



The neural oscillations of conflict adaptation in the human frontal region



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ABSTRACT

Incongruity between print color and the semantic meaning of a word in a classical Stroop task activates the human conflict monitoring system and triggers a behavioral conflict. Conflict adaptation has been suggested to mediate the cortical processing of neural oscillations in such a conflict situation. However, the basic mechanisms that underlie the influence of conflict adaptation on the changes of neural oscillations are not clear. In the present study, electroencephalography (EEG) data were recorded from sixteen healthy human participants while they were performing a color-word Stroop task within a novel look-to-do transition design that included two response modalities. In the 'look' condition, participants were informed to look at the color of presented words but no responses were required; in the 'do' condition, they were informed to make arranged responses to the color of presented words. Behaviorally, a reliable conflict adaptation was observed. Time–frequency analysis revealed that (1) in the 'look' condition, theta-band activity in the left- and right-frontal regions reflected a conflict-related process at a response inhibition level; and (2) in the 'do' condition, both theta-band activity in the left-frontal region and alpha-band activity in the left-, right-, and centro-frontal regions reflected a process of conflict control, which triggered neural and behavioral adaptation. Taken together, these results suggest that there are frontal mechanisms involving neural oscillations that can mediate response inhibition processes and control behavioral conflict.

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1. Introduction

When facing a conflict situation, human beings are capable of flexibly adjusting their executive control in order to resolve the conflict. This conflict adjustment process engages the frontal region (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Cohen & van Gaal, 2012; Koechlin, Ody, & Kouneiher, 2003) and encompasses two basic components: conflict detection and control implementation (Botvinick, Braver, Barch, Carter, & Cohen, 2001; MacDonald, Cohen, Stenger, & Carter, 2000). Operationally, conflict adaptation refers to a conflict-induced decrease in congruency effects of an incongruent type compared with those of a congruent type (Gratton, Coles, & Donchin, 1992). Such a phenomenon can be indexed by the performance differences between the incongruent and congruent types in congruency tasks (Egner, 2007), e.g., the Stroop task (Stroop, 1935), flanker task (Eriksen & Eriksen, 1974), and Simon task (Simon, 1990).

In the congruency tasks, conflict adaptation is typically investigated using a do-to-do transition design, where participants are required to make responses in the sequential 'do' conditions. Because executing a response also involves a recruitment of cognitive control (Aron, Robbins, & Poldrack, 2004; Badre & Wagner, 2004; Egner & Hirsch, 2005; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004), the recruitment of the cognitive control process and the response execution process will happen in the sequential 'do' conditions (Carter & van Veen, 2007). Because the intertrial intervals (ITIs) between these 'do' conditions are typically short (e.g., ranging from 0.8 s to 1.2 s), the cortical processing evoked by the response execution in the previous 'do' condition will unavoidably impair the recruitment of cognitive control in the current 'do' condition. As conflict adaptation involves a sequential regulation of cognition in a trial-to-trial fashion, the previous-trial response execution will make it difficult to examine the unimpaired neural mechanisms of conflict adaptation within the do-to-do transition (Tang, Hu, Li, Zhang, & Chen, 2013).

To avoid the problem described above, in the present study, we developed a novel experimental design, which incorporated a look-to-do transition. In short, participants were required to perform a Stroop task that included two response modalities (i.e., in the 'look' condition, the color of the stimulus was observed but no response was required; in the 'do' condition, a response to the color of the

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stimulus was required). Because no responses were required in the 'look' condition, the stimuli might be processed at a stimulus or response-inhibition level (Milham et al., 2001). In this case, any change in brain activity would be associated with the stimulus representations or response inhibition. However, conflict resolution processing should be induced in the 'do' condition because overt responses were required. Therefore, adopting the look-to-do transition design allows us to examine a pure conflict adaptation that is not confounded by the response execution.

