Conflict-specific Mechanisms of Cognitive Control and their Neural Implementation

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Summary

An important precondition of successful goal-directed behaviour are cognitive control processes that allow resolving conflicts between incompatible information. Information processing conflicts occur at almost every processing stage in the cognitive system: For example, at the perceptual level, the response selection level, and the goal selection level, but also in the domain of emotional processing. For a long time, research on cognitive control has neglected this diversity of information processing conflicts: The influential model of Botvinick, Braver, Barch, Carter, and Cohen (2001) assumed that all conflicts occurring in the brain are response selection conflicts in nature. In addition, the model claimed the existence of a single, domain-general control mechanism modulating attention towards task-relevant information after the detection of a conflict at the response selection stage. However, the assumption of a domain-unspecific control mechanism has been challenged by several functional imaging studies reporting that dissociable brain areas correlate with control processes in interference paradigms involving different types of conflicts.

Building on the results of these previous studies, the current PhD project intended to provide conclusive behavioural and neural evidence for the existence of conflict-specific control mechanisms. In more detail, our experiments aimed at dissociating control mechanisms for (a) conflicts in the emotional vs. the non-emotional domain, (b) stimulus-based vs. response-based conflicts, and (c) perceptual conflicts vs. response selection conflicts.

(a) In most interference paradigms used to measure cognitive control, both the task-relevant and the distracting information are emotionally neutral. However, conflicts can also arise between the emotional values of task-relevant and distracting information, for example if the task-relevant information is related to positive and the distractor information related to negative emotions. We examined whether different control processes are involved in

resolving conflicts in the emotional versus the non-emotional domain (Study 2). Using dual-task paradigms, we found that the demands of a non-emotional working memory task modulated only control processes related to non-emotional but not to emotional conflicts, whereas the demands of an emotional Go/Nogo task interfered selectively with emotional conflict control mechanisms. This double dissociation provided evidence for the existence of specific control processes for conflicts in the emotional and the non-emotional domain.

(b) Conflicts are classified as “stimulus-based” if they arise from incompatible task-relevant and task-irrelevant stimulus dimensions. In contrast, if the task-relevant and the task-irrelevant stimulus dimension do not interfere with each other at an early visual processing stage but activate incompatible response alternatives, conflicts are classified as “response-based”. In a further study of the current PhD project, we found that acoustic warning signals have dissociable effects on conflict control in paradigms measuring stimulus-based (Stroop task) and response-based conflicts (Simon task), suggesting the involvement of different control mechanisms in resolving stimulus-based vs. response-based conflicts (Study 3).

(c) Stimulus-based conflicts can further be subdivided into conflicts occurring at the perceptual and at the response selection level. This is because also stimulus-based conflicts lead to conflict at the response selection stage due to direct response priming (Hubner, Steinhauser, & Lehle, 2010). Using transcranial magnetic stimulus (TMS), we found that dissociable brain areas are involved in resolving perceptual and response selection conflicts and that these control mechanisms operate on different time scales: The pre-supplementary motor area appears to be related to the resolution of response selection conflict predominantly when participants are not prepared for the occurrence of information processing conflicts. In contrast, the posterior parietal cortex may be involved in trial-by-trial adjustments of attention facilitating the resolution of perceptual conflicts (Study 4).

In sum, the results of the current studies show the necessity for revising models of cognitive control assuming a unitary domain-general control mechanism. As suggested by a further study on interference control deficits in ADHD patients, the modular architecture of cognitive control may lead to a better understanding of cognitive deficits in clinically relevant populations because ADHD patients appear to show deficits in controlling response-based conflicts but not stimulus-based conflicts (Study 5). Thus, the conflict-specificity hypothesis of cognitive control represents a fruitful approach which allows formulating predictions and explaining a large number of phenomena in both basic and applied clinical research.

1. General Introduction and Synopsis

Most human actions are goal-directed in nature. In order to guarantee successful goal-directed behaviour, the human cognitive system must be able to flexibly adjust attention and response selection processes in response to changing environmental demands. The mechanisms involved in these flexible adjustments of information processing are subsumed under the term “cognitive control”. One situation in which cognitive control processes are required is the occurrence of conflicts between goal-relevant and distracting information. The occurrence of conflicts requires cognitive control processes that resolve the current conflict or adjust information processing such that subsequent conflicts can be processed more efficiently.

An influential model describing the dynamic adjustment of cognitive control in conflict processing is the conflict monitoring account of Botvinick, Braver, Barch, Carter, and Cohen (2001). This model offers a parsimonious and elegant explanation for many phenomena related to conflict processing and has inspired countless studies on cognitive control in the last decade. One reason for the model’s success is its generality that allows it to be applied to almost every experimental paradigm measuring conflict processing: The conflict monitoring model assumes that all interference paradigms such as the Stroop, the Flanker or the Simon task measure conflict between two different response alternatives at the response selection stage, and this response selection conflict triggers cognitive control adjustments that allow resolving potential conflicts in subsequent trials more efficiently.

Despite the attractiveness of such a general, unifying model, several studies suggest that the assumption of a conflict-unspecific control mechanism may be too simplifying. The first line of evidence challenging the assumptions of the Botvinick et al. (2001) model suggests that conflicts occur not only at the response selection stage, but also at earlier, e.g. perceptual, processing stages (De Houwer, 2003; van Veen & Carter, 2005). In fact, conflicts may even arise between different tasks (Desmet, Fias, Hartstra, & Brass, 2011), or between higher-order goals like economic self-interest and fairness (Fehr & Camerer, 2007). Although the fact that conflicts can have quite different sources does not directly contradict the assumptions of the conflict monitoring account, it seems intuitively questionable that the cognitive system deals with all these different types of conflict in the same way. In fact, evidence for conflict-specific control mechanisms is provided by neuroimaging studies suggesting that dissociable control mechanisms are involved the resolution of perceptual versus response selection conflicts (Egner, Delano, & Hirsch, 2007; van Veen & Carter, 2005), or in the resolution of conflicts occurring in the nonemotional versus the emotional domain (Egner, Etkin, Gale, & Hirsch, 2008). Although it is problematic to infer conclusions from neuroimaging findings to cognitive processes, these results appear to question the idea of a unitary unspecific control mechanism as proposed by the conflict monitoring account.

The aim of the current research project was to examine the hypothesis of conflict-specific control mechanisms in more detail. The relevance of this question should be obvious: If control processes were found to operate conflict-specifically, then conclusions regarding the functionality of cognitive control would have to be restricted to the specific cognitive control mechanism measured by the applied experimental paradigm, i.e. the conflict-specificity of cognitive control would have to be taken into account. This is of particular importance when dealing with divergent findings because the assumption of conflict-specific control mechanisms can help resolving discrepancies between results stemming from different paradigms: For example, a study of Stürmer, Seiss, and Leuthold (1994) found that cognitive control adjustments in the Simon were not modulated when participants were simultaneously performing a working memory task, suggesting that working memory demands have no impact on adjustments of cognitive control. However, another study from our lab found that working memory demands suppress cognitive control processes in the Stroop task (Soutschek, Strobach, & Schubert, 2012). Such apparent inconsistencies could be reconciled if dissociable control mechanisms were found to be involved the Stroop and the Simon task, and that working memory load interferes only with the type of cognitive control engaged in the Stroop task.

The current research project investigated control mechanisms involved in the resolution of conflicts at the following processing levels and domains: (a) emotional conflicts vs. non-emotional conflicts, (b) stimulus-based conflicts vs. response-based conflicts, and (c) perceptual conflicts vs. response selection conflicts. Before addressing these distinctions, I will first provide a more detailed picture of the standard model of cognitive control and how cognitive control processes are thought to be engaged in conflict processing.

Conflict Adaptation and Cognitive Control

A basic finding that is commonly accepted as evidence for the involvement of cognitive control in conflict processing is the conflict adaptation effect. The term “conflict adaptation effect” refers to the finding that the magnitude of the congruency effect (which is thought to reflect the impact of conflicting information on behavioural performance) is reduced when the previous trial encountered a conflict (i.e., has been incongruent) compared to previously congruent trials. Conflict adaptation has been observed in several different interference paradigms including variants of the Stroop task (Egner & Hirsch, 2005; Kerns et al., 2004), the Simon task (Sturmer, Leuthold, Soetens, Schroter, & Sommer, 2002; Sturmer, Redlich, Irlbacher, & Brandt, 2007), and the Flanker task (Ullsperger, Bylsma, & Botvinick, 2005; Verbruggen, Notebaert, Liefooghe, & Vandierendonck, 2006). The conflict adaptation effect is commonly explained by the assumption that the detection of a conflict leads to an enhanced level of cognitive control which allows resolving subsequent conflicts more efficiently (Botvinick, et al., 2001; Egner, 2007). According to the conflict monitoring account (Botvinick, et al., 2001), conflict monitoring processes are neuronally implemented in the dorsal anterior cingulated cortex (dACC) which signals the need for enhanced cognitive control to other brain areas after the detection of a response selection conflict. An empirical study that seemed to provide evidence for this hypothesis was conducted by Kerns et al. (2004): In their fMRI study, they examined the neural correlate of conflict adaptation in the Stroop task. Whereas the occurrence of conflicts correlated with activity in the dACC, conflict adaptation was associated with activity in the dorsolateral prefrontal cortex (DLPFC). Importantly, the authors found a significant positive correlation between dACC activity in incongruent trials and DLPFC activity in subsequent trials, suggesting that conflict-monitoring processes related to dACC activity lead to enhanced task set activation in the DLPFC.

Note, however, that more recent studies question the assumptions that control adjustments are realized by a direct coupling between dACC and DLPFC (Verguts & Notebaert, 2009) and that dACC activity in interference tasks is related to conflict monitoring processes (Alexander & Brown, 2011). Nevertheless, the idea that the conflict adaptation effect reflects flexible adjustments of cognitive control following the occurrence of conflicts appears to be commonly accepted today. It is important to note that the conflict adaptation effect cannot exclusively be explained by stimulus or response repetition effects (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003), because conflict adaptations occurs also after removing all repetition trials from the dataset (Puccioni & Vallesi, 2012; Ullsperger, et al., 2005).

Being an established and accepted measure of cognitive control, most experiments of the current project will focus on the conflict adaptation effect in order to investigate cognitive control processes involved in interference resolution. Altough conflict adaptation occurs in almost every interference paradigm, the specific mechanisms by which conflict adaptation improves conflict resolution may differ between interference tasks, depending on the type of conflict measured in the corresponding paradigm. Therefore, the main goal of the current PhD study was to examine whether dissociable control mechanisms are underlying conflict adaptation in different interference tasks: We hypothesized that conflict resolution mechanisms affect different processing levels, depending on the type of conflict measured by an interference paradigms. For example, if a conflict occurs at the perceptual processing level, then conflict adaptation should facilitate processing of task-relevant perceptual information. In the following, I will present the rationales of the conducted experiments and a synopsis of their main results.

Control over emotional and non-emotional conflicts (Study 1 and Study 2)

Although the conflict monitoring account considers the dACC-DLPFC loop as the neural basis of a conflict-unspecific, non-modular control mechanism, functional imaging studies suggested that the neural underpinnings of conflict adaptation may differ for conflicts in the non-emotional and the emotional domain (Egner, et al., 2008). In particular, Egner et al. compared conflict adaptation between an emotional and a non-emotional variant of the Stroop paradigm. Participants were presented female and male faces with either happy or fearful facial expressions. In the non-emotional task, participants were instructed to respond to the gender of the faces which were additionally overlaid by the distractor words “FEMALE” or “MALE”. In the emotional task, participants responded to the emotional expression of the faces overlaid by the distractor words “HAPPY” or “FEAR”. Importantly, in both tasks, target face and distractor word were either congruent (e.g., “MALE” across a male face or “HAPPY” across a happy face) or incongruent (e.g., “MALE” across a female face or “HAPPY” across a fearful face) in order to induce processing conflicts in the non-emotional and the emotional domain. The analysis of behavioural data showed in both tasks the typical pattern of congruency effects and conflict adaptation: RTs were slower in incongruent than in congruent trials, and the amount of the congruency effects was reduced after previously incongruent compared to after congruent trials. The functional imaging analysis, however, revealed a dissociation between conflict adaptation in the emotional and the non-emotional

Stroop task: Whereas conflict adaptation in the non-emotional Stroop task correlated with DLPFC activity, conflict adaptation in the emotional Stroop task was related to activity in the rostral anterior cingulate cortex (rACC). Thus, these results suggest a dissociation between the neural underpinnings of conflict adaptation in the emotional and the non-emotional Stroop task, challenging the assumption of a domain-general control mechanism. Note, however, that the finding of a neuronal dissociation does not necessarily imply a functional dissociation. Therefore, one aim of the current research project was to test the existence of dissociable conflict control mechanisms in the emotional and the non-emotional domain on a functional level (Soutschek & Schubert, 2013; Chapter 2.2). Based on the results of a previous study showing that working memory demands interfere with conflict adaptation in the Stroop task (Soutschek, Strobach, et al., 2012; Chapter 2.1), we examined whether working memory demands have different effects on conflict adaptation in the emotional and the non-emotional Stroop task. In this experiment, we found that working memory demands suppressed the conflict adaptation effect only in the non-emotional but not in the emotional Stroop task. A further experiment testing the effects of a supplementary emotional Go/Nogo task revealed the opposite result pattern: When participants had to perform an emotional Go/Nogo task simultaneously with either the emotional or the nonemotional Stroop tasks, then no conflict adaptation effect occurred in the emotional Stroop task, whereas conflict adaptation in the nonemotional Stroop task was not affected. Thus, our data support the hypothesis that conflict adaptation in the emotional and the nonemotional domain rely on dissociable cognitive control mechanisms and challenge the assumption of a domain-general control mechanism for conflicts in the emotional and the nonemotional domain (Chiew & Braver, 2010; Ochsner & Gross, 2005).

Control over stimulus-based and response-based conflicts (Study 3)

Similar to the dissociation of emotional vs. non-emotional conflict processing, another fMRI study of Egner et al. (2007) suggests that conflict adaptation in the Stroop and the Simon task are related to distinct neural mechanisms. The Stroop and the Simon task represent two interference paradigms which are often used to measure conflict processing. In the classic variant of the Stroop task, participants have to respond to the ink colour of presented colour words whose semantics are either congruent (e.g., the word “RED” written in red) or incongruent (e.g., “RED” written in blue) with the task-relevant ink colour. Because interference in the Stroop task is thought to derive from a conflict between the task-relevant stimulus dimension (ink colour) and the distracting stimulus dimension (word semantics), Egner et al. classified conflicts in the Stroop task as “stimulus-based”. In the Simon paradigm, the task is to respond to arbitrary stimuli by pressing either a left (e.g., to the letter “X”) or a right response key (e.g., to the letter “O”). Importantly, the targets are presented left or right to the centre of the screen, such that the required response alternative can be compatible (e.g., an “X” on the left) or incompatible (e.g., an “X” on the right) with the distracting stimulus location. The Simon effect is explained by the assumption that the irrelevant target location automatically primes a response alternative at the response selection stage which potentially conflicts with the task-relevant response alternative. For this reason, conflict in the Simon task is thought to be “response-based”. The study of Egner et al. addressed the question whether the different sources of interference also lead to dissociable, conflict-specific control mechanisms. Comparing the neural correlates of conflict adaptation in the Stroop and the Simon task, the authors found activity in the parietal cortex and in the premotor cortex to be associated with conflict adaptation in the Stroop and the Simon task, respectively. Based on this dissociation on a neural level, Egner et al. concluded that distinct cognitive control processes are involved in the Stroop and the Simon task. However, because this hypothesis was solely based on neuronal evidence, we tested the idea of conflict-specific control mechanisms in more detail (Soutschek, Muller, & Schubert, 2012; Chapter 2.3). We found that auditory warning signals which were presented 400 ms before the Stroop or Simon stimuli interfered with conflict adaptation only in the Stroop task but not in the Simon task. Thus, our data strongly support the hypothesis of conflict-specific control processes for resolving “stimulus-based” and “response-based” conflicts (Egner, et al., 2007; Wendt, Kluwe, & Peters, 2006), while they appear incompatible with the idea of a general unspecific control mechanism. Since the Stroop and the Simon task are widely used for measuring interference control, this result has important implications for research on cognitive control: One must be careful with drawing conclusions to cognitive control in general on the basis of results obtained in one of these paradigms; instead, conclusions have to be restricted to cognitive control over stimulus-based or response-based conflicts, depending on the applied paradigm.

Control over perceptual and response selection conflicts (Study 4)

A third important distinction is the distinction between perceptual conflicts and response selection conflicts. It is important to distinguish this classification from stimulus-based versus response-based conflicts. For example, conflicts in the Stroop task are categorized as “stimulus-based” because they derive from conflicts between the task-relevant and the irrelevant dimension of a stimulus. However, the question concerning the origin of a conflict must be distinguished from the question at which processing levels in the cognitive system conflicts occur. There is evidence that conflicts in the Stroop task, despite being “stimulus-based”, lead to interference at a perceptual and, due to response priming processes, also at a response selection stage (De Houwer, 2003; van Veen & Carter, 2005). Perceptual and response selection conflict can be dissociated by using versions of the Stroop task in which two different stimulus dimensions are mapped on one response alternative; for example, if participants have to respond to red and yellow words with a left key and to blue and green words with a right key. This manipulation results in congruent, stimulus-incongruent, and response-incongruent trials: Whereas in congruent trials ink colour and distractor word are identical (e.g., “RED” in red letters), they differ from each other in stimulus-incongruent trials, despite being associated with the same response alternative (e.g., “RED” in yellow letters). In response-incongruent trials, ink colour and distracting semantics do not only differ from each other but are also mapped on distinct response alternatives (e.g., “RED” in blue letters). The findings that RTs are slower in stimulus-incongruent compared to congruent trials as well as in response-incongruent compared to stimulus-incongruent trials suggest that the overall Stroop effect can be spilt up in two different types of conflicts: The (stimulus-incongruent - congruent) contrast reflects perceptual conflict occurring at an early target identification stage independently of later response selection processes. The (response-incongruent – stimulus-incongruent) contrast measures conflict at the response selection stage between the response alternatives to the task-relevant and the distracting stimulus dimension (note that this contrast does not include perceptual conflict due to the subtraction of stimulus-incongruent trails). The functional imaging study of Van Veen and Carter (2005) revealed perceptual conflict to be associated with posterior parietal and superior frontal activity, whereas response selection conflict correlated with activity in the inferior and medial frontal cortex. Similar results were obtained by an event-related potentials study dissociating perceptual and response selection conflict in the flanker task (Nigbur, Cohen, Ridderinkhof, & Sturmer, 2012). However, due to the correlative nature of neuroimaging results, these findings cannot clarify whether the observed neural activity reflects distinct conflict control mechanism for the active resolution of perceptual and response selection conflict rather than the passive processing of conflict per se. The fourth study of the current PhD project addressed this question and tested the existence of separable control mechanisms for perceptual and response selection conflict using transcranial magnet stimulation (TMS; Chapter 2.4). We found that TMS of the pre-supplementary motor cortex (pre-SMA) selectively interfered with the resolution of response selection conflict, whereas TMS of the right posterior parietal cortex (PPC) impaired the resolution of perceptual conflict (Soutschek, Taylor, Müller, & Schubert, in press). In addition, we found significant conflict adaptation effects only for conflicts at the perceptual level, i.e. the magnitude of perceptual conflict was reduced when the previous trial had been stimulus- or response-incongruent. In contrast, response selection conflicts were not modulated as a function of previous trial congruency (see also Verbruggen, et al., 2006). A detailed analysis of the data revealed that TMS of the posterior parietal cortex modulated perceptual conflict by inhibiting the occurrence of conflict adaptation, whereas pre-SMA TMS interfered with response selection conflict mainly when the previous trial had been congruent. Thus, our study provided evidence for the existence of conflict-specific control mechanism for perceptual and response selection conflicts and, in addition, that these control mechanisms act on different time scales. In addition, they are in line with previous studies suggesting that the pre-SMA is related to response selection processes (Forstmann, van den Wildenberg, & Ridderinkhof, 2008; Rushworth, Hadland, Paus, & Sipila, 2002; Taylor, Nobre, & Rushworth, 2007), while the PPC plays a crucial role in adjusting visual attention (Rushworth & Taylor, 2006; Taylor, Muggleton, Kalla, Walsh, & Eimer, 2011; Wang et al., 2010).

Similar to our results for the stimulus-based vs. response-based distinction, the findings of our TMS study put constraints on conclusions based on interference paradigms that include both perceptual and response selection conflict. In most studies, the Flanker or Stroop effect is considered as a measure of interference processing per se, without differentiating between perceptual and response selection components of the overall congruency effect. However, due to the dissociable mechanisms involved in perceptual and response selection conflict, studies measuring only the overall congruency effect leave open the question which level of conflict processing is affected by the experimental manipulation.

Therefore, we recommend to always assess these different stages of conflict processing separately.

