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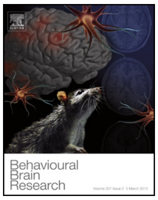

Research report

Event-related potentials and neural oscillations dissociate levels of cognitive control

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HIGHLIGHTS

- The present study applied event-related potentials (ERPs) and investigated neural oscillations during performance of three different nested cognitive control tasks.
- Results demonstrated a parametric modulation of the P300 component as well as beta-band (13–25 Hz) oscillations as a function of different levels of cognitive control.
- Moreover, conditions requiring flexible updating of information exhibited similar alpha-band (8–13 Hz) oscillations, which differed from the condition without flexible updating (low-level).
- These results suggest dissociable mechanisms of flexible information updating and complexity of cognitive control processes indexed by different oscillatory effects.

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ABSTRACT

Recent models of human behavior suggest a hierarchical organization of cognitive control processes. These models assume that different sub-goals of cognitive control processes are nested in each other, such that higher-level sub-goals can only be accomplished when lower-level sub-goals have been realized. While the neuroanatomical localization of this organizational principle has already been successfully tested, the exact temporal nature remains to be explored. The present study applied event-related potentials (ERPs) and investigated neural oscillations during performance of three different nested cognitive control tasks. Results demonstrated a parametric modulation of the P300 component as well as beta-band (13–25 Hz) oscillations as a function of different levels of cognitive control. Moreover, conditions requiring flexible updating of information exhibited similar alpha-band (8–13 Hz) oscillations, which differed from the condition without flexible updating (low-level). These results suggest dissociable mechanisms of flexible information updating and complexity of cognitive control processes indexed by different oscillatory effects.

1. Introduction

Human behavior displays a hierarchical structure comprising nested subroutines [35,42]. Hierarchical structures can be found in various types of behavior, such as language [7], music [47] or action [10]. Action hierarchy can be extended into cognitive control, which refers to the ability to coordinate thoughts and actions in relation to internal representations of goals and intentions [19]. In particular, cognitive control refers to the ability to make flexible adjustments based on internal or external goals, and to maintain goals and intentions at the same time [16,20,41,49]. Cognitive control processes represent a broad collection of functions, such as maintaining current goals in working memory, implementing task strategies, action monitoring or behavioral adjustments when performing errors.

A crucial feature of the hierarchical organization of human behavior is the sequential organization of nested subroutines [4]. Recent models of cognitive control highlight the importance of the

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lateral frontal cortex for the hierarchical organization of human behavior [1,14,65]. Converging evidence suggests that different sub-regions within the lateral frontal cortex are engaged in varying subroutines of cognitive control [29]. Subroutines of cognitive control can be operationalized in neurocognitive experiments using nested tasks with differences in rule complexity, i.e. the number of constituents in a task that need to be related [27]. For example, Stimulus-Response (SR) mapping tasks (If stimulus A, then button press 1) exhibit less rule complexity than task switching paradigms (If cue 1 and if stimulus A, then button press 1). Importantly, less complex cognitive control tasks are nested in medium complex tasks, which in turn are nested in more complex tasks. Thus, the nested task structure is a crucial prerequisite of the hierarchical organization of cognitive control. In other words, the operationalization of hierarchical cognitive control processes necessitates a nested task structure.

While the spatial organization of brain regions involved in the hierarchy of cognitive control has been repeatedly tested, the neural oscillations of the operations underlying this organizational principle remain to be explored. The present study aimed to delineate possible dissociations between cognitive control tasks with varying complexity by electrophysiological means. The exploration of neural oscillations during cognitive control processing has barely begun. To our knowledge, the present EEG study represents the first experiment investigating broad cortical network organizations of the nested organization of cognitive control tasks by means of neural oscillations. Thus, we aim to operationalize a (possible) cognitive control hierarchy by implementing task-sets in which we systematically vary the complexity of the tasks, while measuring ERPs and neural oscillations. Task complexity was manipulated using SR mapping tasks that were nested in each other. We generated three different task sets comprising high-, mid- and low-levels of task complexity. Previous ERP studies on cognitive control applied for instance the task-switching paradigm [5,11,30,32,48] or the Stroop task [37,72,74]. These studies reported a modulation of the P300 component as a function of switch-costs (task-switching paradigm) and incongruency (Stroop task). Thus, we expected a modulation of the P300 amplitude as a function of complexity of cognitive control. In accordance with the model of hierarchical organization of cognitive control we predicted the P300 amplitude to be highest for high-level, intermediate for mid-level, and lowest for low-level of cognitive control.