Previously, the neural mechanisms of conflict adaptation have been studied using the event-related potential (ERP) technique, which offers the promise of excellent temporal resolution (at the millisecond level). An ERP is normally obtained from the across-trial average of several electroencephalographic (EEG) traces. The obtained ERP waveforms are time- and phase-locked to the onset of a stimulus (e.g., a visual stimulus) or a response (e.g., pressing a response button) (Cohen, 2011). In addition to the phase-locked ERP, presentation of a stimulus can induce non-phase-locked modulations of the ongoing oscillatory EEG activity that are not detectable using time-domain across-trial averaging (Makeig, Debener, Onton, & Delorme, 2004). These modulations involve either a transient increase (event-related synchronization, ERS) or decrease (event-related desynchronization, ERD) in EEG power, usually confined to a specific frequency range. ERS and ERD reflect changes in the parameters that control oscillations in neuronal networks. Depending on their frequencies, ERS and ERD may represent neuronal mechanisms involved in cortical activation, inhibition, and binding (Pfurtscheller & Lopes da Silva, 1999). Conflict adaptation is likely to modulate on-going oscillatory EEG activity (Cohen & Cavanagh, 2011; van Steenbergen, Band, & Hommel, 2012), and therefore, investigating these changes may reveal novel neural mechanisms that are involved in the processes of conflict detection and resolution.

Previous work suggests that conflict adaptation involves top-down recruitment of cognitive control (Carter & van Veen, 2007; Kerns et al., 2004; Kerns, 2006; Matsumoto & Tanaka, 2004), with the anterior cingulate cortex (ACC) involved in processing of conflict detection and the prefrontal cortex (PFC) involved in implementing control (Botvinick et al., 2001). In addition, the centro-frontal region has been proposed to interact with the lateral frontal region to coordinate neural networks that are involved in detecting conflict and triggering post-conflict adaptation (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004; Carter & van Veen, 2007; Cavanagh et al., 2011; Cohen, 2011; Ridderinkhof et al., 2004). Thus, the EEG oscillations at specific frequency ranges in these regions may be the mechanisms by which behavioral conflict and post-conflict adaptation are displayed (Cohen & Cavanagh, 2011).

For instance, ERS in the theta-band (4–7 Hz) in the frontal region has been suggested to reflect conflict detection and behavioral adjustment in the Stroop task (Hanslmayr et al., 2008). Additionally, theta oscillations can be considered as a neural signature supporting a coordinated response that indicates alertness, arousal, and/or readiness to process information (Başar, Başar-Eroglu, Karakas, & Schürmann, 2001). ERS in the alpha-band (7–13 Hz) suggests top-down inhibitory control processing, whereas ERD in the alpha-band reflects ongoing neural activity across various cognitive tasks (Jensen & Mazaheri, 2010; Klimesch, Sauseng, & Hanslmayr, 2007; Mathewson et al., 2011; Monto, Palva, Voipio, & Palva, 2008). However, the neural oscillations related to conflict-induced trial-to-trial behavioral adaptation are poorly understood.

In the present study, our aim was to study the modulation of oscillatory EEG activity by conflict adaptation and to understand the relevant neural dynamics of the changes. EEG data were recorded from sixteen healthy human participants, who were instructed to perform the color-word Stroop task within the look-to-do

transition (Tang et al., 2013). Modulation of oscillatory EEG activity, represented as event-related spectral perturbation (ERSP), was estimated using a continuous wavelet transform (CWT) and compared for different types of stimuli in both the 'look' and 'do' conditions.

2. Methods

2.1. Participants

Sixteen right-handed healthy volunteers (nine females), between 20 and 24 years old (21.75 ± 1.34 , mean \pm SD), took part in the experiment. All volunteers reported normal or corrected-to-normal vision and normal color perception. All volunteers gave written informed consent and were paid for their participation. The local ethics committee approved the procedure. In addition, the volunteers were unaware of the purpose of the experiment.