Clinical Relevance of the Conflict-Specificity Hypothesis (Study 5)

A further study of the current project suggests that the assumption of dissociable control mechanisms may help to improve the understanding of cognitive deficits in clinical patient groups. In particular, our study addressed the question whether patients with attention deficit hyperactivity disorder (ADHD) suffer of impairments in conflict control (Soutschek et al., in press; Chapter 2.5). Several previous studies had found that the magnitude of the Stroop effect is increased in ADHD patients compared to in healthy control subjects, suggesting that cognitive control are impaired in ADHD (King, Colla, Brass, Heuser, & von Cramon, 2007; Walker, Shores, Trollor, Lee, & Sachdev, 2000). However, since also mean reaction times were slower for ADHD patients than for controls, we speculated that the increased Stroop effect can be explained by the slower reaction time level in ADHD rather than by cognitive control impairments, because the magnitude of the Stroop effect is known to increase with slower mean reaction times. In fact, using delta plots as an advanced reaction time analysis tool, we did not find significant Stroop effect differences between patient and control group when comparing the Stroop effects at similar response speed levels. Thus, a detailed analysis of performance in the Stroop task which built upon previous research of cognitive control processes allowed us to modify a widely accepted assumption about cognitive control deficits in ADHD.

Interestingly, there is evidence for response control deficits in adult ADHD even when the general performance speed does not differ between ADHD and patient group (Fisher, Aharon-Peretz, & Pratt, 2011), Thus, although the control over “stimulus-based” conflicts in the Stroop task appears to be unaffected in ADHD patients, they may suffer of deficits in control over “response-based” conflicts. This hypothesis underlines the importance and potential clinical relevance of research on conflict-specific control mechanisms, because the modularity account of cognitive control allows reconciling the discrepant results from paradigms measuring stimulus-based and response-based conflicts.

2. Cumulative Thesis

This cumulative thesis consists of five research articles that have been accepted by peer-reviewed scientific journals. In the following, author contributions and abstracts of the papers are presented. The full published and accepted articles are enclosed in Appendix 2.

2.1 Working memory demands modulate cognitive control in the Stroop paradigm

Soutschek, A., Strobach, T., & Schubert, T. (2013)

Psychological Research, 77(3), 333-47

Author contributions: A.S. and T.Schubert designed research; A.S. performed research; A.S. analyzed data; A.S., T.Strobach, and T.Schubert wrote the paper.

Abstract

One important task of cognitive control is to regulate behavior by resolving information processing conflicts. In the Stroop task, e.g., incongruent trials lead to conflict-related enhancements of cognitive control and to improved behavioral performance in subsequent trials. Several studies suggested that these cognitive control processes are functionally and anatomically related to working memory (WM) functions. The present study investigated this suggestion and tested whether these control processes are modulated by concurrent WM demands. For this purpose, we performed three experiments in which we combined different WM tasks with the Stroop paradigm and measured their effects on cognitive control. We found that high WM demands led to a suppression of conflict-triggered cognitive control, whereas our findings suggest that this suppression effect is rather due to WM updating than to maintenance demands. We explain our findings by assuming that WM processes interfere with conflict-triggered cognitive control, harming the efficiency of these control processes.

2.2 Domain-specific control mechanisms for emotional and nonemotional conflict processing

Soutschek, A. & Schubert, T. (2013)

Cognition, 26(2), 234-245

Author contributions: A.S. and T.S. designed research; A.S. performed research; A.S. analyzed data; A.S. and T.S. wrote the paper.

Abstract

Recent neuroimaging studies suggest that the human brain activates dissociable cognitive control networks in response to conflicts arising within the cognitive and the affective domain. The present study tested the hypothesis that nonemotional and emotional conflict regulation can also be dissociated on a functional level. For that purpose, we examined the effects of a working memory and an emotional Go/Nogo task on cognitive control in an emotional and a nonemotional variant of the Stroop paradigm. The data confirmed the hypothesized dissociation: Working memory efforts selectively suppressed conflict regulation in the nonemotional Stroop task, while the demands of an emotional Go/Nogo task impaired only conflict regulation in the emotional Stroop task. We conclude that these findings support a modular architecture of cognitive control with domain-specific conflict regulation processes.

2.3 Conflict-Specific Effects of Accessory Stimuli on Cognitive Control in the Stroop Task and the Simon Task

Soutschek, A., Müller, H.J., & Schubert, T. (2013)

Experimental Psychology, *60(2),* 140-147

Author contributions: A.S. and T.S. designed research; A.S. performed research; A.S. analyzed data; A.S., H.J.M., and T.S. wrote the paper.

Abstract:

Both the Stroop and the Simon paradigm are often used in research on cognitive control, however there is evidence that dissociable control processes are involved in these tasks: While conflicts in the Stroop task may be resolved mainly by enhanced task-relevant stimulus processing, conflicts in the Simon task may are resolved rather by suppressing the influence of task-irrelevant information on response selection. In the present study, we show that these control mechanisms interact in different ways with the presentation of accessory stimuli. Accessory stimuli do not affect cognitive control in the Simon task, but they impair the efficiency of cross-trial control processes in the Stroop task. Our findings underline the importance of differentiating between different types of conflicts and mechanisms of cognitive control.

2.4 Dissociable Networks Control Conflict during Perception and Response Selection: a TMS Study

Soutschek, A., Taylor, P.J.C., Müller, H.J., & Schubert, T. (2013)

Journal of Neuroscience, 33(13), 5647-5654

Author contributions: A.S., P.C.J.T., and T.S. designed research; A.S. and P.C.J.T. performed research; A.S. analyzed data; A.S., P.C.J.T., H.J.M., and T.S. wrote the paper.

Abstract

Current models of conflict processing propose that cognitive control resolves conflict in the Flanker task by enhancing task-relevant stimulus processing at a perceptual level. However, because conflicts occur at both a perceptual and a response selection level in that task, we tested the hypothesis of conflict-specific control networks for perceptual and response selection conflicts using transcranial magnetic stimulation (TMS). TMS of the pre-supplementary motor area (pre-SMA) selectively disrupted the processing of response selection conflict, whereas TMS of the posterior intraparietal sulcus/inferior parietal lobule (IPS/IPL) interfered with perceptual conflict processing. In more detail, the pre-SMA seems to resolve response selection conflict mainly when no conflicts have occurred in the previous trial. In contrast, the IPS/IPL may resolve perceptual conflicts selectively when a conflict has occurred in the previous trial. The current data show the need for revising models of cognitive control by providing evidence for the existence of conflict-specific control networks resolving conflict at different processing levels.

2.5 Interference Control in Adult ADHD: No Evidence for Interference Control Deficits if Response Speed is Controlled by Delta Plots

Soutschek, A., Schwarzkopf, W., Finke, K., Hennig-Fast, K., Müller, H.J., Riedel, M., Möller, H.-J., Sorg, C., & Schubert, T. (2013)

Acta Psychologica (Amst), 143(1), 71-78

Author contributions: A.S., W.S., K.F., and T.S. designed research; A.S. and W.S. performed research; A.S. and W.S. analyzed data; A.S., W.S., K.F., K.H.-F., H.J.M., M.R., H.-J. M., C.S., and T.S. wrote the paper.

Abstract

Several theoretical accounts assume that interference control deficits belong to the core symptoms of adult ADHD. However, findings of increased interference effects in adult ADHD patients compared with healthy adults may be confounded with the simultaneous finding of generally slower responses in the patient group. The current study compared the magnitude of the interference effect in the Stroop task between a group of adults with ADHD and a healthy adult control group in a procedure that accounted for differences in overall response speed by using delta plots. The amount of interference did not differ between patient and control group at comparable reaction time levels. These results challenge the conclusions of previous studies, in that they indicate that interference control is not impaired in adult ADHD.

3. General Discussion: A Modular Model of Cognitive Control

The conflict monitoring model of Botvinick et al. (2001) can be considered as standard model on the role of cognitive control in conflict processing. This model assumes the existence of a general, conflict-unspecific cognitive control mechanism that improves conflict resolution after the detection of response selection conflict. The neural basis of this control mechanism is a dACC-DLPFC loop, with the dACC as conflict monitor and the DLPFC as neural correlate of cognitive control. Together with behavioural and neuroimaging studies from other labs, however, our studies show the assumption of an unspecific control mechanism to be mistaken. Importantly, while most previous studies supporting the conflict-specificity hypothesis of cognitive control only showed that the cognitive control processes in different interference paradigms correlate with dissociable brain regions (Egner, et al., 2007; Egner, et al., 2008; Nigbur, et al., 2012; van Veen & Carter, 2005), the behavioural experiments of the current PhD project show that conflict-specific control processes can be dissociated on a functional level, too. The empirical findings suggest a modular architecture of cognitive control in conflict processing with conflict-specific control mechanisms for (at least) the following types of conflicts: (1) stimulus-based vs. response-based conflicts, (2) perceptual vs. response selection conflicts, and (3) emotional vs. non-emotional conflicts (see Figure 1).

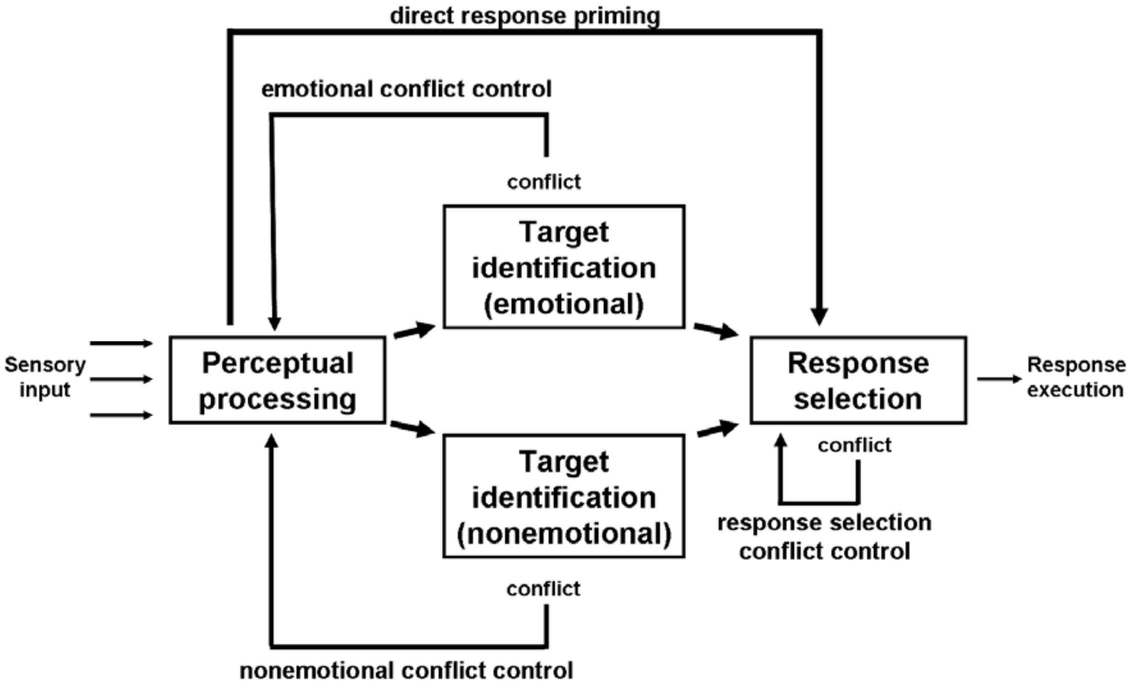

Figure 1. Architecture of control suggested by the current findings.

(1) The first distinction refers to the origin from which conflicts arise, in particular whether they are stimulus-based or response-based. Response-based conflicts occur only at the response selection stage, e.g. if a task-irrelevant stimulus feature primes a response alternative that is in conflict with the task-relevant one; however, the task-relevant and the irrelevant stimulus dimension do not overlap at an earlier processing stage. This is the case in the Simon task where the distracting information (target location) is not related to the task-relevant stimulus information (e.g., whether the presented stimulus is an “X” or “O”). However, if task-relevant and distracting information are semantically or perceptually related to each other, then the resulting conflicts are to be classified as “stimulus-based”. In these cases, already the identification of the task-relevant target is affected by the conflicting information, even before the response selection stage. Experimental paradigms in which stimulus-based conflicts occur are the Stroop and the Flanker task, in which target and distractor information are semantically (ink colour and word semantics) or perceptually (central and surrounding stimuli), respectively, closely related to each other. Importantly,

dissociable control mechanisms are involved in stimulus-based versus response-based conflicts: Whereas stimulus-based conflicts are resolved by directing enhanced attention to the task-relevant stimulus attributes, control processes related to the resolution of response-based conflicts may suppress the impact of the distracting stimulus information on the response selection stage (Egner, et al., 2007; Egner, et al., 2008; Egner & Hirsch, 2005; Soutschek, Muller, et al., 2012; Sturmer, et al., 2002).

(2) Although stimulus-based conflicts lead to conflicts at early sensory processing stages, they also cause response selection conflicts. That is, on the one hand, they impair the identification of the task-relevant target; and only after the resolution of this perceptual conflict and the identification of the correct target, the cognitive system can select the appropriate response to the target stimulus. On the other hand, however, there is empirical evidence that stimulus-based conflicts can also lead to conflict at the response selection stage. This is evidenced by findings from variants of the Stroop and the Flanker paradigm in which perceptual and response selection conflicts can be dissociated. The finding that stimulus-based conflicts lead to response selection conflicts can be explained by two stage models of response selection in interference tasks. According to the model of Hübner, Steinhauser, and Lehle (2010), incompatible target and distractor information results in both perceptual and response selection conflicts because target and distractor information prime – before the perceptual conflict is resolved and the correct target is selected – two response alternatives that compete for response selection. Although the identification of the target helps the cognitive system to select the correct response, the time required to resolve this response selection conflict is reflected by the increased reaction times in response-incongruent compared to stimulus-incongruent trials. The data of the current PhD project suggest dissociable control mechanisms operating also on different time scales to be involved in resolving perceptual and response selection conflicts: Control over of response selection conflicts is related to activity in the pre-SMA and appears to be activated especially if the

cognitive system is in a “low control”-mode. This is in line with previous findings on pre-SMA functioning suggesting a role of the pre-SMA in facilitating response selection under conditions of conflicting response alternatives or task sets (Rushworth, et al., 2002; Taylor, et al., 2011). In contrast, the cognitive system facilitates the resolution of percpetual conflict predominantly if a conflict had occurred in the previous trials and the cognitive system is in a “high control”-mode. We found these flexible adjustments of perceptual conflict processing to be related to activity in the PPC, a brain area thought to be involved in context-dependent adjustments of visual attention (Rushworth & Taylor, 2006).

(3) Stimulus-based conflicts can moreover be split up into conflicts in the cognitive versus in the emotional processing domain. In particular, if target and distractor are associated with different, conflicting emotional valences, the cognitive system recruits different control processes compared to if target and distractor are emotionally neutral. Similar to the stimulus-based vs. response-based distinction, the existence of specific control mechanisms for conflicts in the emotional domain shows that the recruitment of control processes depends on the processing stage at which the conflicts originate. Note that, although also conflicts in the emotional domain can cause conflicts at the response selection stage, response alternatives are “emotionally neutral” such that response selection conflicts always belong to the cognitive and not to the emotional domain.

One important implication of the conflict-specificity of cognitive control is that conclusions regarding cognitive control must be restricted to the type of control assessed by the used paradigm. For example, it seems highly problematic to draw conclusions regarding control processes in the Stroop paradigm on basis of results from the Simon paradigms due to the dissociable control mechanisms involved in these tasks. In addition, the conflict-specificity hypothesis has also clinical implications because cognitive control and inhibition processes are considered as homogenous constructs in clinical psychology and psychiatry. Here again, abandoning the domain-general concept of control may allow reconciling discrepant empirical results as well as providing a deeper understanding of which specific cognitive processes are impaired in a patient group. In this respect, the conflict-specificity hypothesis represents a fruitful theoretical approach improving our understanding of how the brain enables successful goal-directed behaviour.

Future directions

The focus of the current studies was on conflict-specific control mechanisms that are activated in response to conflicts in the preceding trials. However, control processes can also be activated by other factors than experienced conflicts, for example by the anticipation of conflicts or by increased motivation (Carter et al., 2000; Funes, Lupianez, & Humphreys, 2010; Jimura, Locke, & Braver, 2010; Kouneiher, Charron, & Koechlin, 2009; Krebs, Boehler, Egner, & Woldorff, 2011). Whereas the conflict adaptation effect which has been in the focus of the current studies is interpreted as indicator of reactive control adjustments, conflict anticipation and motivation are supposed to activate proactive control processes that allow preparing for upcoming conflicts (Braver, 2012). This raises the question whether not only reactive but also proactive control processes are conflict-specific. Interestingly, there is evidence that the anticipation of conflicts generalizes for conflicts in the Stroop and the Simon task, that is: the expectation of conflicts in the Stroop task improves the resolution of conflicts in the Simon task, too, while the reactive control processes triggered by conflicts in the Stroop task do not affect conflict processing in the Simon task (Funes, et al., 2010). Thus, it is possible that only reactive control processes are domain-specific, whereas proactive control mechanisms may be domain-general. This possibility implies that the modular architecture of cognitive control illustrated in figure 1 must be restricted to reactive, conflict-triggered control processes. Future studies will have to determine the place of proactive control processes in this model and their relationship with reactive control.

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Appendix 1: List of Publications

Soutschek, A., Strobach, T., & Schubert, T. (2013). Working Memory Demands Modulate Cognitive Control in the Stroop Paradigm. *Psychological Research,* 77(3), 333-47.

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Domain-specific control mechanisms for emotional and nonemotional conflict processing

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ABSTRACT

Recent neuroimaging studies suggest that the human brain activates dissociable cognitive control networks in response to conflicts arising within the cognitive and the affective domain. The present study tested the hypothesis that nonemotional and emotional conflict regulation can also be dissociated on a functional level. For that purpose, we examined the effects of a working memory and an emotional Go/Nogo task on cognitive control in an emotional and a nonemotional variant of the Stroop paradigm. The data confirmed the hypothesized dissociation: Working memory efforts selectively suppressed conflict regulation in the nonemotional Stroop task, while the demands of an emotional Go/Nogo task impaired only conflict regulation in the emotional Stroop task. We conclude that these findings support a modular architecture of cognitive control with domain-specific conflict regulation processes.

1. Introduction

An important ability of the human cognitive system is to adapt attention and response selection processes to changing demands of the environment. For example, when we feel disturbed by noise outside the window while we are working on an article in our office, we can more strongly focus on our work and ignore the distracting noise. This phenomenon can be experimentally investigated by various interference paradigms. For example, in the Stroop task participants have to respond to the ink color of a color word whose semantic meaning is either congruent (e.g., the word "RED" printed in red) or incongruent (e.g., "GREEN" printed in red) with the stimulus color (Stroop, 1935; MacLeod, 1991). The typical finding that reaction times (RTs) are slower in incongruent relative to congruent color word combinations is referred to as Stroop effect. The Stroop effect is explained by conflict which emerges due to interference between the task-irrelevant semantic meaning and the task-relevant stimulus color. Importantly, the cognitive system's ability to adapt attention to changing demands can be shown by investigating the Stroop effect in trial sequences. Many studies found that the amount of the Stroop effect was reduced following incongruent compared to congruent trials (Kerns et al., 2004; Notebaert, Gevers, Verbruggen, & Liefooghe, 2006). This trial-by-trial modulation of the Stroop effect can be explained by assuming that the cognitive system flexibly adjusts cognitive control resources in order to deal with increased task demands due to conflicts (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Kerns et al., 2004; Egner, 2007).

In particular, the conflict-monitoring account of Botvinick et al. (2001) proposes a cognitive control loop in which a conflict monitoring system permanently looks for conflicts in the stream of information processing. After the detection of a conflict, the system enhances the level of cognitive control in order to resolve conflicts in subsequent trials more efficiently. Based on this theoretical

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background, several functional imaging studies revealed the neuroanatomical correlates of post-conflict adjustments: Whereas conflict detection processes were correlated with activity in the dorsal anterior cingulate cortex (dACC), enhanced cognitive control was associated with dorsolateral prefrontal cortex (DLPFC) activity (Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000; Egner & Hirsch, 2005).

However, the specificity of the presumed control system is still an open issue. Whereas the original account of Botvinick et al. (2001) assumes that cognitive control is conflict-unspecific, there is evidence that may point to several separated conflict-specific control systems. For example, two experimental studies in which participants performed both the Stroop and the Simon task simultaneously found that the occurrence of a conflict in one of these tasks did not trigger post-conflict adjustments in the other paradigm (Egner, Delano, & Hirsch, 2007; Wendt, Kluwe, & Peters, 2006). Since it is assumed that conflicts are resolved by "stimulus-biasing" in the Stroop task in contrast to "response-biasing" in the Simon task (Egner, 2008; Egner et al., 2007), these findings suggest the existence of conflict-specific control mechanisms at different processing levels. Conflict processing in such specific systems would explain why processing a conflict in the Simon task domain did not evoke conflict-triggered control processes in the Stroop task domain. This assumption would also be consistent with findings of neuroimaging studies which suggest that the brain regions associated with post-conflict adjustments differ between the Stroop and the Simon paradigm (Egner et al., 2007; but see Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Peterson et al., 2002).

