Neuropsychologia 61 (2014) 175–189

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

# Exploring adolescent cognitive control in a combined interference switching task

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ARTICLE INFO

*Article history:*
Received 13 February 2014
Received in revised form
28 May 2014
Accepted 17 June 2014
Available online 24 June 2014

*Keywords:*
Cognitive control
Adolescence
Task switching
Incongruence
brain–behavior correlations
Functional MRI

ABSTRACT

Cognitive control enables individuals to flexibly adapt to environmental challenges. In the present functional magnetic resonance imaging (fMRI) study, we investigated 185 adolescents at the age of 14 with a combined response interference switching task measuring behavioral responses (reaction time, RT and error rate, ER) and brain activity during the task. This task comprises two types of conflict which are co-occurring, namely, task switching and stimulus-response incongruence. Data indicated that already in adolescents an overlapping cognitive control network comprising the dorsal anterior cingulate cortex (dACC), dorsolateral prefrontal cortex (DLPFC), pre-supplementary motor area (preSMA) and posterior parietal cortex (PPC) is recruited by conflicts arising from task switching and response incongruence. Furthermore our study revealed higher blood oxygenation level dependent (BOLD) responses elicited by incongruent stimuli in participants with a pronounced incongruence effect, calculated as the RT difference between incongruent and congruent trials. No such correlation was observed for switch costs. Furthermore, increased activation of the default mode network (DMN) was only observed in congruent trials compared to incongruent trials, but not in task repetition relative to task switch trials. These findings suggest that even though the two processes of task switching and response incongruence share a common cognitive control network they might be processed differentially within the cognitive control network. Results are discussed in the context of a novel hypothesis concerning antagonistic relations between the DMN and the cognitive control network.

## 1. Introduction

The ability to flexibly adapt to environmental challenges and changing task demands in an appropriate and adjusted way is commonly referred to as "cognitive control" (Banich, 2009; Braver, 2012; Goschke, 2013; Miller & Cohen, 2001; Miyake et al., 2000). Cognitive control processes are mechanisms that allow us to plan our long-term goals, to focus on them, and to suppress distracting stimuli or competing impulses. It also enables us to differentiate between more or less important situational information as well as to register a change in its weighting. Elucidating the underlying neural mechanisms of cognitive control is essential to better understand, identify, and treat diseases associated with impairments of cognitive control, like substance use disorder, mood disorders, obsessive compulsive disorder (OCD), and attention deficit hyperactivity disorder (ADHD) (Braver, Barch, & Cohen, 1999; Bühringer, Wittchen, Gottlebe, Kufeld, & Goschke, 2008; Goschke, 2014; Melcher, Falkai, & Gruber, 2008). To do so, it is essential to investigate and understand cognitive control profoundly not only in adults but also in adolescents since this is the period where many psychiatric disorders set in (Paus, Keshavan, & Giedd, 2008).

There are two major conflict phenomena that have been experimentally manipulated and explored in the context of cognitive control: (1) conflicts between incongruent responses and (2) conflicts due to between-task crosstalk in task switching paradigms:

(1) Conflicts due to response incongruence stem from an incompatibility on the stimulus-response level: in interference tasks (e.g., the Stroop color naming task) a stimulus contains a task-relevant (e.g., color) and an irrelevant dimension (e.g., word meaning), which can either be congruent (i.e. relevant and irrelevant dimensions are mapped to the same response) or incongruent (i.e. the two dimensions are mapped to different responses) (Egner, 2007). Hence, incongruence causes a response conflict

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http://dx.doi.org/10.1016/j.neuropsychologia.2014.06.022
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and requires the recruitment of cognitive control in order to enhance the neuronal representation of the relevant and/or inhibit the representation of the irrelevant stimulus dimension.

(2) In task switching paradigms, switch costs arise when participants have to switch between task sets, compared to when they repeat the same task (for review see Monsell, 2003). Switch costs reflect a number of separable processes, including advance preparation and context-dependent selection of the appropriate task (Goschke, 2000; Gruber, Karch, Schlueter, Falkai, & Goschke, 2006; Hyafil, Summerfield, & Koechlin, 2009; for review see Ruge, Jamadar, Zimmermann, & Karayanidis, 2013), as well as between-task competition (Yeung, Nystrom, Aronson, & Cohen, 2006) and proactive interference from the previously active (but currently irrelevant) task set (Allport, Styles, & Hsieh, 1994; Goschke, 2000; Kiesel et al., 2010). On the behavioral level, both types of conflict show up in increased reaction times (RT) and error rates (ER) compared to non-conflicting trials (i.e. congruent trials and task repetition trials) and show higher switch costs in incongruent trials (i.e., a supra-additive interaction effect; Goschke, 2000).

