (500 randomizations) procedure (Maris & Oostenveld, 2007). A cluster p-value below 5% (two-tailed testing) was considered significant.

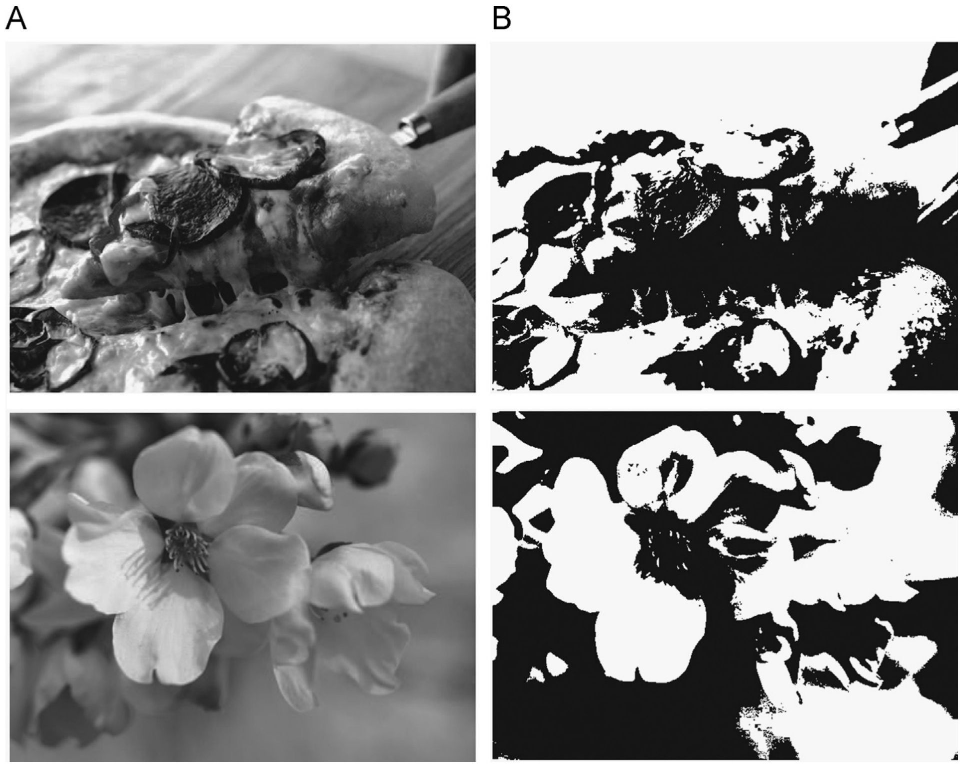

Fig. 1. Sample stimuli. (A) Natural gray images of a pizza and flowers and (B) 2-tone versions of these natural images.