Whereas the assumption of specific control mechanisms at different processing levels is empirically well supported, there may exist a further distinction between different conflict adaptation processes, which relates conflict resolution to different processing domains. Recent evidence, however, is not unequivocal whether there exist different domain-specific control processes for conflicts in the emotional and the nonemotional domains. In detail, several studies propose the existence of a domain-general control mechanism which is involved in the monitoring and resolution of conflicts across the cognitive and affective domain. This hypothesis is mainly based on findings from functional imaging studies showing that both tasks involving nonemotional and emotional or social conflicts are associated with activity in the dACC and the DLPFC (Chiew & Braver, 2011; Ochsner, Hughes, Robertson, Cooper, & Gabrieli, 2009; Zaki, Hennigan, Weber, & Ochsner, 2010). These studies suggest that dACC and DLPFC may form the core of a domain-general control network regulating conflicts both in the cognitive and the affective domain.

Yet, not all studies support the assumption of a domain-general organization of cognitive control such as, for example, the study of Egner, Etkin, Gale, and Hirsch (2008). In their fMRI study, participants had to categorize either the gender (female vs. male) or the emotional expression (fearful vs. happy) of faces presented on a screen. While the first situation was defined a nonemotional Stroop task, the second was defined an emotional Stroop task. Depending on the task, nonemotional ("FEMALE" vs. "MALE") or emotional distractor words ("FEAR" vs. "HAPPY") were written across the faces, generating nonemotional (e.g., when "FEMALE" was written over a male face) or emotional conflict (e.g., "FEAR" written over a happy face). On a behavioral level, the data of Egner et al. (2008) revealed a similar pattern of RT congruency effects and post-conflict adjustments for the emotional and the nonemotional Stroop task as for the classic color-word Stroop task, i.e. RTs were slower in incongruent than in congruent trials and the amount of the Stroop effect was smaller after previously incongruent than after congruent trials. The neuroimaging data, however, revealed a dissociation between nonemotional and emotional conflict processing: For nonemotional conflicts, the authors found that conflict monitoring and cognitive control was associated with dACC and DLPFC activity, respectively (see also Kerns et al., 2004). For emotional conflict processing, however, increased activity was found both in the amygdala and the dACC in incongruent relative to congruent trials, while enhanced cognitive control processes after conflict trials was correlated with activity in the rostral anterior cingulate cortex (rACC) but not in the DLPFC (see also Etkin, Egner, Peraza, Kandel, & Hirsch, 2006). From these findings, Egner et al. (2008) concluded that two distinct reactive control loops exist in the human brain: While the dACC serves as a conflict monitor both for emotional and nonemotional conflicts, the occurrence of post-conflict adjustments is associated with enhanced DLPFC activity only for nonemotional conflicts. In contrast, post-conflict adjustments after emotional conflicts are associated rather with rACC activity.

Although these results clearly challenge the assumption of a domain-general control process, the finding that emotional and nonemotional conflict control rely on partially dissociable neural networks does not necessarily imply a functional dissociation between these two processes. This is so because the observed neuroanatomical dissociation indicates merely that different brain areas *correlate* with conflict control in the emotional and nonemotional Stroop task, but not that distinct brain regions (and distinct cognitive processes associated with these regions) are *causally* involved in the execution of nonemotional and emotional conflict control processes. Therefore, the aim of the present study was to test the hypothesis that emotional and nonemotional conflict control processes can be dissociated also on a functional level. If that hypothesis is correct, then the current study would strongly support the assumption of domain-specific control mechanisms for cognitive and affective conflicts in interference paradigms.

We tested this hypothesis by investigating whether post-conflict adjustments in the emotional and the nonemotional Stroop task can differently be modulated by supplementary tasks taxing different cognitive demands. The main experimental idea was as follows: If post-conflict adjustments in the emotional and the nonemotional Stroop task are based on dissociable conflict regulation processes, then they should show different interference effects in specific dual-task situations. In more detail, the efficiency of post-conflict adjustments in the emotional

Stroop task should be impaired when a secondary task exposed additional load on emotional processing as compared to a task which does not. The same holds true for the reversed case in which post-conflict adjustments in the nonemotional Stroop task should be reduced when a secondary task exposes additional nonemotional load.

Experiment 1 tested the effects of a secondary working memory (WM) task on post-conflict adjustments in versions of the emotional and the nonemotional Stroop tasks of Egner et al. (2008). Several previous studies found that high WM load interferes with control processes that are comparable to those in the nonemotional task of Egner et al. (e.g. Lavie, Hirst, de Fockert, & Viding, 2004; Schmeichel, 2007). For example, Soutschek, Strobach, and Schubert (2012) have shown that participants could not exert post-conflict adjustments in a (nonemotional) color word version of the Stroop paradigm when they were simultaneously performing a WM task in which they had to carry out arithmetic calculations. These findings suggest that the WM load exposed by an additional secondary task may interfere with nonemotional control processes (see also Kane & Engle, 2003). The assumption that nonemotional conflict control and WM processes are functionally interdependent would also be consistent with findings from neuroimaging studies: several studies reported a correlation between WM efforts and the amount of activity in the DLPFC (Braver et al., 1997; Garavan, Ross, Li, & Stein, 2000), a region that has regularly been associated with post-conflict adjustments in the nonemotional Stroop task (Egner et al., 2008; Kerns et al., 2004).

Contrary to the nonemotional Stroop task, we expected the secondary WM load task not to have an effect on the post-conflict adjustments in the emotional Stroop task because we decided to use a WM load task that does not involve any emotional content (see below). Such a selective effect of a secondary WM task would be in accord, again, with recent findings of neuroimaging studies, which showed that emotional post-conflict adjustments are associated with activity in the rACC activity but not in the DLPFC or other brain regions which are commonly correlated with nonemotional WM processes (Egner et al., 2008; Etkin et al., 2006). Taken together, these considerations suggest that post-conflict adjustments in the emotional Stroop task should be less affected by a simultaneous task requiring nonemotional WM load as compared to a task requiring emotional processing components. Experiment 1 therefore tested the hypothesis that additional nonemotional WM efforts interfere with post-conflict adjustments in the nonemotional and not in the emotional Stroop task.

Experiment 2 addressed the question whether post-conflict adjustments in the emotional Stroop task can also selectively be modulated by secondary tasks. For that purpose, we tested the effects of an emotional Go/Nogo task on post-conflict adjustments in the emotional and the nonemotional Stroop task. Since emotional Go/Nogo tasks expose high demands on emotional processing (Chiu, Holmes, & Pizzagalli, 2008; Elliott, Rubinsztein, Sahakian, & Dolan, 2000; Hare et al., 2008; Murphy et al., 1999), we hypothesize that the performance of a supplementary emotional Go/Nogo task should interfere with post-conflict adjustments in the emotional rather than in the nonemotional Stroop task because it might selectively disturb the activation of emotion-specific conflict control processes.

2. Experiment 1

Experiment 1 tested the hypothesis that supplementary nonemotional WM efforts suppress post-conflict adjustments only in the nonemotional but not in the emotional Stroop task. For that purpose, participants performed the nonemotional and the emotional Stroop task simultaneously with an arithmetic WM task which was administered either in a WM load or a control condition. In the WM load condition, arithmetic stimuli (plus or minus signs) were presented in the interval between two stimuli for the Stroop task. Participants had to maintain two numbers in their WM and to count up or down in steps of two from these numbers. Consequently, this arithmetic task required the maintenance and updating of WM contents. In the control condition, participants were instructed to attend to the presented arithmetic stimuli without performing mental calculations. The control condition therefore required the maintenance of a second task instruction additionally to the Stroop task instruction; its administration allowed us to control for the effects of a dual-task situation and of perceptual load on conflict processing in the Stroop tasks.

2.1. Methods

2.1.1. Participants

Thirty-two right-handed volunteers (M_{age} = 26.31 - years; 21 female) participated in Experiment 1. All participants had normal or corrected-to-normal vision, were not informed about the purpose of the experiment and were paid 10 € for their participation.

2.1.2. Stimuli and apparatus

Stimuli were presented with Experimental Run Time System (ERTS; Behringer, 1993) on a 17 inch color monitor. Participants sat in a distance of 50 cm from the monitor in a dimly-lit soundproof experimental cabin.

For the emotional and nonemotional Stroop task, a photographic stimulus was presented on a black screen, depicting either a happy or fearful female or male face (Ekman & Friesen, 1976). The stimulus set included altogether 16 different face stimuli, consisting of four female and four male faces showing either a happy or a fearful emotional expression. For the nonemotional Stroop task, we presented faces with either the word ‘‘FRAU’’ or ‘‘MANN’’ (German for ‘‘FEMALE’’ and ‘‘MALE’’) written in red capital letters across the face, resulting in gender-congruent (e.g., ‘‘FRAU’’ written over a female face) and gender-incongruent stimuli (e.g., ‘‘FRAU’’ written over a male face). Participants were instructed to categorize the gender of the presented faces by pressing the left control key for female faces and the right control key for male faces on a QWERTZ keyboard while ignoring the task-irrelevant word stimuli. For the emotional Stroop task, we presented the same face stimuli with either the word ‘‘FROH’’ or ‘‘ANGST’’ (German

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for "HAPPY" and "FEAR") written across the face in order to produce emotion-congruent and emotion-incongruent stimuli. Participants were instructed to press the left control key for happy faces and the right control key for fearful faces.

In the WM task conditions, three white "x" were presented as fixation cross row on a black screen, whereas the left or right "x" could change either into a plus (+) or a minus (−) sign. In the WM load condition, we instructed participants to keep twice the number "50" in mind at the start of a block and to perform the arithmetic operations shown at the left "x" with the first number in mind and the operations presented at the right "x" with the second number in mind. To increase task difficulty, we instructed participants to add "2" or to subtract "2" if a plus or a minus sign was presented, respectively. For example, if a plus sign was presented at the right position (the left and the central "x" stayed unchanged in this case), then participants had to add "2" to the second maintained number while the first number remained as in the preceding trial. Consequently, participants permanently had to maintain two numbers in WM during an experimental block and to conduct arithmetic operations on these numbers in every trial. After every block including the WM load condition, participants had to write the two final results of the arithmetic calculations on a separate sheet of paper. In the control condition, the same stimuli were presented as for the arithmetic WM load condition, but participants only had to attend to these stimuli without performing arithmetic operations. Note that, for the purpose of the present experiment, it was not important whether participants really attended to the arithmetic stimuli in the control condition, because the focus of the experiment was on the effects of a dual-task condition entailing WM load on performance in the emotional and nonemotional Stroop task compared to a task situation without these high WM demands.

All stimuli were presented in 18-point Helvetia Font.

2.1.3. Design and procedure

The procedure was basically identical for all task conditions: At the start of each trial, three white "x"s were presented as fixation cross row for 500 ms, then the left or right "x" changed into a plus or minus sign for 1,500 ms. Following an interstimulus interval (ISI) of 2000 ms, a face stimulus was presented with a distractor word for 300 ms. Depending on the Stroop task condition, participants had to respond either to the gender or to the emotional expression of the face within a response interval of 1200 ms following the presentation of the face (2.1% of all responses were executed after that response interval); afterwards the next trial started (see Fig. 1).

The experimental setting included four different block types: In the *Nonemotional-control* and *Nonemotional-WM load* conditions, participants performed the nonemotional (gender categorization) Stroop task and the control or WM load task, respectively. In analogy, they performed the emotional (emotional expression categorization) Stroop task and the control or WM load task in the *Emotional-control* and the *Emotional-WM load* condition, respectively. Every block consisted of 48 trials in which each of the 16 facial stimuli was presented twice with a congruent and once with an incongruent distractor word, resulting in 32 congruent (C) and 16 incongruent (I) trials. In line with Kerns et al. (2004), we decided to administer a larger number of congruent than incongruent trials in order to increase the size of the congruency effect. Since we were interested in sequential modulations of the Stroop effect, we differentiated between the congruency of the current trial (C vs. I) and the congruency of the previous trial (c vs. i). Facial stimuli were presented in randomized order with fixed numbers of cC (23), cI, iC, and iI (each 8) trial sequences per block. In order to control for possible confounding influences on post-conflict adjustments, each of the four types of trial sequences included the same proportions of response repetition to response alternation trials (50%). There were also no direct repetitions of the same facial stimulus to control for specific priming effects of such direct face repetitions (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003). In addition, we controlled for possible influences of other types of repetition effects, i.e. at the level of response or gender repetitions, by calculating additional statistical analyses which will be described later.

We presented three blocks for every experimental condition. Half of the participants started with the blocks for the nonemotional Stroop task conditions (nonemotional-control and nonemotional-WM load) in alternating order; the first block type was balanced across participants. We subsequently presented the blocks for the emotional Stroop task conditions (emotional-control and emotional-WM load), again in alternating order and with balanced starting block type. For the remaining half of participants, the order of blocks of nonemotional and emotional Stroop task conditions was reversed.

2.1.4. Statistical analysis

For the Stroop tasks conditions, RTs and error rates were analyzed. All trials including and following errors were excluded from the RT analysis. In line with Egner, Ely, and Grinband (2010), we defined post-conflict adjustments as the difference between the amount of the Stroop effect after previously congruent and previously incongruent trials; post-conflict adjustments = (cI − cC) − (iI − iC). We analyzed performance in the high WM load task by computing the difference between the true and the calculated final results for every block and participant, and averaged the difference values separately for all nonemotional-high load and all emotional-high load blocks.

For tests of significance, ANOVAs as well as one-sample and paired-samples *t*-tests were used with a significance threshold of 5%. We used Huynh–Feldt corrections (Huynh & Feldt, 1976) in order to adjust the *p*-values of the ANOVAs. As effect sizes, partial eta square (η_p^2) was calculated for the ANOVAs.

2.2. Results

2.2.1. Stroop task

2.2.1.1. RT analysis. RTs were analyzed by a 2 × 2 × 2 × 2 repeated-measures ANOVA with the factors Stroop type (nonemotional vs. emotional), WM task (control vs. WM

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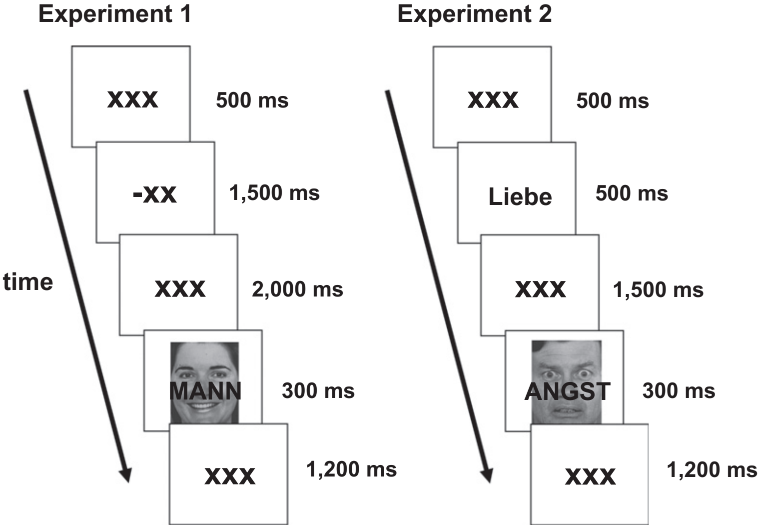

Fig. 1. Example trials for Experiment 1 and Experiment 2. The basic procedure was identical in all conditions of the experiments. In conditions including the emotional Stroop task, emotionally charged distractor words were presented ("FROH" and "ANGST", German for happy and fear), while emotionally neutral distractor words were shown in conditions including the nonemotional Stroop task ("FRAU" and "MANN", German for female and male). The depicted example trial for Experiment 1 represents a nonemotional Stroop task, the example trial for Experiment 2 an emotional Stroop task.

load), Previous trial congruency (c vs. i) and Current trial congruency (C vs. I). The findings are illustrated in Fig. 2. Participants responded faster in congruent (580 ms) than in incongruent trials (635 ms), $F(1,31) = 74.54$, $p < .001$, $\eta_p^2 = .706$, in control (576 ms) than in WM load blocks (630 ms), $F(1,31) = 63.89$, $p < .001$, $\eta_p^2 = .673$, and in the nonemotional (540 ms) than in the emotional Stroop task (657 ms), $F(1,31) = 68.53$, $p < .001$, $\eta_p^2 = .689$. The effect of current trial congruency was modulated by the WM task conditions, $F(1,31) = 27.01$, $p < .001$, $\eta_p^2 = .400$, indicating that increased congruency effects occurred in WM load relative to control blocks. The significant Previous trial congruency × Current trial congruency interaction, $F(1,31) = 14.54$, $p < .001$, $\eta_p^2 = .319$, pointed to the occurrence of post-conflict adjustments. This result was specified by the significant Stroop type × Previous trial congruency × Current trial congruency interaction, $F(1,31) = 4.13$, $p < .05$, $\eta_p^2 = .118$, and, importantly, also by the four way interaction between Stroop type, WM task, previous trial congruency, and current trial congruency, $F(1,31) = 6.13$, $p < .05$, $\eta_p^2 = .165$. Consequently, the amount of post-conflict adjustment was differently affected by the WM task conditions in the emotional and the nonemotional Stroop task.

In the next step, we calculated planned comparisons to test under which experimental conditions post-conflict adjustments were modulated by the factor WM task (see Fig. 3). In line with our hypothesis, post-conflict adjustments in the nonemotional Stroop task were larger in the control than in the WM load condition, $t(31) = 2.17$, $p < .05$; significant post-conflict adjustments occurred only

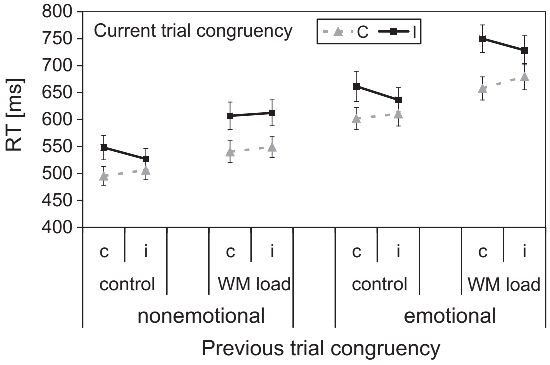

Fig. 2. Mean reaction times (RTs) for the Stroop task conditions of Experiment 1. In the WM load conditions, participants performed an arithmetic WM task simultaneously with the nonemotional and the emotional Stroop task, whereas in the control conditions they were instructed to attend to the presented arithmetic stimuli but to perform no calculations with them. Error bars indicate the standard error of mean. (C/c, congruent; I/i, incongruent).

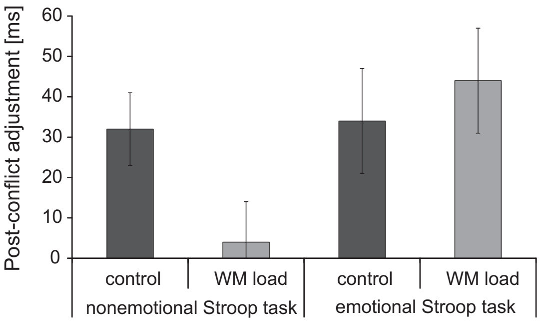

Fig. 3. Post-conflict adjustments (in ms) for the Stroop task conditions of Experiment 1. Post-conflict adjustments were calculated as the RT difference between the Stroop effects after previously congruent and after previously incongruent trials. Error bars indicate the standard error of mean.

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in control, (cI – cC) – (iI – iC) = 32 ms, $t(31) = 3.47$, $p < .01$, not in WM load blocks, (cI – cC) – (iI – iC) = 3 ms, $t(31) < 1$. In the emotional Stroop task, the amount of post-conflict adjustment did not differ between control and WM load blocks, $t(31) < 1$. We found significant post-conflict adjustments both in the control, (cI – cC) – (iI – iC) = 34 ms, $t(31) = 2.61$, $p < .05$, and the WM load condition, (cI – cC) – (iI – iC) = 43 ms, $t(31) = 3.38$, $p < .01$.

Note that not only conflict-triggered control adjustments may have contributed to the observed pattern of post-conflict adjustments, but they may potentially also contain repetition priming effects (Hommel et al., 2004; Mayr et al., 2003). Although we excluded repetitions of the same facial stimulus in two subsequent trials, priming might still arise from, e.g., response repetitions. To control for such repetition effects, we re-analyzed our data by including the additional variable response repetition (repetition vs. alternation; see Egner & Hirsch, 2005). Importantly, the non-significant Previous trial congruency × Current trial congruency × Response repetition interaction ($p > .68$) indicated that the amount of post-conflict adjustment did not depend on response alternations/repetitions. Also the Stroop type × WM task × Previous trial congruency × Current trial congruency interaction ($p > .23$) was not modulated by the factor response repetitions, suggesting that response repetitions cannot explain the observed load-dependent modulation of post-conflict adjustments. Note that also in this analysis the important Stroop type × WM task × Previous trial congruency × Current trial congruency interaction suggested dissociable effects of WM demands on post-conflict adjustments in the emotional and the nonemotional Stroop task ($p = .05$). In addition, we tested whether stimulus priming arising from gender or facial expression repetitions may have affected our results by re-analyzing the data with the additional variables gender repetition (repetition vs. alternation) and expression repetition (repetition vs. alternation). Importantly, the Stroop type × WM task × Previous trial congruency × Current trial congruency interaction was neither modulated by gender repetitions ($p > .12$) nor by expression repetitions ($p > .47$), indicating that such stimulus repetitions cannot explain the observed result pattern.