2.2. Stimuli

The stimuli were presented using E-Prime software (Psychology Software Tools, Inc. Pittsburgh, PA) on a 17-in computer monitor. The viewing distance was approximately 60 cm. Responses were registered using a standard QWERTY keyboard. The stimuli consisted of four words (RED, YELLOW, BLUE, and GREEN; in Chinese with Song Ti font) that were presented in a red, green, blue or yellow font. The RGB values for the stimulus colors were 255, 0, 0 (red); 0, 255, 0 (green); 0, 0, 255 (blue); and 255, 255, 0 (yellow). For the congruent type stimuli, the color and word matched (e.g., the word RED was in red font); for the incongruent type stimuli, the color and the word were different (e.g., the word RED was in blue font).

To assess conflict adaptation, trial sequences were separated into four types by congruency: for the 'look' condition ('c' was congruent, 'i' was incongruent) and for the 'do' condition ('C' was congruent, 'I' was incongruent), resulting in cC, cI, iC, and iI types. Trials that did not follow the look-to-do format were excluded from the subsequent analysis. Within the look-to-do transition, there were 320 look-to-do paired trials. In the 'look' condition, each of the congruent and incongruent types contained 160 trials. In the 'do' condition, each of the cC, cI, iC, and iI types contained 80 trials. In addition, we excluded repetition-priming trials by using experimental manipulation to avoid distractor (word)-to-distractor, distractor-to-target (color), target-to-distractor, and target-to-target repetitions.

2.3. Procedure and task

Fig. 1A shows a representative sequence of trials (bottom) and the detailed timing of one trial (top). In each trial, the stimuli were presented as follows: (1) a fixation for 0.5 s; (2) a blank interval for 0.5–0.8 s (the interval varied randomly); (3) a colored word until a key was pressed or for 1.5 s if there was no response; and (4) a blank interval for 0.8–1.2 s (interval varied randomly). For each trial, the fixation was an asterisk (*) or a crosshair (+), which indicated whether the corresponding trial was a 'look' condition or a 'do' condition, respectively. For the 'look' condition, the participants were instructed to look at the color of stimuli, without any response (overt or covert). For the 'do' condition, participants were instructed to press the "D" key using the left middle finger if the color of the word was red, the "F" key using the left forefinger if the color of the word was green, the "J" key using the right forefinger if the color of the word was yellow, and the "K" key using the right middle finger if the color of the word was blue. Participants were instructed to perform the task as fast as possible without sacrificing accuracy. Prior to completion of six experimental blocks, participants completed a training block with 64 trials to acclimate to the task conditions. Participants were instructed to rest for two minutes between blocks and to continue with the experiment by pressing the space bar.

2.4. Electrophysiological recording and analysis

The EEG data were collected using a 64-channel Brain Products system (Brain Products, GmbH, Germany; pass band: 0.01–100 Hz, sampling rate: 500 Hz) using a standard EEG cap based on the extended 10–20 system. The left mastoid was used as the reference channel, and all channel impedances were kept below 5 k Ω . The electro-oculographic (EOG) signals were recorded from four surface electrodes, which were placed over the upper and lower eyelids and laterally 1 cm from the outer corner of the left and right orbits to monitor ocular movements and eye blinks.

EEG data were preprocessed and analyzed using Letswave (<http://amoureux.wenode.com>) (Mouraux & Iannetti, 2008) and EEGLAB (Delorme & Makeig, 2004). Within the look-to-do transition, all 'look' trials and 'do' trials, where the responses were correct and the response time (RT) was less than 1.5 s, were selected for the following analysis. Continuous EEG data were band-pass filtered between 0.1 and 30 Hz. EEG epochs were segmented in 1.5-s time-windows (pre-stimulus 0.5 s and post-stimulus 1 s) and baseline corrected using the pre-stimulus time interval. Trials contaminated with EOG artifacts (mean EOG voltage exceeding $\pm 80 \mu\text{V}$) or those with artifacts due to amplifier clipping, bursts of electromyographic (EMG) activity, or peak-to-peak deflection exceeding $\pm 80 \mu\text{V}$ were excluded from analysis. The remaining EOG artifacts were subtracted using a validated method based on

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