In addition, we predicted a similar modulation of neural oscillations during task performance. Several studies have demonstrated that cognitive processing is accompanied by rhythmic fluctuations, linking the oscillatory patterns of neuronal activity to periodic fluctuations in perception, attention, decision-making or memory reactivation [28]. Oscillations in the alpha-band (8–13 Hz) and beta-band (14–31 Hz) are increasingly viewed as an index of cognitive control mechanisms [26,62]. Oscillations in the alpha- and beta-bands have a direct role in top-down modulatory mechanisms, which enhance neural activity associated with relevant information and suppress activity for irrelevant information, thus establishing a foundation for both attention and memory processes [46,61,23,21]. Changing tasks in task-switching paradigms require top-down control [50]. Using a modified version of the Wisconsin card sorting task [11], demonstrated that both alpha and beta oscillatory activity was suppressed during task switching relative to task repetition. Strengthened alpha synchrony with amplitude suppression was also shown in some other studies [67,66,36,46]. Prominent beta oscillations were seen during controlled memory retrieval as well as suppression, suggesting that these oscillations may have a more general control-related role [31]. In the domain of working memory, alpha-band oscillations have been related to memory-updating, whereas beta-band oscillations have been linked to the active maintenance of information in working memory [6,40]. Based on these findings we predicted alpha-band and beta-band suppressions as a function of task complexity, such that the higher the task complexity the stronger the power suppression.

2. Materials and methods

2.1. Participants

Thirty-two right-handed volunteers from the participant database at the Universität zu Lübeck took part in the study. Data sets from 28 participants (15 women, aged 18–31 years, M = 23, SD = 3.3) were analyzed. Data of the other four participants could not be used due to excessive artifacts. Handedness was assessed with the Edinburgh Handedness Inventory (M = 90, range 64–100) [45]. All participants had normal or corrected-to-normal vision and were neurologically healthy.

This study was carried out in accordance with the recommendations of the ethical standards of the ethics committee of the University of Lübeck on human experimentation (institutional and national) and with the Helsinki Declaration of 1975. Informed consent was obtained from all participants for being included in the study.

2.2. Experimental design

The experiment featured two different task rules that were applied to the digits 2, 4, 7 or 9 which were shown on a screen. Participants either judged their parity (i.e., is a given digit odd or even?) or their magnitude (i.e., is a given digit smaller or larger than 5?). We chose these two task rules, because they are equally difficult and frequently used in task-switching paradigms.

Three different levels of task complexity (low, mid, high) were implemented. The low-level of task complexity was instantiated as a simple SR mapping task and comprised only one rule (e.g. if stimulus A, then press button 1). Pink or purple colors were randomly assigned to the digits, because the color information was irrelevant in this condition. Pink and purple colors were only presented in the low-level of control condition. Thus participants learned that these colors had no meaning and that they could ignore the color of the digit in this condition.

At the mid-level of task complexity, participants were assigned one of two tasks based on a color cue, e.g. blue or yellow color of a digit. This task-switching consisted of two rules, e.g. if color 1 and if stimulus A, then press button 1. This mid-level of task complexity thus involved increased rule complexity relative to the low-level task complexity. At this level, the digit color yellow or blue indicated either the magnitude or parity task.

At the high-level of task complexity, a spatial cue (cue-cue) in front of the digit determined which cue-task assignment was valid for the next digit. A *triangle pointing up* specified that the color red of a digit indicated the magnitude task and the color green of a digit indicated the parity task. In contrast, a *triangle pointing down* specified that the digit color green indicated the magnitude task and the digit color red indicated the parity task. This level consisted of three rules, e.g. if cue–cue X, and if color 1, and if stimulus A, then press button 1. The high-level of task complexity thus had the highest rule complexity in the present experiment. (Fig. 1)

2.3. Stimuli and procedure

The experiment was subdivided into three blocks, comprising a total of 160 trials for each level of task complexity (low, mid, high). Each trial started with a cue–cue (white triangle, 1500 ms), followed by a fixation cross (1000–1500 ms). Next, a digit (2, 4, 7 or 9; 1500 ms) was presented, followed by a response-mapping screen (2000 ms). Stimuli subtended $2.29^\circ \times 1.72^\circ$ of visual angle.