2.2.1.2. Error analysis. Error rates were analyzed by a repeated-measures ANOVA with the same factors as the RT analysis. All four main effects were significant: Participants committed more errors in the emotional (7.9%) than in the nonemotional Stroop task (4.4%), $F(1,31) = 16.58$, $p < .001$, $\eta_p^2 = .348$, and in blocks including the WM load (7.0%) compared to the control condition (5.3%), $F(1,31) = 13.12$, $p < .01$, $\eta_p^2 = .297$. Moreover, error rates were increased in incongruent (9.0%) compared to congruent trials (4.8%), $F(1,31) = 45.17$, $p < .001$, $\eta_p^2 = .593$, and after previously congruent (6.5%) compared to after incongruent trials (5.9%), $F(1,31) = 4.93$, $p < .05$, $\eta_p^2 = .137$. Similar to the RT analysis, the effect of current trial congruency interacted with WM task, $F(1,31) = 9.49$, $p < .01$, $\eta_p^2 = .234$, and also with previous trial congruency, $F(1,31) = 4.25$, $p < .05$, $\eta_p^2 = .121$. This indicates the occurrence of post-conflict adjustments in the error rates with a smaller Stroop effect after previously incongruent (3.1%) than after congruent trials (5.5%). However, these post-conflict adjustments were not modulated by the factors Stroop type or WM task. Additionally, WM task interacted with previous trial congruency, $F(1,31) = 5.36$, $p < .05$, $\eta_p^2 = .161$. No further interaction passed the statistical threshold (see also Table 1).

2.2.2. WM task

We compared performance in the WM load task between the nonemotional-WM load and the emotional-WM load condition with a paired-samples *t*-test. There was no significant difference between the nonemotional-WM load ($M = 2.4$) and the emotional-WM load condition ($M = 2.0$), $t(31) = 1.11$, $p > .27$, indicating that the mean deviation of the final results calculated by the participants from the true final results was similar across the two conditions.

2.3. Discussion

Experiment 1 examined the effects of nonemotional WM load on conflict regulation in the nonemotional and the emotional Stroop task. In line with our hypothesis, the data revealed that post-conflict adjustments were significantly reduced by WM load compared to the control condition in the nonemotional Stroop task. In contrast, post-conflict adjustments were not affected by WM load in the emotional Stroop task.

The particular finding of a load-dependent modulation of post-conflict adjustments in the nonemotional Stroop task can be explained by the assumption that WM processes and post-conflict adjustments in that task are functionally interdependent processes (Kane & Engle, 2003; Soutschek et al., 2012). This finding is also consistent with observations of neuroimaging studies showing that these two processes are both related to DLPFC activity (Braver et al., 1997; Garavan et al., 2000; Kerns et al., 2004). Moreover, we hypothesized that post-conflict adjustments in the emotional Stroop task should not interact with nonemotional WM load as the related processes are supposed to use separable cortical systems. Note that emotional post-conflict adjustments had been shown to be related to activity in the rACC but not in brain regions related to WM processes (Egner et al., 2008; Etkin et al., 2006). The present data are consistent with the hypothesis that the corresponding processes are not related by showing that post-conflict adjustments in the emotional Stroop task are not affected by additional WM processes.

Importantly, our interpretation of the dissociation between the effects of the secondary task in the nonemotional and the emotional Stroop task condition does not depend on whether participants really followed the instruction of the control condition and directed attention to the presented arithmetic stimuli. Although one might argue that the current control condition did not allow us to control whether participants had directed attention to the presented arithmetic stimuli or not, it would not invalidate our conclusion if participants had ignored these stimuli. This is because only post-conflict adjustments in the nonemotional and not in the emotional Stroop task were

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Table 1
Error rates (in %) for the Stroop task conditions of Experiment 1. Standard errors of mean are in brackets. (C/c, congruent; I/i, incongruent).

Previous trial congruency	c		i	
Current trial congruency	C	I	C	I
Nonemotional-control	2.8 (.6)	5.8 (1.1)	2.6 (.8)	4.5 (.9)
Nonemotional-WM load	3.8 (.9)	10.4 (1.7)	3.9 (1.1)	6.2 (1.3)
Emotional-control	5.3 (1.5)	9.3 (1.4)	7.0 (1.5)	9.1 (1.7)
Emotional-WM load	6.8 (1.4)	15.4 (2.4)	5.8 (1.4)	11.9 (2.2)

suppressed by the WM demands in the WM load conditions, irrespective of how demanding the control condition actually was.

In sum, Experiment 1 showed that nonemotional WM load interferes with post-conflict adjustments in the nonemotional Stroop task but not in the emotional Stroop task. Experiment 2 tested whether post-conflict adjustments in the emotional Stroop task can selectively be modulated by an additional task exposing specific demands on emotional processing.

3. Experiment 2

In Experiment 2, participants performed the nonemotional and the emotional Stroop task simultaneously with an emotional Go/Nogo task. In the emotional Go/Nogo task, we presented words with either positive or negative valence. Participants had to give a motor response only if, for example, the presented word was positive (Go condition) but not if the word was negative (or vice versa, depending on whether positive or negative words were defined as “Go”-stimuli). The application of the emotional Go/Nogo task as a secondary task allowed us to assess the effects of emotion categorization and emotional response monitoring processes on post-conflict adjustments in the emotional and nonemotional Stroop task. In contrast to the arithmetic WM task applied in Experiment 1, the emotional Go/Nogo task required almost no WM maintenance or updating processes (except maintaining the task instruction), but the categorization of the emotional valence of the currently presented Go/Nogo stimulus.

We hypothesized that the emotion categorization processes required by the Go/Nogo task should interfere with control processes in the emotional Stroop task, resulting in decreased post-conflict adjustments. In analogy to the effect of WM demands on post-conflict adjustments in the nonemotional Stroop task, the emotional categorization of the Go/Nogo words may interfere with the updating of control in the emotional conflict regulation system. This hypothesis is in accord with findings of neuroimaging studies that investigated the neural correlates of performance in the emotional Go/Nogo task and showed that the execution of an emotional Go/Nogo task results in similar modulations of rACC activity as the execution of post-conflict adjustments in the emotional Stroop task (Chiu et al., 2008). In regard to the nonemotional Stroop task, we expected the demands of the emotional Go/Nogo task to have no (or only a small) effect on post-conflict adjustments.

It is important to note that we excluded all trials from the analysis in which participants executed an overt motor response in the Go/Nogo task. This is because Stürmer, Seiss, and Leuthold (2005) showed that the need to execute manual responses in Go/Nogo tasks might impair cognitive control in a simultaneously performed interference task. The exclusion of the related trials allowed us to control for such possible influences.

3.1. Methods

3.1.1. Participants

Twenty-eight right-handed volunteers (M_{age} = 26.7 - years; 23 female) participated in Experiment 2. All participants had normal or corrected-to-normal vision, were not informed about the purpose of the experiment and were paid 8 € for their participation.

3.1.2. Stimuli and apparatus

As in Experiment 1, participants sat in an experimental cabin in a distance of 50 cm from a 17 inch color monitor on which stimuli were presented with ERTS.

Participants performed the emotional and the nonemotional Stroop task in the same way as in Experiment 1. Additionally, they performed an emotional Go/Nogo task in which words with either positive (e.g., “Liebe”, German for love) or negative valence (e.g., “Schmerz”, German for pain) were presented on a screen in 18-point Helvetia Font. For the Go condition, we instructed participants to press the left shift key with the index finger of their left hand if the currently presented word had either a positive valence or a negative valence, depending on the task condition. The particular Go signal (i.e., word with positive or negative valence) was defined at the start of each block with a corresponding instruction. We used eight words with positive and eight words with negative valence that were selected from a word list of Windmann and Chmielewski (2008).

3.1.3. Design and procedure

In all task conditions, first three white “x”s were presented as fixation row for 500 ms, followed by a positive or negative word for the Go/Nogo task (500 ms). After an ISI of 1500 ms in which participants had to respond to the word if it represented a Go stimulus, a face stimulus with a distractor word for the emotional or the nonemotional Stroop task was presented for 300 ms. Participants had to respond to the face stimulus within an interval of 1200 ms in which again the fixation row was presented (1.2% of all responses were executed after that response interval); afterwards the next trial started.

The experimental setting contained four different block types: In the *Nonemotional-control* and *Emotional-control* conditions, participants performed the nonemotional and the emotional Stroop task, respectively. In these control conditions, we presented the words for the Go/Nogo task additionally to the stimuli for the Stroop task in order to control for effects of perceptual load on cognitive control, but we instructed participants not to respond to them. In the *Nonemotional-Go/Nogo* and the *Emotional-Go/Nogo* conditions, participants performed both the corresponding Stroop task and the emotional Go/Nogo task. Every block contained a total of 48 trials in which the facial stimuli were presented randomly in the same way as in Experiment 1. Since we excluded all trials from the analysis in which participants responded to a Go/Nogo stimulus, we aimed to reduce the number of response trials in the Go/Nogo task and thus the number of trials to be excluded: Therefore, each of the eight "Go"-words (e.g., positive words) was presented only once during one block while each of the eight "Nogo"-words (e.g., negative words) were presented five times.

We presented three blocks of every condition, with block order balanced in the same way as in Experiment 1.

3.1.4. Statistical analysis

For the analysis of the Stroop task conditions, we removed all trials in which participants had responded in the Go/Nogo task (note that we obtained a similar result pattern when we did not remove the Go/Nogo response trials from the analysis). For the RT analysis, we additionally removed all trials including or following an error. Performance rates in the Go/Nogo task were defined as the percentage of correct Go/Nogo target responses. Statistical tests were computed in the same way as in Experiment 1.

3.2. Results

3.2.1. Stroop task

3.2.1.1. RT analysis. We analyzed RTs with a repeated-measures ANOVA including the factors Stroop type (nonemotional vs. emotional), Go/Nogo task (control vs. Go/Nogo), Previous trial congruency (c vs. i) and Current trial congruency (C vs. I). The results are depicted in Fig. 4. Participants responded faster in the nonemotional (537 ms) than in the emotional Stroop task (637 ms), $F(1,27) = 60.78$, $p < .001$, $\eta_p^2 = .692$, and in the control (570 ms) relative to the Go/Nogo condition (604 ms), $F(1,27) = 15.23$, $p < .001$, $\eta_p^2 = .361$. Moreover, we found a significant effect of current trial congruency, $F(1,27) = 47.93$, $p < .001$, $\eta_p^2 = .640$, which interacted with the factor Go/Nogo task, $F(1,27) = 9.43$, $p < .01$, $\eta_p^2 = .259$, indicating a larger congruency effect in Go/Nogo than in control blocks. The effect of current trial congruency interacted also with previous trial congruency, $F(1,27) = 15.05$, $p < .001$, $\eta_p^2 = .358$, indicating the occurrence of post-conflict adjustments. Importantly, we found a significant Stroop type × Go/Nogo task × Previous trial congruency × Current trial congruency interaction, $F(1,27) = 5.52$, $p < .05$, $\eta_p^2 = .170$. This interaction reflects the fact that the amount of post-conflict adjustment was differently affected by the levels of the factor Go/Nogo task in the emotional and the nonemotional Stroop task.

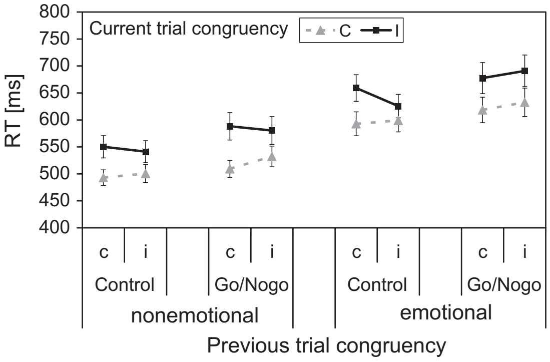

Fig. 4. Mean reaction times (RTs) for the Stroop task conditions of Experiment 2. In the Go/Nogo condition, participants performed the nonemotional the emotional Stroop task and additionally an emotional Go/Nogo task in which they evaluated the emotional valence of the presented faces. In the control condition, the stimuli for Go/Nogo task were presented but participants did not have to evaluate their valence. Error bars indicate the standard error of mean. (C/c, congruent; I/i, incongruent).

Next, we examined in more detail under which conditions post-conflict adjustments were modulated by the factor GoNogo task (see Fig. 5). In the emotional Stroop task, post-conflict adjustments were reduced in the Go/Nogo relative to the control condition, $t(27) = 2.30$, $p < .05$. Significant post-conflict adjustments occurred only in the control condition, $(cI - cC) - (iI - iC) = 40$ ms, $t(27) = 4.94$, $p < .001$, but not in the Go/Nogo condition, $(cI - cC) - (iI - iC) = 0$ ms, $t(31) < 1$. In contrast, the amount of post-conflict adjustments in the nonemotional Stroop task did not differ between control and Go/Nogo blocks, $t(27) < 1$; here, significant post-conflict adjustments were present in both conditions, i.e. in the control, $(cI - cC) - (iI - iC) = 17$ ms, $t(27) = 2.55$, $p < .05$, and in the Go/Nogo condition, $(cI - cC) - (iI - iC) = 30$ ms, $t(27) = 2.47$, $p < .05$.

As for Experiment 1, we controlled for possible response repetition effects by re-analyzing the data with the additional factor Response repetition (repetition vs. alternation). Again, the non-significant Previous trial congruency × Current trial congruency × Response repetition ($p > .94$)

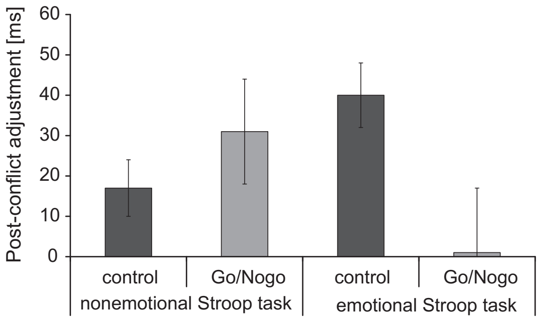

Fig. 5. Post-conflict adjustments (in ms) for the Stroop task conditions of Experiment 2. Post-conflict adjustments were calculated as the RT difference between the Stroop effects after previously congruent and after previously incongruent trials. Error bars indicate the standard error of mean.

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and Stroop type × Go/Nogo task × Previous trial congruency × Current trial congruency × Response repetition ($p > .10$) interactions showed that neither post-conflict adjustments *per se* nor their task-dependent modulation were affected by response repetitions/alternations (note that the Stroop type × Go/Nogo task × Previous trial congruency × Current trial congruency interaction was still significant in this ANOVA, $p < .05$). Further tests revealed that the Stroop type × Go/Nogo task × Previous trial congruency × Current trial congruency interaction was neither modulated by gender repetitions ($p > .40$) nor by expression repetitions ($p > .85$). Thus, stimulus category or response priming effects did not contribute to the observed effect pattern. Moreover, we also tested for possible effects of the valence of the presented Go/Nogo stimuli by computing an ANOVA with the factor Go/Nogo valence (positive vs. negative) additionally to the factors Stroop type, Go/Nogo task, Previous trial congruency, and Current trial congruency. Since the five-way interaction was not significant ($p > .16$), the observed modulation of post-conflict adjustments was not affected by the valence of the Go/Nogo stimulus in the current trial.

3.2.1.2. Error analysis. We analyzed error rates by a repeated-measures ANOVA that included the same factors as the RT analysis. Participants committed more errors in the emotional (8.1%) than in the nonemotional Stroop task (5.3%), $F(1,27) = 9.69$, $p < .01$, $\eta_p^2 = .264$, after previously congruent (7.5%) than after incongruent trials (5.9%), $F(1,27) = 7.29$, $p < .01$, $\eta_p^2 = .227$, and in incongruent (9.5%) relative to congruent trials (3.9%), $F(1,27) = 42.31$, $p < .001$, $\eta_p^2 = .610$. The main effect of current trial congruency was modulated by the factors Go/Nogo task, $F(1,27) = 2.56$, $p < .05$, $\eta_p^2 = .144$, and Previous trial congruency, $F(1,27) = 21.11$, $p < .001$, $\eta_p^2 = .439$; the size of the Stroop effect was smaller after previously incongruent (3.6%) than after congruent trials (7.5%). In contrast to the RT analysis, these post-conflict adjustments were not modulated by the factors Stroop type and Go/Nogo task. No further interaction passed the statistical threshold (see also Table 2).

3.2.2. Go/Nogo task

Performance rates in the Go/Nogo task were compared by a paired-samples *t*-test between the nonemotional-Go/Nogo and the emotional-Go/Nogo condition. We found no significant difference between the nonemotional-Go/Nogo (94%) and the emotional-Go/Nogo condition (95%), $t(27) < 1$.

3.2.3. Between-experiment analysis

Subsequently, we tested whether the different effect patterns of the influence of the supplementary tasks on the post-conflict adjustments in Experiments 1 and 2 can statistically be dissociated across the two experiments. For this purpose, we calculated a mixed-design ANOVA with the amount of post-conflict adjustment as dependent variable, experiment (Experiment 1 vs. Experiment 2) as between-subject factor, and Stroop type (nonemotional vs. emotional) and task condition (single task vs. dual task) as within-subject factors. The factor Task condition represented a combination of the factors WM task and Go/Nogo task of Experiments 1 and 2, respectively. As single tasks, we considered the control conditions in Experiment 1 and Experiment 2, whereas the WM load condition and the Go/Nogo condition were regarded as dual-task conditions in Experiment 1 and 2, respectively. As a result, we found a significant interaction between Stroop type, task condition, and experiment on post-conflict adjustments, $F(1,58) = 11.60$, $p < .01$, $\eta_p^2 = .167$, indicating that the supplementary tasks applied in Experiment 1 and 2 had statistically dissociable effects on post-conflict adjustments in the emotional and the nonemotional Stroop task.

3.3. Discussion

The aim of Experiment 2 was to investigate the effects of an emotional Go/Nogo task on post-conflict adjustments in the emotional and the nonemotional Stroop task. For the emotional Stroop task, we found significant post-conflict adjustments only in the control condition and not when participants performed simultaneously the Go/Nogo task. Importantly, the difference between the post-conflict adjustments in these two conditions was significant, indicating that the demands of the emotional Go/Nogo task interfered with post-conflict adjustments in the emotional Stroop task. These results are in line with our hypothesis which was based on the assumption that the requirement to categorize the emotional valence of the Go/Nogo stimuli should interfere with the modulation of post-conflict adjustments in the emotional Stroop task.

In analogy to the case of nonemotional post-conflict adjustments in Experiment 1, we believe that post-conflict adjustments in the emotional Stroop task consist of an enhanced focusing on the task-relevant emotional expression of a face stimulus after the occurrence of a conflict. In such a situation, the simultaneous need to categorize the emotional valence of the Go/Nogo stimuli interferes with the enhanced concentration on the emotional facial expression, similar to the nonemotional Stroop task situation in Experiment 1. Note that in Experiment 1 the simultaneous

Table 2
Error rates (in %) for the Stroop task conditions of Experiment 2. Standard errors of mean are in brackets. (C/c, congruent; I/i, incongruent).

Previous trial congruency	c		i	
Current trial congruency	C	I	C	I
Nonemotional-control	2.7 (.6)	9.0 (1.4)	2.7 (.8)	6.8 (1.5)
Nonemotional-Go/Nogo	2.5 (.5)	10.9 (1.6)	1.6 (.6)	6.4 (1.2)
Emotional-control	4.9 (1.1)	11.6 (1.8)	5.6 (1.0)	7.6 (1.5)
Emotional-Go/Nogo	5.1 (1.0)	13.6 (2.2)	6.5 (1.0)	9.7 (2.2)

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WM demands suppressed the conflict-triggered updating of task-representations. While this seems to be a reasonable interpretation for the current findings, further research is necessary to determine the precise mechanisms of post-conflict adjustments in the emotional Stroop task.

Evidence supporting our argumentation comes from the research area of neuroimaging studies, which suggest that both post-conflict adjustments in the emotional Stroop task and the execution of an emotional Go/Nogo task are associated with identical brain regions, i.e. the amygdala and the rACC (Chiu et al., 2008; Egner et al., 2008; Etkin et al., 2006; Hare et al., 2008).

In the nonemotional Stroop task, we did not find a significant difference between post-conflict adjustments in the control and the Go/Nogo condition. Thus, the simultaneous performance of the emotional Go/Nogo task did not reduce post-conflict adjustments in the nonemotional Stroop task relative to the control condition. Summarizing these findings, we conclude that the demands of the emotional Go/Nogo task resulted in a selective modulation of post-conflict adjustments in the emotional compared to the nonemotional Stroop task.

4. General discussion

4.1. Summary of findings

The present study tested the hypothesis of domain-specific control mechanisms for the regulation of conflicts in the cognitive and the affective domain. This hypothesis was based on findings of Egner et al. (2008) who claimed that post-conflict adjustments in the nonemotional Stroop task are associated with enhanced DLPFC activity, while post-conflict adjustments in the emotional Stroop task are related to increased rACC activity. If post-conflict adjustments in the emotional and nonemotional Stroop task rely on separable mechanisms, then it should be possible to selectively modulate cognitive control in the emotional and nonemotional Stroop task by applying secondary tasks which expose different demands on emotional and nonemotional processing. Our results are in accordance with this expectation: While an additional high nonemotional WM load decreased post-conflict adjustments selectively in the nonemotional Stroop task, the demands of an emotional Go/Nogo task reduced post-conflict adjustments only in the emotional Stroop task. The finding that nonemotional WM load suppressed post-conflict adjustments in the nonemotional Stroop task is consistent with previous studies reporting a close functional relationship between the involved cognitive control processes and the required WM mechanisms. In contrast, the emotion categorization processes required by the Go/Nogo task interfered with post-conflict adjustments in the emotional Stroop task, but not with post-conflict adjustments in the nonemotional Stroop task. Taken together, these results support the assumption that emotional and nonemotional post-conflict adjustments rely (at least partially) on dissociable domain-specific control mechanisms. Interestingly, post-conflict adjustments in error rates were not modulated by the demands of the secondary tasks, suggesting that conflict adaptation in error rates may be more robust and less prone to dual-task interference than in RTs.