Several imaging studies (Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Hyafil et al., 2009; Silton et al., 2010) and meta-analyses in adults (Derrfuss, Brass, Neumann, & von Cramon, 2005; Nee, Wager, & Jonides, 2007) have shown that an overlapping network of higher order association cortices is involved in the processing of these two types of conflict, including the dorsal anterior cingulate cortex (dACC) and dorsolateral prefrontal cortex (DLPFC). The DLPFC comprises Brodmann areas (BA) 9, 46, and the superior part of BA 47, whereas the dACC is located in BA 32. Both of these areas serve as "relay stations" in the complex coordination of cognitive control. Besides the dACC and DLPFC, the pre-supplementary motor area (preSMA, medial parts of BA 6) as well as the posterior parietal cortex (PPC, including BA 5 and 7) are involved in this fronto-parietal network (Brass, Ullsperger, Knoesche, von Cramon, & Phillips, 2005; Egner, Delano, & Hirsch, 2007; Liston, Matalon, Hare, Davidson, & Casey, 2006). The precise neuronal mechanisms underlying the context-sensitive adjustment of cognitive control in response to conflict as well as the possible hierarchical organization and the interaction of the dACC and the DLPFC are still debated (e.g. Alexander & Brown, 2011; Banich, 2009; Egner & Hirsch, 2005; Roelofs, van Turennout, & Coles, 2006). One influential theory is the so-called "conflict monitoring theory" (Botvinick, Cohen, & Carter, 2004; Braver, Barch, Gray, Molfese, & Snyder, 2001; Kerns et al., 2004) according to which the dACC monitors and detects conflicts. This information is conveyed to the DLPFC which then adjusts the level of cognitive control and triggers an enhanced top-down modulation of the processing of task-relevant stimulus features and the selection of motor responses in the PPC and preSMA, respectively.

As it has been suggested that task-set switching and the overcoming of response incongruence engage similar neural systems, particularly the aforementioned "cognitive control network" comprising the dACC, DLPFC, PPC and preSMA, the meta-analysis of task switching and interference paradigms by Derrfuss et al. (2005) indicated that one region in the lateral prefrontal cortex, the inferior frontal junction (IFJ), appears to play a crucial role in the activation and/or updating of task representations, which is important both for resolving conflicts between incongruent responses and conflicts between competing task-sets (Derrfuss, Brass, & von Cramon, 2004; Derrfuss, Brass, von Cramon, Lohmann, & Amunts, 2009). Brass and colleagues introduced a paradigm which combines both types of conflict (Brass & von Cramon, 2004; Hedden & Gabrieli, 2010) and allows one to directly explore the processes of selecting the relevant stimulus information (in case of incongruence) and selecting a specific task set (in the case of task-set switching). Instead of the aforementioned IFJ, Brass and colleagues found a more anterior region (i.e. the posterior inferior frontal sulcus, pIFS) and claimed a hierarchical organization within the lateral prefrontal cortex, where the IFJ is responsible for the representation and updating of the relevant task-set and the pIFS is involved in directing selective attention to the task-relevant stimulus information.

To investigate trial sequence effects and the neural interaction of response incongruence and task switching Hyafil et al. (2009) used a combined interference switching task: a color background indicated which of two spatial tasks to perform, accordingly spatial and semantic stimuli could be congruent (indicating the same response) or incongruent (indicating different responses). Regarding the neural interaction between task switching and response incongruence Hyafil et al. (2009) could demonstrate that dACC and DLPFC activity parallel previously described behavioral findings, i.e. a higher neuronal switch costs in incongruent trials.

A further trend in recent years of neuropsychological research was the development of network-based models and the investigation of the interplay between neural networks (Brown, Reynolds, & Braver, 2006; Chen et al., 2013; Pearson, Heilbronner, Barack, Hayden, & Platt, 2011). Especially the interaction between the cognitive control network and the default mode network (DMN, Raichle et al., 2001) has gained much interest as they were first suggested to be merely anti-correlated (Fox et al., 2005), but recent studies suggested a rather flexible "communication" between those two networks. It even has been hypothesized that the posterior cingulate cortex (a core node of the DMN) might play a role in adaptive behaviors (i.e. learning, memory, reward processing and task switching, Pearson et al., 2011). Considering these findings, it is of great importance to evaluate non-conflicting trials (i.e. congruent trials and task repetition trials) which are meant to increase DMN activity as thoroughly as conflict trials (McKiernan, Kaufman, Kucera-Thompson, & Binder, 2003). Even though it seems as non-conflicting trials have a great impact on the interaction between the DMN and the cognitive control network they have not gained much attention, especially not in a developmental context.

Given that the effect of incongruence and switch costs are both characterized by an increase in RT and brain activity, analyzing their relations – so called brain–behavior correlations – is an important approach to further elucidate the functional role of conflict-induced brain activation. Doing so, one has to discern two particular approaches of brain–behavior correlations: investigating intra- or inter-individual differences. Intra-individual differences refer to within-subject variability and could reflect transient changes in behavior (e.g. due to learning effects or attention). The analysis of inter-individual differences depicts between-subject variation and elucidates neural correlates of more general performance differences. The approach to relate RT differences to task-dependent brain activation across individuals has received increasing attention in recent years. In fact, functional imaging studies related to inter-individual differences in cognitive control found inconsistent results between RT and brain activation (Hester, Fassbender, & Garavan, 2004; Lawrence, Ross, Hoffmann, Garavan, & Stein, 2003; Melcher & Gruber, 2009). In a study on a Stroop task Melcher and Gruber (2009) reported both positive associations between interference costs (due to response-incompatibility) and activation in the premotor cortex, but also negative correlations between interference costs and activation in the ACC, insula and thalamus, which the authors took as evidence that these regions jointly exert top-down control to overcome interference. Hyafil et al. (2009) demonstrated increased behavioral switch costs in subjects with more pronounced DLPFC activity during incongruent trials. However, Andrews-Hanna and colleagues showed in a developmental study different patterns of brain–behavior correlations between adolescents and adults (Andrews-Hanna et al., 2011). They observed a