While our findings suggest a rather specific effect of the supplementary load specifically on post-conflict adjustments, we found, in addition, an increase of the actual Stroop effect under conditions of secondary task conditions independently of whether participants performed the emotional or the nonemotional Stroop task. This is consistent with previous studies which showed that the amount of the Stroop effect generally increases with slower mean RTs (Bub, Masson, & Lalonde, 2006; Pratte, Rouder, Morey, & Feng, 2010). Thus, the observed modulation of the actual Stroop effect may be explained with the slower RTs in the dual-task relative to the control conditions. It seems to reflect a rather general influence on conflict processing which has to be distinguished from the observed specific modulations of the post-conflict adjustments which depend on the domains of the secondary and the main task conditions.We have to note that some accounts questioned the assumption that post-conflict adjustments are related to conflict-triggered control adjustments; instead, they may (at least partially) be explainable by a feature binding or stimulus priming account (Hommel et al., 2004; Mayr et al., 2003). We controlled for such potential priming effects by testing whether response or category repetitions had an effect on our result pattern. Since these analyses revealed no significant effect of one of these potential confounds, they clearly support the assumption that the post-conflict adjustments which we observed in the current study are related to cognitive control.

4.2. Implications for models of cognitive control

The results of the present study relate to recent models of cognitive control. The model of Botvinick et al. (2001), for example, assumes a non-modular model of cognitive control with a conflict-unspecific cognitive control loop. In detail, the output of the conflict monitoring module in this model contains information only about the occurrence of a conflict, irrespective of the type of conflict. In contrast to that assumption, our results show that the cognitive system contains conflict-specific cognitive control processes for emotional and nonemotional conflicts. Considering that previous studies have already provided evidence for conflict-specific control mechanisms at different processing levels which resolve conflicts by “stimulus-biasing” in the Stroop task in contrast to by “response-biasing” in the Simon task (Egner et al., 2007; Wendt et al., 2006), the results of the present study show that there are also domain-specific control mechanisms which are specialized for resolving conflicts in the cognitive and the emotional domain. Thus, the current data challenge the assumption of a domain-general, unspecific control process which was mainly based on the results of previous neuroimaging studies (Chiew & Braver, 2011; Ochsner et al., 2009; Zaki et al., 2010). Importantly, if cognitive control is organized in a modular way, then one has to be cautious with generalizing findings stemming from a specific interference paradigm to cognitive control in general. For example, if a cognitive process modulates cognitive control in a specific interference paradigm, then the conclusions

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drawn from this finding should be confined to the specific control process involved in this paradigm rather than to cognitive control in general.

Our findings are also consistent with neuroanatomical considerations assuming that the demands of the applied secondary tasks are associated with activity in brain regions that are differently related to post-conflict adjustments in the nonemotional and the emotional Stroop task: Concerning Experiment 1, both WM processes and post-conflict adjustments in the nonemotional Stroop task were found to be correlated with activity in the DLPFC (Braver et al., 1997; Egner et al., 2008; Garavan et al., 2000. In contrast, the findings of Egner et al. (2008) suggest that the regulatory control loop involved in emotional post-conflict adjustments is not related to DLPFC activity, being consistent with the assumption that emotional post-conflict adjustments are not (or at least less) connected to WM processes. The findings of Experiment 2 are also consistent with findings of recent neuroimaging studies: The categorization of the emotional words required by the Go/Nogo task was found to be related to rACC activity (Chiu et al., 2008; Hare et al., 2008) and therefore shares a common neuroanatomical basis only with post-conflict adjustments in the emotional but not in the nonemotional Stroop task. Taken together, the observed dissociation confirms our hypothesis that conflict regulation in the emotional and the nonemotional Stroop task represent dissociable cognitive control systems. This hypothesis is supported both by functional and neuroanatomical considerations.

A puzzling issue is related to the particular observation of Egner et al. (2008) that the detection both of emotional and nonemotional conflicts is associated with dACC activity. This observation raises the question of how the conflict monitoring system can decide which cognitive control process needs to be triggered if one and the same neural region is associated with different types of conflict processing. A recent fMRI study of Kanske and Kotz (2011) gives an interesting hint for a possible answer to that question: the authors reported increased functional connectivity between the rACC and the dACC in response to emotionally charged relative to neutral task-relevant stimuli in conflict situations. Thus, it is possible that the context, e.g. whether task-relevant stimuli are emotionally salient or not, may signal to the conflict monitoring system which particular kind of conflict is present and as a consequence this determines the particular type of regulatory loop.

4.3. Relation to other mechanisms of emotional control

Whereas our results suggest the existence of domain-specific control mechanisms for emotional and nonemotional conflicts, most previous studies investigating the relationship between cognitive control and emotions have focused on two different questions: In particular, these studies asked how affective states modulate nonemotional control processes or how voluntary control strategies can regulate emotion processing. In regard to the first question, studies have found that positive mood or performance feedback may impair the efficiency of nonemotional control processes (van Steenbergen, Band, & Hommel, 2009; van Steenbergen, Band, & Hommel, 2010) or may increase the degree of cognitive flexibility and distractibility (Dreisbach & Goschke, 2004). In contrast to these approaches, the present study examined in which way cognitive control processes in the emotional and nonemotional Stroop task can be modulated by supplementary demands on emotional and nonemotional processing. Interestingly, we did not find an effect of the emotional Go/Nogo task on post-conflict adjustments in the nonemotional Stroop task. Thus it seems that, in contrast to the induction of positive mood, supplementary processing demands exposed by an additional emotional task do not affect simultaneously ongoing nonemotional control processes.

Moreover, it is important to differentiate between the emotional post-conflict adjustments we investigated in the present study and other, more strategic emotion regulation processes. In the current emotional Stroop task, participants are not instructed to actively suppress or modulate emotional processing as in other emotion regulation tasks (e.g., Ochsner, Bunge, Gross, & Gabrieli, 2002; Schmeichel, 2007), and behavioral adjustments following emotional conflicts are supposed to rely not on voluntary cognitive strategies. Consequently, one should be cautious when generalizing the present findings to other emotion regulation processes which require the active suppression (or regulation) of emotional responses. In contrast, as cognitive emotion regulation strategies such as reappraisal are associated with DLPFC activity (Ochsner et al., 2002; Ochsner & Gross, 2005), it is possible that they might be impaired by simultaneous WM demands in a similar way as nonemotional post-conflict adjustments.

There are important differences between the emotional Stroop paradigm we used and “traditional” emotional Stroop tasks: In “traditional” emotional Stroop tasks, participants typically have to respond to the color of presented words which in some cases have an emotional valence (e.g., the word “WAR”). Several clinical studies found that the task-irrelevant emotional processing of the word interferes with the color processing in some clinical subpopulations, but normally not in healthy participants (Mathews & MacLeod, 1985; Williams, Mathews, & MacLeod, 1996). In contrast, the conflict in the emotional Stroop task of the present study does not result from the intrusion of emotional into nonemotional processing but from the interference of emotional distractors with emotional target processing. Although conflict processing in the “traditional” emotional Stroop task was found to correlate with rACC activation (Whalen et al., 1998), the question whether our findings can be extended to the “traditional” emotional Stroop task remains open.

To summarize, the present study provided evidence that conflict regulation processes in the emotional and nonemotional Stroop task may (partly) rely on functionally dissociable processes. Previous studies have already revealed that post-conflict adjustments are correlated with DLPFC activity in the nonemotional Stroop paradigm and with rACC acitivity in the emotional Stroop paradigm. We extended this neuroanatomical dissociation to a functional level by showing that emotional and nonemotional post-conflict adjustments interfere differently with additional cognitive demands. In conclusion, our results underline

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the importance of differentiating between domain-specific control mechanisms in the human cognitive system and support the idea of a modular architecture of conflict control.

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ORIGINAL ARTICLE

Working memory demands modulate cognitive control in the Stroop paradigm

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Abstract One important task of cognitive control is to regulate behavior by resolving information processing conflicts. In the Stroop task, e.g., incongruent trials lead to conflict-related enhancements of cognitive control and to improved behavioral performance in subsequent trials. Several studies suggested that these cognitive control processes are functionally and anatomically related to working memory (WM) functions. The present study investigated this suggestion and tested whether these control processes are modulated by concurrent WM demands. For this purpose, we performed three experiments in which we combined different WM tasks with the Stroop paradigm and measured their effects on cognitive control. We found that high WM demands led to a suppression of conflict-triggered cognitive control, whereas our findings suggest that this suppression effect is rather due to WM updating than to maintenance demands. We explain our findings by assuming that WM processes interfere with conflict-triggered cognitive control, harming the efficiency of these control processes.

Introduction

In everyday life, we often focus our attention on behaviorally relevant stimuli while ignoring distracting ones. For example, we are concentrating on writing an article in our office and, at the same time, ignoring the noise outside the window. One basic mechanism behind these phenomena is cognitive control. According to many theoretical approaches, cognitive control is defined as a collection of processes allowing humans to modify their behavior to achieve their action goals (e.g., Baddeley, 1986; Norman & Shallice, 1986).

Recent studies have shown that humans may enhance cognitive control and improve its operation after the occurrence of information processing conflicts. The operation of such enhanced cognitive control is especially reflected by improved conflict resolution in interference tasks in which participants process conflicting response information. In these situations, processing improvements usually occur in an actual trial if participants processed a conflict compared to no conflict in the preceding trial (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Kerns et al., 2004; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wühr & Kunde, 2008; but see Mayr, Awh, & Laurey, 2003). Such trial-to-trial modulations were reported by Kerns et al. (2004) for the case of the Stroop task, in which participants name the ink color of a color word and in which reaction times (RT) are increased in incongruent (I) conditions (e.g., the word "RED" in green ink) compared to congruent (C) ones (e.g., "RED" in red ink). Kerns et al. have shown that the interference effect (i.e., the RT difference between I and C trials; Stroop effect) is smaller in trials which are preceded by a conflict trial compared to a non-conflict trial. Similar trial-to-trial modulations were also observed for other interference tasks

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such as the Eriksen-flanker task (Botvinick et al., 2001; Gratton, Coles, & Donchin, 1992) and the Simon task (Stürmer et al., 2002; Stürmer & Leuthold, 2003).

An influential theory of Botvinick et al. (2001) explains the occurrence of trial-to-trial modulations with a specific mechanism of cognitive control. According to that theory, the cognitive system monitors ongoing response processing to identify conflicts. If a conflict is detected, e.g., as a result of stimulus or response processing, the level of cognitive control is enhanced to adjust conflict processing in the subsequent trial. For example, such adjustments may enhance and/or suppress the processing of task-relevant stimulus or response characteristics to enable successful behavior (Botvinick et al., 2001; Egner, Delano, & Hirsch, 2007; Egner & Hirsch, 2005a).

While the theory of Botvinick et al. (2001) allows explaining the occurrence of post-conflict adjustments in the Stroop task and other paradigms and while it is in line with a large body of evidence, an open question refers to the specific factors which determine the efficiency of cognitive control. Previous studies have already shown that such post-conflict adjustments are modulated by the processing demands of supplementary tasks (Fischer, Dreisbach, & Goschke, 2008; Fischer, Plessow, Kunde, & Kiesel, 2010; Stürmer, Seiss, & Leuthold, 2005) or by emotional contexts (van Steenbergen, Band, & Hommel, 2009, 2011). In the present study, we address the question whether an additional working memory (WM) load may affect the efficiency of control-triggered post-conflict adjustments in the Stroop paradigm.

WM functions are of special interest here because converging evidence from different research areas suggests that cognitive control and WM processes rely on related mechanisms. For example, many authors assume that task representations are maintained in WM during ongoing interference task processing (Braver et al., 1997; Kane & Engle, 2003; MacDonald, Cohen, Stenger, & Carter, 2000). Since cognitive control is usually operating on these task representations (e.g., Dreisbach & Haider, 2009), the availability of a sufficient amount of WM resources can be considered as an important precondition for an efficient operation of cognitive control.

In favor of that assumption, several studies have observed that an additional WM load may reduce the efficiency of cognitive control processes (Lavie, Hirst, de Fockert, & Viding, 2004; Schmeichel, 2007; Ward & Mann, 2000). Although these studies investigated other mechanisms than post-conflict adjustments, their findings seem relevant for post-conflict adjustments in interference tasks as well. For example, Lavie et al. reported that the inhibition of task-irrelevant distractors was impaired in a selective attention task by simultaneous WM load. In detail, participants performed a WM task and simultaneously an Eriksen-flanker task in which they reacted on a central target surrounded by distractor stimuli. The WM task required participants to indicate whether a presented probe digit was present or absent in a preceding memory set of either six (high WM load) or one digit (low WM load). Lavie et al. found that the flanker interference effect was larger in the high than in the low WM load condition. According to the authors, the control functions involved in distractor inhibition are closely associated with WM processes, and a larger WM load reduces the resources for distractor inhibition, causing an increased flanker effect. Taken together, these considerations and empirical results are suggestive for the assumption of a close functional relationship between cognitive control and WM processes. In addition, they support the hypothesis that, per analogy, post-conflict adjustments in the Stroop task may be impaired by a simultaneous high WM load.

That hypothesis can also be supported by considering the neuroanatomical basis of WM processes and post-conflict adjustments. For example, Kerns et al. (2004) found a significant negative correlation between the amount of post-conflict adjustments and dorsolateral prefrontal cortex (DLPFC) activity. According to the authors, this correlation suggests that DLPFC activity is closely related to the maintenance of task-relevant information in WM during Stroop task performance (see also Carter et al., 1998; MacDonald et al., 2000). In line with that assumption, several neuroimaging studies suggest that DLPFC activity is generally related to the maintenance and updating of WM contents (Braver et al., 1997; D'Esposito et al., 1998; Garavan, Ross, Li, & Stein, 2000; Schumacher et al., 1996; Smith & Jonides, 1999; Sylvester et al., 2003). Since it is assumed that two processes show strong interference if they share a common neuroanatomical basis (Kinsbourne & Hicks, 1978; Klingberg, 1998), WM processes and cognitive control processes may interfere due to their overlapping neuroanatomy. Hence neuro-scientific considerations provide further support for the expectation that post-conflict adjustments in the Stroop task can be modulated by simultaneous WM demands.

Experimental rationales and hypotheses

The present experiments investigated whether WM demands interfere with cognitive control in the Stroop task. Based on the assumption that cognitive control and WM processes are functionally and anatomically related to each other, we predict that concurrent WM demands in an unrelated task should lead to a reduction of post-conflict adjustments in the Stroop task. We tested this hypothesis by combining the Stroop paradigm with different WM tasks. As WM tasks, we used an arithmetic task in Experiment 1, a version of the n-back paradigm in Experiment 2, and a WM maintenance task in Experiment 3.

It is important to note that some authors questioned the interpretation that sequential trial-to-trial modulations of interference effects result from control-related post-conflict adjustments. For example, Mayr et al. (2003) proposed an alternative account for the explanation of sequential trial-to-trial modulations in the flanker task. This account assumes that episodic memory traces of information of former trials prime stimulus and response features in subsequent trials. Similar considerations have also been proposed by other authors (Davelaar & Stevens, 2009) and for other paradigms (e.g., the Simon task; Hommel, Procter, & Vu, 2004; Wendt, Kluwe, & Peters, 2006). However, we note that a priming-based explanation is not sufficient as a sole explanation for the observed trial-by-trial modulations in the Stroop task as they can be observed even after removing all feature repetition trials (Puccioni & Vallesi, in press). To address the possibility of a priming-based explanation of our results, we controlled for different types of feature repetition effects when analyzing post-conflict adjustments.

Experiment 1

Experiment 1 tested whether concurrent WM demands interfere with post-conflict adjustments in the Stroop task. Participants performed a Stroop task together with a WM task, which was presented either in a high load or a low load condition. In the high load condition of the WM task, participants had to maintain two numbers in WM and to count up or down in steps of two from one of these numbers. Consequently, this task required the updating and monitoring of WM contents. In the low load condition, we presented only the arithmetic stimuli in addition to the Stroop task. Participants were instructed to attend to these stimuli without performing arithmetic operations. Consequently, participants had to maintain a second task representation additionally to the representation of the Stroop task in WM both in the high load and the low load conditions, but the task was much more demanding in the high load (perform arithmetic operations) than in the low load condition (attend to presented stimuli). In a third single-task condition, participants performed the Stroop task in isolation with no additional second-task instructions and stimuli.

Methods

Participants

Twenty-eight right-handed participants ($M_{\text{age}} = 24.21$ years; 20 female) were recruited by advertisement at the Department of Psychology at the LMU Munich and were paid 8€/hour for their participation. All subjects had normal or corrected-normal vision and were not informed about the aims of the experiment.

Stimuli and apparatus

The experiment took place in a dimly-lit soundproof experimental cabin. The participants sat 50 cm in front of a 17 in. monitor on which stimuli were presented. All stimuli were presented with Experimental Run Time System (ERTS, Behringer, 1993) on a standard PC.

As illustrated in Fig. 1, participants performed three different tasks: the Stroop task, the high WM load task and the low WM load task. In the *Stroop task*, participants were presented one of three different color words (“BLAU”, “ROT”, and “GRÜN”; German for *blue*, *red*, and *green*, respectively) written in capital letters colored either in blue, red, or green ink on a black screen. Participants were instructed to respond to the color of the stimuli as fast and as accurately as possible by pressing the “B”-key (for blue) with the index finger, the “N”-key (for red) with the middle finger or the “M”-key (for green) with the ring finger of the right hand on a QWERTZ-keyboard.

In the *high WM load task*, three white “x” were presented as fixation cross row on a black screen, whereas either the left or the right “x” could change into a plus (+) or a minus (−) sign. In each block, participants started with the number “50” both for the “x” at the left and the right position and performed the arithmetic operations shown at

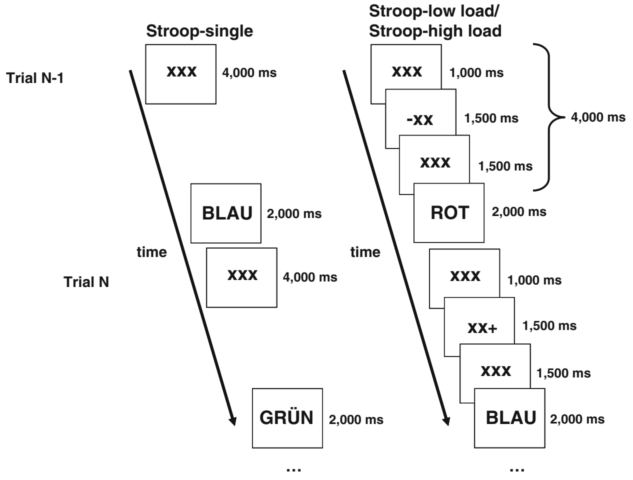

Fig. 1 Example trial sequences for the different task conditions in Experiment 1. The procedure was identical for the Stroop-low load and the Stroop-high load condition. In the Stroop-high load condition, participants performed the Stroop and the arithmetic task, while in the Stroop-low load condition they were instructed to perform the Stroop task and to attend the arithmetic stimuli. The Stroop task stimuli were presented in blue, red or green color, and all other stimuli were presented in white

the left “x” with the first number in mind and the operations presented at the right “x” with the second number in mind. To increase task difficulty, they were instructed to add “2” if a plus sign was presented and to subtract “2” if a minus was presented. For example, if a plus sign was presented at the right position (the left and the central “x” stayed unchanged in this case), then participants had to add “2” to the second number in WM while the first number remained unchanged compared to the preceding trial (note that only one arithmetic stimulus was presented in each trial). Thus, participants always had to maintain two numbers in WM and to conduct arithmetic operations on them. After each block including the high WM load task, the two final results of the continuous arithmetic calculations had to be written on a separate sheet of paper. In the *low WM load task*, the same stimuli were presented as for the arithmetic high WM load task, i.e., the three “x” as fixation cross row, whereas in every trial either the left or right “x” changed into a plus or minus sign. Participants were instructed to attend to these stimuli without performing arithmetic operations with them.

All stimuli were presented in 18-point size of Helvetia Font.

Design and procedure

Participants performed the Stroop task in three different WM load conditions: Stroop-single, Stroop-high load, and Stroop-low load. While the Stroop task was performed in isolation in the Stroop-single condition, it was combined with the high WM load and the low WM load task in the Stroop-high load and Stroop-low load conditions, respectively. In addition to the Stroop task conditions, participants performed the high WM load task in isolation in the high load-single condition.

In the Stroop task conditions (i.e., Stroop-single, Stroop-high load, and Stroop-low load), each block consisted of 12 (27%) incongruent and 33 (73%) congruent trials (see Kerns et al., 2004). Note that the ratio of C and I trials is supposed to trigger proactive control processes which may have to be distinguished from the post-conflict adjustments we were interested in (Funes, Lupiáñez, & Humphreys, 2010). But since these proactive control processes are assumed to have equal effects on conflict processing after previously congruent and incongruent trials (i.e., the level of proactive control is constant across all trials of a block), they should not confound with our analysis of post-conflict adjustments.

Trial order was randomized with the following two constraints: First, the number of CI (previous trial C, current trial I) and II trial sequences was equal per block (6 trials each). Second, the same number of congruent trials with a blue, red, or green word was followed by an incongruent one (thus 2 trials each, as we administered 6 CI trial sequences). In the high WM load conditions, the number of arithmetic signs (+ vs. −) and their specific location (left vs. right) differed across blocks to prevent predictability of the final results.

In the *Stroop-single* condition, a trial started with a foreperiod of 4,000 ms in which three white “x” were shown at the center of the screen, then a color word was presented for 2,000 ms or until a response was executed. Participants had to respond within the stimulus presentation time for the color word, then the next trial started immediately after the response. Also in the *high load-single* condition, the foreperiod including the presentation of three white “x” took 4,000 ms, then an arithmetic sign was displayed for 2,000 ms on the left or right position. In the *Stroop-high load* and *Stroop-low load* conditions, the basic procedure was as follows: After a foreperiod of 1,000 ms in which the fixation cross row (i.e., the three “x”) was displayed, one of the two outer crosses changed into a plus or a minus sign for 1,500 ms. After an inter-stimulus interval (ISI) of further 1,500 ms, the color word of the Stroop task was presented for an interval of 2,000 ms or until a response was executed. In the Stroop-high load condition, we instructed participants to perform the Stroop and the high WM load task simultaneously with equal priority, while in the Stroop-low load condition they were instructed to perform the Stroop task and to attend to the arithmetic stimuli but to perform no arithmetic operations.

Half of the participants started the experiment with eight blocks of the single conditions, i.e., Stroop-single and high load-single, in alternating order. The first type of block was balanced across participants. Following, eight blocks of dual-task conditions, i.e., Stroop-high load and Stroop-low load, were presented in alternating order and with balanced starting block type. For the remaining half of participants, the order of single-task and dual-task conditions was changed.

Statistical analysis

In the Stroop task conditions, RTs and error rates were analyzed. We removed all trials in which the target or distractor feature was repeated as target or distractor, respectively (39% of all Stroop trials; Kerns et al., 2004) to control for the effects of such feature repetitions on the trial-by-trial modulations of the Stroop effect (Mayr et al., 2003). In addition, we performed further analyses controlling for possible negative priming effects (see below). For the RT analysis of the Stroop task, we furthermore removed all trials including or following an error. As a result of these exclusions, a mean of 412 trials per participant was included in the analysis. Post-conflict adjustments were defined as the RT difference between the Stroop effect after previously congruent trials and the

Stroop effect after previously incongruent trials (CI-CC)-(II-IC).

To analyze performance in the high WM load task, we computed the difference between the true and the calculated final results in every block and averaged the difference values separately for all high load-single blocks and all Stroop-high load blocks.

For tests of significance, ANOVAs and paired-sample *t* tests as planned comparisons were used with a significance threshold of 5%. Huynh–Feldt corrections (Huynh & Feldt, 1976) were used to adjust the *p* values of the ANOVAs. As effect sizes, partial eta square (η_{p}^2) was calculated for the ANOVAs.

Results

Stroop task

Reaction times We analyzed RTs (see Fig. 2) in the Stroop task by conducting a 3 × 2 × 2 repeated-measures ANOVA with the factors WM load (Stroop-single vs. Stroop-low load vs. Stroop-high load), Previous trial congruency (congruent vs. incongruent) and Current trial congruency (congruent vs. incongruent). The analysis revealed a significant main effect of WM load, $F(2, 54) = 15.38$, $p < .001$, $\eta_{\mathrm{p}}^2 = 0.363$: Mean RTs were larger in the Stroop-high load ($M = 806$ ms) than in the Stroop-single ($M = 700$; $p < .001$) and the Stroop-low load conditions ($M = 712$; $p < .001$), while no significant difference was found between the last two conditions ($p > .3$). Participants responded faster in currently congruent ($M = 686$) than in incongruent trials ($M = 868$), $F(1, 27) = 94.02$, $p < .001$, $\eta_{\mathrm{p}}^2 = 0.777$. Furthermore, the significant interaction between previous trial congruency and current trial congruency, $F(1, 27) = 10.76$, $p < .01$, $\eta_{\mathrm{p}}^2 = 0.285$, pointed to the occurrence of post-conflict adjustments. Most importantly, the three-way interaction between WM load, previous trial congruency, and current trial congruency was significant, $F(2, 54) = 5.26$, $p < .05$, $\eta_{\mathrm{p}}^2 = 0.163$. This suggests that the amount of the post-conflict adjustments depended on the task condition.

Next, we calculated planned comparisons to determine in which way post-conflict adjustments were modulated by WM load. We found significant post-conflict adjustments only in the Stroop-single, (CI-CC)-(II-IC) = 106 ms, $t(27) = 3.54$, $p < .001$, and in the Stroop-low load conditions, (CI-CC)-(II-IC) = 56 ms, $t(27) = 2.53$, $p < .05$, but not in the Stroop-high load condition, (CI-CC)-(II-IC) = −15 ms, $t(27) < 1$, $p > .5$. In addition, we tested whether the amount of the post-conflict adjustments differed between the task conditions. We found that post-conflict adjustments were significantly reduced in the Stroop-high load relative to the Stroop-single, $t(27) = 2.76$, $p < .01$, and to the Stroop-low load conditions, $t(27) = 2.08$, $p < .05$. No significant difference was found between the Stroop-single and the Stroop-low load conditions, $t(27) = 1.19$, $p > .1$.

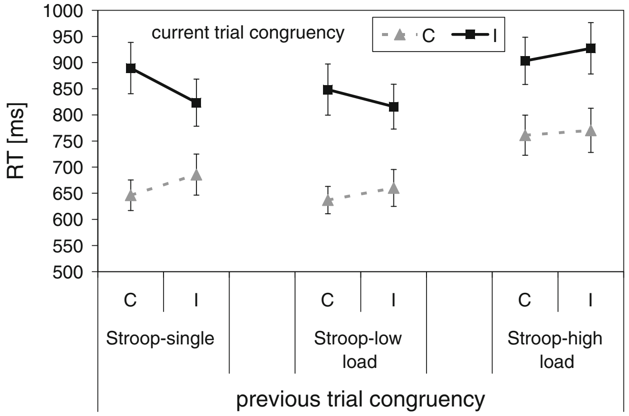

Fig. 2 Mean reaction times (RTs) in the Stroop task conditions in Experiment 1. *Error bars* indicate the standard error of mean (*C* congruent, *I* incongruent)

Note that we removed all trials from our analysis that included a repetition either of the color or the word feature, called within-dimension repetitions to exclude an impact of such feature repetitions on post-conflict adjustments (Hommel et al., 2004; Mayr et al., 2003). In addition, we controlled for possible influences of negative priming effects on our findings by adopting a different approach than that for controlling for the within-dimension feature repetition effects. In particular, negative priming may occur when the distractor feature of the previous trial becomes target feature in the current trial, or vice versa (across-dimension repetitions). It is important to note that, to control for influences of such across-dimension repetitions, we could not simply exclude the corresponding trials from the analysis (in addition to the exclusion of the within-dimension repetition trials) because this would have led to a complete removal of all II trials in the Stroop paradigm. Therefore, to test for possible negative priming influences, we calculated post-conflict adjustments in the three Stroop task conditions twice, i.e., once after removing all trials with within-dimension repetitions (the usual procedure in experiments with the Stroop paradigm, Egner, 2007; Kerns et al., 2004) and once after removing all trials with across-dimension repetitions. Next, we entered the resulting values into an ANOVA with the amount of post-conflict adjustments as dependent variable and with excluded trial type (within-dimension repetitions vs. across-dimension repetitions) and WM load (Stroop-single vs. Stroop-low load vs. Stroop-high load) as within-subject factors (for a similar procedure, see Egner & Hirsch, 2005a). Most importantly, the results of this ANOVA showed similar effects of WM load on the amount of post-conflict adjustments independently of which way the trial exclusion procedure was adopted. Thus, the current effects are not confounded by possible negative priming effects and effects of across-dimension feature repetitions. In detail, a significant main effect of WM load indicated that the amount of the post-conflict adjustments depended on the level of WM load, $F(2, 54) = 3.46$, $p < .05$, $\eta_p^2 = 0.114$, while the lacking effects of excluded trial type and the interaction between excluded trial type and WM load, both Fs < 1, suggested that the modulation of post-conflict adjustments is independent of which trials were excluded from the analysis. This is consistent with the assumption that the current WM load effects on the post-conflict adjustments are not confounded by possible negative priming effects and effects of across-dimension repetitions.

Error rates We analyzed error rates with a repeated-measures ANOVA including the factors WM load, Previous trial congruency, and Current trial congruency. Only the main effects of current trial congruency, $F(1, 27) = 77.55$, $p < .001$, $\eta_p^2 = 0.742$, and previous trial congruency, $F(1, 27) = 6.00$, $p < .05$, $\eta_p^2 = 0.182$, passed the statistical threshold. Subjects committed more errors in incongruent ($M = 7.5\%$) than in congruent trials ($M = 2.7\%$) and following congruent trials ($M = 5.8\%$) compared to following incongruent trials ($M = 4.4\%$). No other main effect or interaction was significant (see Table 1).

WM task

Performance rates We compared the performance rates in the WM task under dual-task and single-task conditions with a paired-sample t test. The significant difference between the error rates in the high load-single ($M = 3.7$) and the Stroop-high load condition ($M = 6.6$), $t(27) = 3.67$, $p < .01$, shows that performance in the WM task deteriorated in the dual-task condition.

Discussion

Experiment 1 investigated whether post-conflict adjustments can be modulated by WM demands. While no post-conflict adjustments occurred in the Stroop-high load condition, we found significant post-conflict adjustments both in the Stroop-single and the Stroop-low load conditions. Most importantly, post-conflict adjustments were significantly reduced in the Stroop-high load relative to the Stroop-low load condition. This is consistent with the assumption that post-conflict adjustments in the Stroop task can be modulated by additional WM demands. The observed modulation of post-conflict adjustments was independent of which kinds of feature repetition trials were excluded from the analysis, suggesting that this effect cannot be explained by a feature priming account.

Table 1 Error rates (in percent) in the Stroop task conditions of Experiment 1

Previous trial congruency:	C		I	
Current trial congruency:	C	I	C	I
Stroop-single	2.7 (.4)	12.7 (2.9)	2.5 (1.3)	6.2 (1.6)
Stroop-low load	2.7 (.7)	9.1 (3.)	1.4 (1.0)	6.5 (1.6)
Stroop-high load	4.9 (2.3)	10.9 (3.8)	7.2 (2.1)	9.7 (2.9)

Standard errors of mean are in brackets

C congruent, *I* incongruent

Against the proposed explanation of the modulated post-conflict adjustments, one might argue that the secondary task in the Stroop-low load condition might not have exposed any additional WM demands and participants might have processed that condition as a Stroop-single task and not in a dual-task mode. Such an argument may, in theory, be raised because for this type of secondary task, there was no control for participants' performance and attention to the presented stimuli. Therefore, we conducted Experiment 2 in which we administered a different WM task than that in Experiment 1, which allowed us to control for the impact of different levels of a concurrent WM load on the performance in post-conflict adjustments.

Experiment 2

In Experiment 2, we combined the Stroop task with a letter-variant of the n-back paradigm, which allowed manipulating the WM load of a secondary task in several steps (Braver et al., 1997). In the n-back task, a stream of letters was sequentially presented to the participants who decided whether a currently presented letter was identical to a previously (n-back) presented one. In the case that they were identical, participants responded with a finger keypress reaction, while no keypress reaction was required in the remaining cases.

We manipulated WM load in three steps: In the 2-back condition, participants had to report whether a currently presented letter was identical to the letter two trials before, while in the 1-back condition they had to respond if a letter was repeated in two subsequent trials. In addition, we administered a 0-back condition in which participants had to respond to a pre-specified letter. Thus, contrary to Experiment 1, the current control condition (0-back) exposed an apparent WM load in a controlled way because at least one item had to be maintained in WM.

The current n-back task required the maintenance and updating of WM contents and, in addition, the monitoring of overt motor response execution (Morris & Jones, 1990). Since overt motor response monitoring processes may affect Stroop task performance, we restricted our analyses of the Stroop task to those trials in which no overt response to an n-back target occurred. This is necessary because Stürmer et al. (2005) have shown that the need for overt motor response monitoring in a secondary task condition may suppress the occurrence of post-conflict adjustments in an interference task. In the study of Stürmer et al., participants performed a Simon task simultaneously with a two-choice and a simple response time task, and in both cases post-conflict adjustments were decreased relative to the Simon task alone. Consequently, by restricting the analysis to trials without overt motor responses in the n-back task, we can investigate the influence of a concurrent WM load on the Stroop task performance in Experiment 2.

Methods

Participants

Seventeen right-handed participants ($M_{\text{age}} = 26.24$ years; 13 females) were recruited for the experiment at the Department of Psychology at the LMU Munich and were paid 8€/hour. All had normal or corrected-to-normal vision and were not informed about the hypotheses of the experiment.

Stimuli and apparatus

The apparatus was identical to that in Experiment 1.

Participants performed the Stroop and the n-back task. The Stroop task was performed in the same way as in Experiment 1 with the only difference that a single "+" was used as fixation cross. For the n-back task, we used a letter-version of the n-back procedure of Braver et al. (1997) in which white letters were successively presented on a black screen. In the 1-back and the 2-back conditions, participants were asked to indicate whether the currently presented letter (= the target stimulus) was identical to the letter presented one or two trials before (= the cue stimulus), respectively, by pressing the left shift key on the keyboard with their left index finger. Therefore, both conditions required the permanent updating and maintenance of information in WM. We used phonologically similar letters in German (B D G P T W) to increase task difficulty.

In the 0-back condition, participants had to press the shift key with the left index finger only if a specific letter was presented on the screen. The instruction before each 0-back block indicated which letter represented the target stimulus in the subsequent block. The 0-back condition required mainly selective attention and response monitoring and, relative to the 1-back and 2-back conditions, a smaller maintenance load and no updating of information in WM.

Design and procedure

Participants performed three different task conditions in which they performed the Stroop task and simultaneously an n-back task (Stroop-0-back, Stroop-1-back, and Stroop-2-back). For the Stroop task, the trial order within one block was randomized with the same constraints as in Experiment 1, however one block contained 90 trials (66 congruent, 24 incongruent). For the n-back conditions, the order of the letters was randomized whereas each of the 6 letters was presented 15 times. Every block contained a total of 18 target stimuli.

The basic procedure was identical for all task conditions. After a foreperiod of 800 ms, a letter for the n-back task was presented (1,000 ms) and then, after an ISI of 1,200 ms, the color word for the Stroop task followed for 2,000 ms. Participants had to respond to the Stroop stimulus during the stimulus presentation time, afterwards the next trial started. We presented three blocks of each of the three experimental conditions in randomized order during the experiment. We instructed participants to respond as fast and as accurately as possible in the Stroop task, while they should mainly try to avoid errors in the n-back task. Since we wanted all participants to use the same strategy in the n-back task, participants were, in addition, instructed to solve the 1-back and 2-back task by internally rehearsing the last one or two presented letters, respectively.

Statistical analysis

For the Stroop task analysis, we removed all trials which contained either a repetition of the color or the word from the data set (38% of all trials). For the RT analysis, we also removed all error and post-error trials and, in addition, all trials in which participants had responded to an n-back stimulus, such that finally a total of 290 trials were included in the analysis.

To analyze performance in the n-back task, we calculated performance rates for every participant and n-back condition. The performance rate was defined as the number of correct answers divided by the number of all target stimuli.

Statistical tests were computed in the same way as in Experiment 1.

Results

Stroop task

Reaction times We computed a 3 × 2 × 2 repeated-measures ANOVA including the factors WM load (Stroop-0-back vs. Stroop-1-back vs. Stroop-2-back), Previous trial congruency (congruent vs. incongruent), and Current trial congruency (congruent vs. incongruent). The results are illustrated in Fig. 3. The significant main effect of WM load indicated different RTs across the Stroop task conditions, $F(2, 32) = 9.86$, $p < .001$, $\eta_{\mathrm{p}}^2 = 0.381$. In more detail, RTs were slower in the Stroop-2-back than in the Stroop-0-back and the Stroop-1-back conditions ($ps < .001$). In addition, RTs were slower in currently incongruent (750 ms) than in congruent trials (590 ms), $F(2, 32) = 67.37$, $p < .001$, $\eta_{\mathrm{p}}^2 = 0.808$, pointing to the occurrence of a Stroop effect of 160 ms. This effect of current trial congruency was modulated by the factor WM load, $F(2, 32) = 4.64$, $p < .05$, $\eta_{\mathrm{p}}^2 = 0.255$, suggesting that the amount of the Stroop effect differed between the WM load conditions. Additional post hoc analyses of the Stroop effect after previously congruent trials showed that the Stroop effect was significantly reduced in the Stroop-2-back (133 ms) compared to the Stroop-0-back (180 ms) and Stroop-1-back (183 ms) conditions, both $ps < .05$.

The Current trial congruency × Previous trial congruency interaction was not significant, $F(2, 32) < 1$, $p > .5$. Importantly, however, the significant WM load x Current trial congruency x Previous trial congruency interaction, $F(2, 32) = 3.97$, $p < .05$, $\eta_{\mathrm{p}}^2 = 0.199$, suggested that the amount of post-conflict adjustments depended on the level of WM load. Planned comparisons revealed that significant post-conflict adjustments occurred only in the Stroop-0-back, (CI-CC)-(II-IC) = 48 ms, $t(16) = 2.16$, $p < .05$, but not in the Stroop-1-back, (CI-CC)-(II-IC) = 2 ms, $t(16) < 1$, $p > .9$, and the Stroop-2-back conditions, (CI-CC)-(II-IC) = = −17 ms, $t(16) < 1$, $p > .5$. Importantly, the amount of post-conflict adjustment was significantly larger in the Stroop-0-back than in the Stroop-1-back, $t(16) = 2.04$, $p < .05$, one-tailed, and in the Stroop-2-back conditions, $t(16) = 2.75$, $p < .01$, one-tailed.

As for Experiment 1, we investigated whether the observed modulation of post-conflict adjustments remained stable when controlling for possible negative priming effects. For that purpose, we applied the same procedure as in Experiment 1 for analyzing whether the effect of the WM load on the post-conflict adjustments would change if we exclude trials with within-dimension repetitions or trials with across-dimension repetitions from the data set (see also Results section of Experiment 1). An ANOVA with the amount of post-conflict adjustments as dependent variable and with the factors Excluded trial type (within-dimension repetitions vs. across-dimension repetitions) and WM load (Stroop-0-back vs. Stroop-1-back vs. Stroop-2-back) revealed a significant main effect of WM load, $F(2, 32) = 6.65$, $p < .01$, $\eta_{\mathrm{p}}^2 = 0.294$. Importantly, neither the main effect of excluded trial type nor the Excluded trial type x WM load interaction was significant, $ps > .14$, indicating that the observed modulation of the post-conflict adjustments was independent of which trials were excluded from the analysis. In other words, the current WM load effects on the post-conflict adjustments are not confounded by possible negative priming effects and effects of across-dimension repetitions.

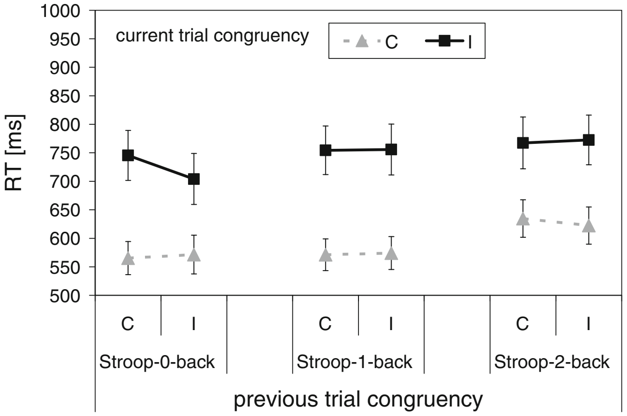

Fig. 3 Mean reaction times (RTs) in the Stroop task of Experiment 2. The *error bars indicate* the standard error of mean (*C* congruent, *I* incongruent)

Error rates We analyzed error rates by a repeated-measures ANOVA including the factors WM load, Previous trial congruency, and Current trial congruency. Only the main effect of current trial congruency was significant, $F(1, 16) = 13.82$, $p < .01$, $\eta_{\mathrm{p}}^2 = 0.463$; more errors were committed in incongruent (9.2%) than in congruent trials (3.5%). No further effect or interaction passed the statistical threshold (see Table 2).

WM task

Performance rates We analyzed performance rates in the n-back task by conducting a repeated-measures ANOVA including the factor WM load (Stroop-0-back vs. Stroop-1-back vs. Stroop-2-back). The main effect of WM load was significant, $F(2, 32) = 12.32$, $p < .001$, $\eta_{\mathrm{p}}^2 = 0.445$. Participants showed the best performance rate in the 0-back task (98%), followed by the 1-back (88%) and, finally the 2-back task (72%), all $ps < .05$.

Discussion

The data of Experiment 2 revealed significant post-conflict adjustments only in the Stroop-0-back, but not in the Stroop-1-back and the Stroop-2-back conditions. Importantly, while post-conflict adjustments did not differ between the Stroop-1-back and the Stroop-2-back conditions, they were significantly reduced in these conditions compared to Stroop-0-back blocks. Hence, the data of Experiment 2 show that high WM demands (which were

Table 2 Error rates (in percent) in the Stroop task conditions of Experiment 2

Previous trial congruency:	C		I	
Current trial congruency:	C	I	C	I
Stroop-0-back	2.2 (.4)	7.5 (1.4)	1.9 (.3)	6.7 (1.3)
Stroop-1-back	3.3 (.6)	7.6 (.6)	1.8 (.3)	6.8 (1.3)
Stroop-2-back	4.2 (.8)	9.9 (1.9)	2.6 (.5)	6.6 (1.3)

Standard errors of mean are in brackets

C congruent, *I* incongruent

present both in the Stroop-1-back and the Stroop-2-back conditions) lead to a suppression of conflict-triggered cognitive control, being consistent with the main hypothesis of the current work.

In addition, the current experiment allows rejecting an important counter argument which may be related to the current dual-task methodology: According to that argument, the reduced post-conflict adjustments in the 1-back and 2-back conditions might be explained by the requirement to permanently switch between the Stroop and the corresponding n-back task, instead of by the concurrent WM demands (see also discussion of Experiment 1). Importantly, however, also the Stroop-0-back condition clearly represents a dual-task situation in which participants have to switch between the Stroop and the 0-back task in every trial. Since the post-conflict adjustments in the Stroop-1-back and Stroop-2-back conditions were significantly reduced relative to the Stroop-0-back condition, task switching demands cannot account for the observed modulation of post-conflict adjustments. Instead, this effect must specifically be explained by the higher WM demands of the 1-back and 2-back compared to the 0-back task.

The results of Experiment 2 furthermore allow discussing the question of which specific WM processes are responsible for the suppression of post-conflict adjustments. A cognitive process which was required by the 1-back and 2-back tasks, but not by the 0-back task, is the updating of WM contents (Braver et al., 1997). This process requires the repeated substitution of the current WM content by another relevant WM content, which differs from the pure maintenance of WM content over a longer period of time. Consequently, the requirement for permanent WM updating seems to have impaired the enhancement of cognitive control after the detection of a conflict, resulting in suppressed post-conflict adjustments.

However, an open question concerns whether increasing demands for pure maintenance of items in WM would affect the occurrence of post-conflict adjustments just as the updating requirement. This question is of interest because the 0-back condition in Experiment 2 required maintaining only one item in WM and this represents a fairly low maintenance demand. To test whether larger demands on the pure maintenance of items in WM would or would not affect the amount of post-conflict adjustments we conducted Experiment 3. In this experiment, we applied a WM task as secondary task, which exposed different demands on WM maintenance and which spared the updating component.

Experiment 3

In Experiment 3, we combined the Stroop task with a WM task in which participants had to maintain either one or six numbers in the WM. The numbers were presented at the start of each Stroop task block. After each block, we asked participants which numbers had been presented at the start of the block. Consequently, this task required the maintenance but not the updating of WM contents during Stroop task performance. This paradigm allowed us to test whether high demands on WM maintenance lead to a reduction of post-conflict adjustments.

Methods

Participants

Fifteen right-handed participants ($M_{\text{age}} = 27.13$ years; 10 females) were recruited at the Department of Psychology at the LMU Munich and were paid 8€. All had normal or corrected-to-normal vision and were not informed about the hypotheses of the experiment.

Stimuli and apparatus

The apparatus was identical to the one in Experiment 1.

Participants performed the Stroop and the n-back task. The Stroop task was performed in the same way as in Experiment 2. For the WM task, participants had to memorize either one number (low load) or six numbers (high load) between zero and nine at the start of each block. At the end of a block, i.e., after the Stroop task trials, participants had to enter these numbers on the keyboard.

Design and procedure

Participants performed the Stroop task and simultaneously either the low load (Stroop-low load) or high load WM task (Stroop-high load). Every block contained 12 Stroop task trials (9 congruent, 3 incongruent) which were presented in randomized order and which had a similar ratio of congruent (75%) to incongruent (25%) trials as the task blocks in the Experiments 1 and 2. The procedure was identical for all conditions. At the start of a block, the numbers for the WM task were presented for 5,000 ms, followed by the Stroop task trials. After an ISI of 1,500 ms at the start of these trials, a color word was presented for 2,000 ms or until participants executed a response, then the next trial started. At the end of the block, we asked participants which numbers had been shown at the start of the block.

Participants performed 30 blocks of both the Stroop-low load and the Stroop-high load conditions in randomized order, resulting in a total of 270 congruent and 90 incongruent trials for each condition.

Statistical analysis

We analyzed the Stroop task trials in the same way as in the previous experiments. We removed 27% of all trials due to stimulus repetitions. In addition, we removed all blocks in which the WM task was not solved correctly, as well as error and post-error trials, such that on mean, a total of 216 trials were included in the analysis.

In the WM task, we considered a response as correct only if all numbers presented at the start of a block were correctly replicated. Performances rates were calculated as the percentage of correct responses of all responses in the low load or high load condition.

We computed statistical tests in the same way as in the previous experiments.

Results

Stroop task

Reaction times We computed a 2 × 2 × 2 repeated-measures ANOVA including the factors WM load (Stroop-low load vs. Stroop-high load), Previous trial congruency (congruent vs. incongruent) and Current trial congruency (congruent vs. incongruent). The findings are depicted in Fig. 4. RTs were slower in incongruent (642 ms) than in congruent trials (534 ms), $F(1, 14) = 51.37$, $p < .001$, $\eta_p^2 = 0.786$, and after previously incongruent (580 ms) than after congruent trials (565 ms), $F(1, 14) = 10.16$, $p < .01$, $\eta_p^2 = 0.420$. The significant Current trial congruency × Previous trial congruency interaction points to the occurrence of post-conflict adjustments, $F(1, 14) = 8.41$, $p < .05$, $\eta_p^2 = 0.375$: We found significant post-conflict adjustments both in the Stroop-low load, (CI-CC)-(II-IC) = 39 ms, $t(14) = 1.85$, $p < .05$, one-tailed, and the Stroop-high load conditions, (CI-CC)-(II-IC) = 50 ms, $t(14) = 2.48$, $p < .05$, one-tailed. Importantly, the WM load × Current trial congruency x Previous trial congruency interaction was not significant, $F(1, 14) < 1$, $p > .7$, $\eta_p^2 = 0.011$, which suggests that the number of items maintained in WM has no impact on the occurrence of post-conflict adjustments in the current paradigm.

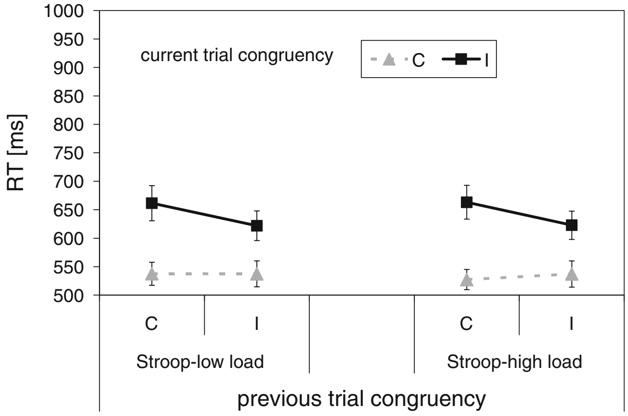

Fig. 4 Mean reaction times (RTs) in the Stroop task of Experiment 3. The *error bars* indicate the standard error of mean (*C* congruent, *I* incongruent)

As in the pervious experiments, we controlled for possible negative priming effects by calculating an ANOVA including the amount of post-conflict adjustments as dependent variable and the factors Excluded trial type (within-dimension repetitions vs. across-dimension repetitions) and WM load (Stroop-low load vs. Stroop-high load). No effect passed the statistical threshold, all Fs < 1.

Error rates A repeated-measures ANOVA including the same factors as the RT analysis revealed that participants committed more errors in currently incongruent (8.2%) than in congruent trials (3.1%), $F(1, 14) = 21.86$, $p < .001$, $\eta_p^2 = 0.610$, as well as after previously congruent (5.2%) than after incongruent trials (4.0%), $F(1, 14) = 7.45$, $p < .05$, $\eta_p^2 = 0.347$. No further effect was significant (see Table 3).

WM task

Performance rates A paired-sample t test showed that performance rate was higher in the low load (98%) than in the high load condition (94%), $t(14) = 2.83$, $p < .05$.

Discussion

The results of Experiment 3 show that the number of items maintained in WM does not affect conflict-triggered control. In detail, the amount of post-conflict adjustments did not depend on whether the task was to maintain one (low load) or six items (high load). Note that the higher error rate in the high load compared to the low load task shows that the high load task was more difficult and thus required more WM efforts than the low load task, even if participants had used a chunking strategy, which would have reduced the number of stored chunks below six items (see Miller, 1956). Moreover, performance rate in the high load

Table 3 Error rates (in percent) in the Stroop task conditions of Experiment 3

Previous trial congruency:	C		I	
Current trial congruency:	C	I	C	I
Stroop-low load	4.1 (.7)	10.4 (1.6)	2.7 (1.3)	6.1 (1.7)
Stroop-high load	3.3 (.6)	9.1 (2.2)	.0 (.0)	7.3 (1.3)

Standard errors of mean are in brackets

C congruent, *I* incongruent

condition of Experiment 3 was similar to the performance rate in the 1-back condition of Experiment 2 (in which no post-conflict adjustments occurred), suggesting that these two WM tasks were of comparable difficulty. Consequently, increased demands on WM maintenance processes had no effect on the operation of post-conflict adjustments in Experiment 3.

General Discussion

The purpose of the present study was to investigate whether WM demands modulate post-conflict adjustments in the Stroop task. In Experiments 1 and 2, we found no post-conflict adjustments in the Stroop task when participants simultaneously performed a demanding WM task (an arithmetic task, or a 1-back and a 2-back task, respectively), while significant post-conflict adjustments occurred when participants performed a secondary task with less WM demands (Stroop-low load or Stroop-0-back condition) or the Stroop task alone (Stroop-single condition). The finding of significantly reduced post-conflict adjustments in the Stroop-1-back compared to the Stroop-0-back condition suggests that updating and not maintenance of WM contents led to a suppression of conflict-triggered control, since the demands on WM maintenance should not have differed between the 0-back and the 1-back condition.

This conclusion is supported by the results of Experiment 3: Significant post-conflict adjustments occurred even when participants simultaneously maintained six numbers in WM, hence a number of items which is clearly larger than the number of WM items in the 1-back task (one item). Taken together, these results suggest that simultaneous demands on WM updating interfere with conflict-triggered cognitive control in the Stroop task, while the simple maintenance of up to six items in WM had no effect on these control processes in Experiment 3. Note that a conclusion that WM maintenance does not impair post-conflict adjustments at all must be considered with caution, since we cannot be sure about the impact of a load higher than six items on post-conflict adjustments (even though the number of six items is already close to the maximum WM capacity, Miller, 1956).

The observed interference between WM demands and cognitive control fits well with current assumptions about the processes involved in the two mechanisms and their neural implementation: First, current theoretical approaches suggest that cognitive control and WM processes are functionally interdependent. Cognitive control processes are involved in the selection of information that enters WM (Baddeley, 1986; Hasher & Zacks, 1988) and, moreover, the operation of cognitive control requires the maintenance and updating of task representations in WM and hence the availability of WM resources (Dreisbach & Haider, 2009; MacDonald et al., 2000). Second, these functional considerations were supported by neuroanatomical findings suggesting that overlapping brain regions such as the DLPFC and the anterior cingulate cortex are involved both in WM processes and post-conflict adjustments. The results of the present study clearly fit with the predictions based on these functional and anatomical considerations and moreover also with the findings of previous studies which reported an impairment of other cognitive control processes by WM demands (Lavie et al., 2004; Schmeichel, 2007; Ward & Mann, 2000).

An important issue which needs to be discussed is which reasons can be accounted for the observed reductions of post-conflict adjustments. Several possible explanations have to be discussed: First, according to a view that was recently substantiated by Schmeichel (2007), it is possible that WM and cognitive control processes both require the same capacity-limited processing resources. If this is correct, then specific executive control processes required in the Stroop task and memory updating processes would share a common resource, i.e., common processing mechanisms. According to that view, the suppression of post-conflict adjustments occurs because the WM demands deplete all available processing resources so that no further cognitive control could be executed after the occurrence of a conflict. In terms of the conflict monitoring account of Botvinick et al. (2001), the resource-depletion account suggests that not the detection of response conflicts is impaired under WM load but the execution of subsequent cognitive control enhancements after conflict trials. Note that these authors assume that control-triggered post-conflict adjustments lead to an enhanced representation of task demands which, in consequence, biases task-relevant stimulus processing. In the framework of that model, the need to update WM contents related to another task (like the arithmetic or the n-back stimuli) may impede the conflict-triggered updating of the Stroop task representation, resulting in a suppression of post-conflict adjustments.

However, we have to consider a second possibility how, in theory, increased WM demands may have affected the occurrence of post-conflict adjustments. According to that view, not the execution of cognitive control itself but already the detection of conflicts may be impaired by the concurrent WM task. It is important to note that this explanation does not imply that conflicts do not occur under WM load, but it assumes that participants do not become aware of these conflicts when they occur. As a consequence of such a view, we would have to assume that the conscious awareness of the conflict is a precondition for the operation of consequential control processes leading to trial-to-trial modulation of the RTs.

However, it is unclear whether the detection of a conflict by the conflict monitoring system requires the conscious awareness of conflict or whether it represents an unconscious, rather automatic process. Importantly, a recent study of van Gaal, Lamme, and Ridderinkhof (2010) showed that also unconscious conflicts lead to post-conflict adjustments. This finding is supported by an event-related potentials study which showed that conscious awareness of processing outcomes might not be a necessary pre-condition for the cognitive system to detect that something goes wrong or that a conflict is occurring (Pavone, Marzi, & Girelli, 2009). In particular, these authors found an error-related negativity in a visual discrimination task in error trials independently of whether participants became aware or non-aware of the error (see also Endrass, Reuter, & Kathmann, 2007). As the error-related negativity component is supposed to reflect the detection of errors as well as of response conflicts in the ACC (Masaki, Falkenstein, Stürmer, Pinkpank, & Sommer, 2007; Ullsperger & von Cramon, 2006; Yeung, Cohen, & Botvinick, 2004), this finding suggests that a possible unawareness of a conflict or error may not impair conflict detection itself. However, if that is the case, then the possible lack of awareness of a conflict which may have been caused by WM load would not be sufficient to explain the reduced post-conflict adjustments we observed, since conflict detection can occur even despite of unconsciousness of the error. Hence it is more parsimonious to explain the modulated post-conflict adjustments by a suppression of cognitive control enhancements.

A further alternative interpretation of our findings requiring discussion is that the WM demands in Experiment 1 and 2 may not have suppressed the exertion of cognitive control, but, in contrast, may have led to a tonically increased level of control such that no further transient post-conflict adjustments could occur. This claim may be based on the results of Plessow, Fischer, Kirschbaum, and Goschke (2011) who found that acute stress induces a high level of sustained control, while it depresses flexible control adjustments. If that account is correct, however, then a suppression of post-conflict adjustments should always be accompanied by a decreased Stroop effect even after congruent trials, since the increased level of control should result in a smaller congruency effect. In contrast to that prediction, the amount of the Stroop effect after congruent trials did not differ between the 0-back and the 1-back condition of Experiment 2, despite the suppressed post-conflict adjustments in the 1-back condition. Hence, the current data cannot be explained by the assumption that the WM tasks induced a high level of sustain control and, by this, impaired the exertion of post-conflict adjustments.

In addition, the present data also allow rejecting the possibility that the observed interference effects in conditions of high WM load can be explained by the need to switch between the WM and the Stroop task. Such task-switching processes were required by the 2-back, 1-back, and the 0-back conditions in Experiment 2. Importantly, the 0-back task required comparing the currently presented letter with the target letter in WM and deciding whether a response has to be executed in the current trial. Consequently, Stroop-0-back clearly represents an experimental condition in which participants permanently have to switch between the Stroop and the 0-back task. Since post-conflict adjustments in the Stroop-1-back and Stroop-2-back conditions were significantly reduced relative to the Stroop-0-back condition, a possible interference of task-switching processes with cognitive control alone cannot explain the observed effects. On the contrary, we believe that the specific processing characteristics related to the particular secondary task (i.e., WM updating) are the decisive characteristics, which affect the operation of post-conflict adjustments. The current findings are consistent with the assumption that tasks exposing sufficiently high WM demands affect post-conflict adjustments, while secondary tasks without such WM demands do not; this shows that pure switching between different tasks cannot be the reason for the disappearance of post-conflict adjustments in the current study.

Interestingly, not all studies investigating WM effects on cognitive control found an influence on trial-by-trial modulations. For example, Stürmer et al. (2005) reported that post-conflict adjustments in the Simon task were not suppressed when participants simultaneously performed a WM task (which was similar to the arithmetic task of Experiment 1). There are two possible reasons for the discrepancy between our findings and those of Stürmer et al.: First, although the WM task of Stürmer et al. was superficially similar to the arithmetic task in the present Experiment 1, it was less difficult than the present task. In particular, participants had to count up or down only in steps of one (instead of two), and, moreover, counting up was restricted to the arithmetic stimuli presented on one side of the screen while counting down to the stimuli of the other side. Therefore, this task was perhaps not sufficiently demanding to suppress the occurrence of post-conflict adjustments.

Another possible reason for the observed discrepancy in findings focuses on possible differences between the conflict processes in the two paradigms applied in the present study and the study of Stürmer et al. (2005). In detail, several theoretical accounts of response conflict assume that the processes in the Stroop and the Simon paradigm differ concerning their origins of conflict as well as their conflict resolution mechanisms. Thus, while conflicts are rather stimulus-based in the Stroop task, they are rather response-based in the Simon task (Kornblum, 1994; Kornblum, Hasbroucq, & Osman, 1990; Kornblum & Lee, 1995; Kornblum, Stevens, Whipple, & Requin, 1999; Zhang, Zhang, & Kornblum 1999). Concerning conflict resolution, there is evidence that cognitive control leads to an amplification of task-relevant stimulus-processing in the Stroop task while it leads to a suppression of the influence of task-irrelevant information on motor output in the Simon task (Egner et al., 2007; Egner & Hirsch, 2005a; Stürmer et al., 2002; Stürmer & Leuthold, 2003). Although conflict-related DLPFC activity was also found in the Simon task (Garavan, Ross, & Stein, 1999; Peterson et al., 2002), the effects of cognitive control on conflict resolution may differ between the Stroop and the Simon task (Egner, 2008). If post-conflict adjustments in the Stroop and the Simon task represent distinct forms of conflict regulation, then WM demands may have dissociable effects on these conflict-specific control processes.

One might have expected that WM processes should interfere also with within-trial control processes (Morishima, Okuda, & Sakai, 2010; Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011; Taylor, Nobre, & Rushworth, 2007). As a consequence, this might have caused an increased Stroop effect in conditions of high compared to low WM demands. In contrast to that expectation, however, the amount of the Stroop effect did not differ between the low load and the high load conditions of Experiment 1 and 3, and it was even decreased in the 2-back compared to the 0-back and 1-back conditions of Experiment 2. If any, then this result pattern is not consistent with the assumption that WM load increases the current Stroop effect by harming current within-trial control processes; it may also suggest that within-trial control processes differ from the mechanisms involved in trial-by-trial post-conflict adjustments (Boy, Husain, & Sumner, 2010). The impact of WM load on the Stroop effect may also depend on the specific type of the applied WM task. For example, there is evidence that verbal and spatial WM load have dissociable effects on the congruency effect in the Simon task (Wühr & Biebl, 2011; Zhao, Chen, & West, 2010). However, since the focus of the present study was on the modulation of post-conflict adjustments, further research will be needed to clarify whether different WM tasks have also dissociable effects on within-trial control processes in the Stroop task.

It is important to note that the present data cannot be explained within the framework of a stimulus priming account (Davelaar & Stevens, 2009; Hommel et al., 2004; Mayr et al., 2003). Although we analyzed only trials which contained neither a repetition of the word nor of the color, significant post-conflict adjustments occurred in all experiments of the present study. Note that we could not simultaneously control for negative priming, since II trials contain either within-dimension repetitions (target or distractor feature is repeated as target or distractor feature, respectively) or across-dimension repetitions (target feature is repeated as distractor feature, or vice versa) in the version of the Stroop paradigm we used. However, further analyses revealed that the observed modulations of post-conflict adjustments remained stable when we excluded across-dimension instead of within-dimension repetition trials. Since the results of the present study consequently did not depend on which feature repetition trials were excluded, we conclude that it is very unlikely that our findings result from WM effects on feature priming. Note moreover that negative priming effects are typically very small relative to the size of the congruency effects (Fox, 1995; May, Kane, & Hasher, 1995) and are often not detectable when ISIs are longer than 2,000 ms (Neill & Valdes, 1992; Egner & Hirsch, 2005b).

In sum, the present study revealed that post-conflict adjustments in the Stroop task can be modulated by simultaneous WM updating demands. We predicted this modulation effect on the basis of evidence suggesting a common functional and neuroanatomical basis of WM and cognitive control processes. We speculate these two processes rely at least partially on the same capacity-limited processing resources, such that the resources necessary for post-conflict adjustments were depleted by the WM demands. An open question remains whether these findings can be generalized to conflict-related control processes in other paradigms. As Stürmer et al. (2005) did not find a suppression of post-conflict adjustments by WM demands in the Simon task, it is tempting to assume that WM processes interfere selectively with specific conflict resolution mechanisms.

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Research Article

Conflict-Specific Effects of Accessory Stimuli on Cognitive Control in the Stroop Task and the Simon Task

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Abstract. Both the Stroop and the Simon paradigms are often used in research on cognitive control, however, there is evidence that dissociable control processes are involved in these tasks: While conflicts in the Stroop task may be resolved mainly by enhanced task-relevant stimulus processing, conflicts in the Simon task may be resolved rather by suppressing the influence of task-irrelevant information on response selection. In the present study, we show that these control mechanisms interact in different ways with the presentation of accessory stimuli. Accessory stimuli do not affect cognitive control in the Simon task, but they impair the efficiency of cross-trial control processes in the Stroop task. Our findings underline the importance of differentiating between different types of conflicts and mechanisms of cognitive control.

Keywords: cognitive control, conflict processing, Stroop task, Simon task, accessory stimuli

Successful goal-directed actions require control processes that dynamically adjust performance to changing task demands. For example, in case of action errors or information processing conflicts, the cognitive system has to increase the level of control to guarantee successful behavior. An influential model of the function of cognitive control in conflict resolution is the so-called "conflict monitoring account" (Botvinick, Braver, Barch, Carter, & Cohen, 2001). On this account, detection of a conflict leads to enhanced cognitive control to resolve subsequent conflicts more efficiently.

An experimental setting in which such control adjustments can be investigated is the Stroop paradigm. In the standard version of this paradigm, participants respond to the ink color of a color word while ignoring its semantic meaning. The typical finding is that reaction times (RTs) are slower with incongruent (I) (e.g., "RED" written in blue) than with congruent (C) color-word combinations (e.g., "RED" written in red). This so-called "Stroop effect" is commonly explained in terms of a processing conflict between the task-relevant color and the task-irrelevant word semantics (MacLeod, 1991). Importantly, the amount of Stroop interference has been found to be reduced on a given trial *n* after encountering an incongruent color-word combination, versus congruent combination, on the previous trial $n - 1$ (Egner, 2007; Kerns et al., 2004; Notebaert, Gevers, Verbruggen, & Liefooghe, 2006). In line with the account of Botvinick et al. (2001), this sequence-dependent modulation of the Stroop effect can be attributed to the encountering of a conflict leading to enhanced cognitive control and to improved conflict resolution on subsequent trials.

Importantly, similar sequential adjustments of control have also been observed in many other paradigms (e.g., Dreisbach & Fischer, 2011; Langner, Eickhoff, & Steinborn, 2011). In the Simon task, for instance, participants respond to task-relevant stimuli (e.g., the letters "X" and "O") which are presented either on the left or on the right side of the screen by pressing a left (e.g., for an "X") or a right response key (e.g., for an "O"). RTs are typically faster when the task-irrelevant stimulus location and the required response are congruent (e.g., an "X" located on the left side), compared to when they are incongruent (e.g., an "X" located on the right side). Similar to the Stroop effect, the impact of the conflicting information (stimulus location) on a given trial *n* is reduced if this follows an incongruent, versus a congruent, trial $n - 1$ (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wühr, 2005).

Although the neurocognitve mechanisms underlying post-conflict adjustments in the Stroop and the Simon tasks may partially overlap (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Peterson et al., 2002), there is evidence that the cognitive system employs dissociable, conflict-specific control strategies in these tasks: In the Stroop paradigm, conflicts are mainly resolved by enhancing the processing of task-relevant information; by contrast, in the Simon task, conflicts are resolved by suppressing the effect of task-irrelevant information on response selection (Egner, 2008; Egner & Hirsch, 2005; Stürmer & Leuthold, 2003; Stürmer et al., 2002). Consistent with this assumption, (Egner, Delano, & Hirsch, 2007) provided evidence for a dissociation between post-conflict adjustments in the Stroop and the Simon tasks on a neuroanatomical level. Given this

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neuroanatomical dissociation, the present study tested whether control processes in the Stroop and the Simon tasks can be dissociated also on a functional level. If it could be demonstrated that these control processes interfere with other cognitive processes in a conflict-specific way, this would provide strong support for a differentiation between separable networks of conflict processing. The present study addressed this question by investigating the effects of accessory stimuli on conflict resolution in the Stroop and the Simon paradigms, respectively.

Accessory stimuli, such as arbitrary tones presented prior to the task-relevant stimulus, are of special interest in this context as, like cognitive control, they are thought to improve task performance by enhancing the efficiency of information processing. Depending on task demands, accessory stimuli are assumed to facilitate processes of response selection (Fischer, Schubert, & Liepelt, 2007; Hackley & Valle-Inclán, 1999; Johnson & Proctor, 2004; Sanders, 1980) and/or processes of selective attention and stimulus recognition (Böckler, Alpay, & Stürmer, 2011; Matthias et al., 2010).

The effects of accessory stimuli on post-conflict adjustments in the Simon task have already been examined in two recent studies (Böckler et al., 2011; Fischer, Plessow, & Kiesel, 2010). Both studies failed to find a modulatory influence of these accessory stimuli on post-conflict adjustment processes. This finding was explained in terms of a dual-route framework (De Jong, Liang, & Lauber, 1994; Stürmer & Leuthold, 2003; Stürmer et al., 2002), according to which the task-relevant stimulus attribute and its associated response are processed via a slow, indirect route, whereas the task-irrelevant location primes a potentially false response alternative via a fast, direct route. On incongruent trials, the (inappropriate) response activated by the direct route is in conflict with the (appropriate) response mediated by the indirect route. Post-conflict adjustments in the Simon task are explained by assuming that enhanced cognitive control suppresses the source for the potentially false response, that is, the direct route – so that the stimulus location no longer impacts (or impacts less) on the response selection stage (Stürmer & Leuthold, 2003; Stürmer et al., 2002). Within this framework, the findings of Böckler et al. (2011) and Fischer, Plessow, and Kiesel (2010) would imply that accessory stimuli do not affect the control-triggered suppression of the direct route.

The hypothesis of dissociable post-conflict adjustment mechanisms operating in the Simon and Stroop tasks, respectively, raises the question whether accessory stimuli have also no, or whether they have an, impact on post-conflict adjustments in the Stroop task: As already mentioned, there is evidence that post-conflict adjustments in the Stroop task help in resolving future conflicts mainly by enhancing the processing of task-relevant information Egner and Hirsch (2005), in contrast to the suppression of irrelevant sources of information in the Simon task. In Egner and Hirsch's (2005) fMRI study, participants were presented with faces of actors and politicians that were either congruently or incongruently overlaid by names of famous actors or politicians; participants had to decide whether the displayed face represented an actor or a politician. The results revealed increased activity in the fusiform face area on trials with high control (i.e., after incongruent trials) relative to trials with low control (i.e., after congruent trials) – indicating that post-conflict adjustments in the Stroop task improve conflict resolution by "stimulus biasing," that is, by enhancing the processing of task-relevant stimulus attributes.

In a follow-up study, Egner et al. (2007) found a double dissociation between the Stroop and the Simon paradigm on a neuronal level: In the Stroop task, post-conflict adjustments correlated with activity in posterior parietal cortex; by contrast, in the Simon task, they were associated with premotor activity. Thus, given a "modular" architecture of cognitive control, the effects of accessory stimuli on post-conflict adjustments may well differ between the Stroop and the Simon task.

Accordingly, the aim of the present study was to examine whether accessory stimuli modulate cognitive control processes in the Stroop task, and whether these effects would deviate from the findings for the Simon task. If the effects of accessory stimuli on post-conflict adjustments were found to differ between the two paradigms, this would underscore the importance of differentiating between conflict-specific control processes in the Stroop and the Simon tasks. Experiment 1 was designed to replicate and extend the findings of Böckler et al. (2011) and Fischer, Plessow, and Kiesel (2010) for the Simon task. Experiment 2 then examined for the effects of accessory stimuli in the Stroop task.

Experiment 1

In Experiment 1, we adopted a version of the Simon paradigm in which participants responded to the identity of a presented letter by pressing either a left or a right response key. Contrary to the studies of Böckler et al. (2011) and Fischer, Plessow, and Kiesel (2010), we presented accessory stimuli blockwise and not in half of the trials within a block. This procedure allowed testing whether the results of these studies can be extended to an experimental setup in which the impact of accessory stimuli on task performance is held constant across all trials of a block, such that differences between previous and current trials can conclusively be attributed to control-triggered post-conflict adjustments and not to possible differences in the level of alertness, since the latter is constant across all trials of a block.

Methods

Participants

Twenty-two students (mean age = 24.50 years, standard deviation = 6.55, 15 female) of the Ludwig Maximilians University, Munich with normal or corrected-to-normal vision participated in the experiment for payment (€8 per hour).

Stimuli and Apparatus

The experiment was conducted in a dimly-lit, sound-proof cabin. Participants were seated at a distance of 50 cm from a 17-inch monitor on which stimuli were presented by Experimental Run-Time System (ERTS; Behringer, 1993). A white cross was presented at the center of a black screen as fixation marker. For the Simon task, a white "X" or "O" was presented on the left or the right side, at an eccentricity of 3.1° visual angle relative to screen center. Participants were instructed to press the left or the right control key on a QWERTZ keyboard if an "X" or an "O," respectively, was presented. Accessory stimuli were presented by the internal speaker of the computer (which was placed centrally in front of the participants) with a frequency of 650 Hz (~ 50 dB).

Design and Procedure

Experiment 1 followed a 2 × 2 × 2 within-subjects design with the factors Accessory Stimulus (no-AS vs. AS), Previous trial congruency (c vs. i), and Current trial congruency (C vs. I). Trials with and without accessory stimuli were presented blockwise, with blocks including 66 congruent trials (53 cC, 12 iC) and 24 incongruent trials (12 cI, 12 iI). The first trial of each block was congruent and excluded from the analysis.

The procedure was basically the same for trials with and without accessory stimuli. On trials including an accessory stimulus (AS condition), first a white fixation cross was presented on a black screen for 2,400 ms, followed by a random interval. The length of this interval was drawn from an exponential function with a mean of 800 ms. This interval was followed by an acoustic accessory stimulus (200 ms) and thereafter by an interstimulus interval of 400 ms. The Simon stimulus was presented for 2,000 ms or until a response was executed, upon which the next trial started. On trials without an accessory stimulus (no-AS condition), the length of the interval before the Simon stimulus was 3,000 ms plus the random interval.

Three blocks with and three blocks without accessory stimuli were presented in alternating order. The starting block type was balanced across participants. We instructed participants to respond as fast and as accurately as possible.

Statistical Analysis

RTs and error rates were analyzed. For the RT analysis, we excluded error and post-error trials. We defined the error rate as the percentage of error trials in an experimental condition. Post-conflict adjustments were calculated by subtracting the Simon effect after previously incongruent trials from the Simon effect after previously congruent trials (cI – cC) – (iI – iC) (Stürmer, Nigbur, Schacht, & Sommer, 2011). To control for effects of repetition priming on post-conflict adjustments, we removed all repetition trials from the data (Stürmer et al., 2002). For tests of significance, we calculated ANOVAs and paired-samples *t*-tests with significance thresholds of 5%.

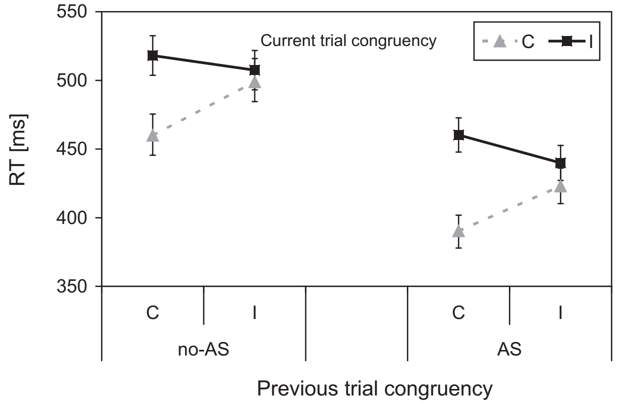

Figure 1. Mean reaction times (RTs) for the Simon task conditions in Experiment 1. Error bars indicate the standard error of mean. *Notes*. C/c = congruent; I/i = incongruent; AS = accessory stimulus.

Results

Reaction Times

RT data were examined by a 2 × 2 × 2 repeated-measures ANOVA with the factors Accessory stimulus, Previous trial congruency, and Current trial congruency (Figure 1). RTs were significantly faster in AS (411 ms) than in no-AS blocks (479 ms), $F(1, 21) = 118.48$, $p < .001$, $\eta_p^2 = .849$, and on trials after previously congruent (437 ms) compared to previously incongruent trials (467 ms), $F(1, 21) = 12.97$, $p < .01$, $\eta_p^2 = .382$. In addition, RTs were overall faster for congruent (432 ms) than for incongruent trials (481 ms), $F(1, 21) = 66.34$, $p < .001$, $\eta_p^2 = .760$, indicating the occurrence of a Simon effect. This Simon effect was modulated by the congruency of the previous trial, $F(1, 21) = 39.75$, $p < .001$, $\eta_p^2 = .654$, indicative of the occurrence of post-conflict adjustments. Importantly, these post-conflict adjustments were not modulated by the factor Accessory stimulus, $F(1, 21) < 1$, $p > .6$: significant post-conflict adjustments occurred both in the no-AS (cI – cC) – (iI – iC) = 50 ms, $t(21) = 4.86$, $p < .001$, and in the AS condition (cI – cC) – (iI – iC) = 53 ms, $t(21) = 6.70$, $p < .001$. In contrast to post-conflict adjustments, the Simon effect was influenced by the presence versus the absence of an accessory stimulus, $F(1, 21) = 6.02$, $p < .05$, $\eta_p^2 = .223$: the Simon effect was increased in AS (54 ms) compared to no-AS blocks (45 ms). In more detail, accessory stimuli significantly increased the Simon effect after congruent trials, $t(21) = 2.06$, $p < .05$, one-tailed, with a tendency for an increase also after incongruent trials, $t(21) = 1.40$, $p < .09$, one-tailed. Moreover, accessory stimuli speeded RTs in both congruent and incongruent trials, *p*s < .001.

Table 1. Error rates for the Simon task of Experiment 1. In parentheses are the standard errors of mean

Previous trial congruency	c		i	
Current trial congruency	C	I	C	I
no-AS	0.7 (.3)	5.5 (1.1)	2.2 (.7)	4.1 (1.4)
AS	0.2 (.1)	4.6 (1.3)	1.4 (.4)	4.3 (1.6)

Notes. C/c = congruent; I/I = incongruent; AS = accessory stimulus.

Error Rates

A repeated-measures ANOVA with the same factors as for the RT analysis revealed that participants committed more errors on incongruent (4.6%) than on congruent trials (0.7%), $F(1, 21) = 10.12$, $p < .01$, $\eta_p^2 = .325$, and this congruency effect was modulated by the congruency of the previous trial, $F(1, 21) = 7.99$, $p < .01$, $\eta_p^2 = .276$. No further effect passed the statistical threshold (Table 1).

Discussion

Experiment 1 aimed to replicate the findings of previous studies (Böckler et al., 2011; Fischer, Plessow, & Kiesel 2010) using an experimental design in which accessory stimuli were presented blockwise to keep their impact on performance constant within a block. Although significant post-conflict adjustments occurred, they were not affected by the presentation of accessory stimuli. Accordingly, accessory stimuli did not affect conflict-triggered control processes in the Simon task, reinforcing the conclusions from previous studies (Böckler et al., 2011; Fischer, Plessow, Kunde, & Kiesel, 2010).

Additionally, we found that the Simon effect was increased in AS compared to no-AS blocks. Such increases were also reported in previous studies (Böckler et al., 2011; Fischer, Plessow, & Kiesel, 2010, 2012) and explained by assuming that accessory stimuli speed up processing via the direct route. On congruent trials, the location-primed response matches the task-relevant response, so that RT performance benefits from accessory stimulus-induced enhancement of direct-route processing. By contrast, RTs on incongruent trials do not benefit from speeded direct-route processing, since the location-primed response deviates from that required by the task-relevant stimulus attribute, resulting in an increased Simon effect following accessory stimuli. Moreover, we found that RTs were generally speeded on (both congruent and incongruent) AS trials. We explain this effect by assuming that accessory stimuli enhance task-relevant stimulus processing, expediting the identification of task-relevant stimulus attributes (Böckler et al., 2011; Fischer, Plessow, Kunde, et al., 2010).

Experiment 2

There are several studies suggesting that conflict resolution processes may differ between the Stroop and the Simon task (Egner, 2008; Egner et al., 2007). Experiment 2 examined whether the finding that accessory stimuli do not affect post-conflict adjustments in the Simon task (Experiment 1) extends to the Stroop task. There are two main possibilities how accessory stimuli may interact with post-conflict adjustments in the Stroop task. One possibility is that accessory stimuli do *not* interact with post-conflict adjustments in the Stroop task, as is the case with the Simon task. However, it is also possible that accessory stimuli may lead to reduced post-conflict adjustments in the Stroop task, for two alternative reasons: First, since both accessory stimuli and conflict-triggered control processes in the Stroop task are assumed to have a facilitatory effect on the processing of task-relevant information (Böckler et al., 2011; Egner & Hirsch, 2005; Egner et al., 2007; Matthias et al., 2010), accessory stimuli may reduce post-conflict adjustments by speeding up perceptual processes of target identification to a (near-optimal) level at which there is little room for cognitive control to additionally improve conflict resolution (*sensory optimization account*). Alternatively, accessory stimuli may exert a distractive influence on cognitive control, as a result of which any post-conflict adjustments would be reduced (*distraction account*).

Whichever of the two alternatives is true, the finding that the presentation of accessory stimuli leads to reduced conflict adjustments in the Stroop task would support the idea that accessory stimuli have dissociable, conflict-specific effects on cognitive control between the Stroop and the Simon task. We tested these alternatives in an experimental paradigm in which participants performed the Stroop task in both an AS and a no-AS condition.

Methods

Participants

Thirty right-handed volunteers (mean age = 25.87 years, standard deviation = 5.62, 20 female) participated in the experiment and were paid 8€ per hour.

Stimuli and Apparatus

Participants performed a Stroop task in which three different color words were presented in capital letters ("BLAU," "ROT," and "GRÜN"; German for blue, red, and green, respectively) in blue, red, or green ink. In congruent (C) trials, distractor semantics matched the task-relevant color, whereas semantics and color differed in incongruent (I) trials. The task was to respond to the color of the words with the keys V (for blue), B (for red), and N (for green) on a QWERTZ keyboard using the index, middle, and ring finger of the right hand, respectively.

Design and Procedure

As in Experiment 1, accessory stimuli were presented blockwise. Each block included 53 cC, 12 iC, 12 cI, and

12 iI trials. The trial procedure was adopted from Experiment 1, with the only difference that stimuli for the Stroop task were presented instead of for the Simon task. Every participant performed four blocks of the AS and the no-AS condition in alternating order, the starting block type was balanced across participants.

Statistical Analysis

We removed all trials in which the target or distractor feature was repeated as target or distractor, respectively, to control for effects of such stimulus repetitions on post-conflict adjustments (Hommel, Procter, & Vu, 2004; Mayr, Awh, & Laurey, 2003). For the RT analysis, we additionally excluded error and post-error trials.

Results

Reaction Times

A 2 × 2 × 2 repeated-measures ANOVA with the factors Accessory Stimulus, Previous trial congruency, and Current trial congruency revealed overall faster RTs in AS (643 ms) than in no-AS blocks (718 ms), $F(1, 29) = 88.57, p < .001$, $\eta_p^2 = .753$. The main effect of current trial congruency indicated that participants responded faster in congruent (627 ms) than in incongruent (836 ms) trials, $F(1, 29) = 111.36$, $p < .001$, $\eta_p^2 = .793$, yielding a Stroop effect of 209 ms. The significant Current Trial Congruency × Previous Trial Congruency interaction indicated the occurrence of post-conflict adjustments, $F(1, 29) = 21.40$, $p < .001$, $\eta_p^2 = .425$. Importantly, the Accessory Stimulus × Current Trial Congruency × Previous Trial Congruency interaction was also significant, $F(1, 29) = 8.82$, $p < .01$, $\eta_p^2 = .233$, suggesting that post-conflict adjustments were modulated by the accessory stimuli. We found significant post-conflict adjustments only in no-AS blocks (cI – cC) – (iI – iC) = 80 ms, $t(29) = 4.70$, $p < .001$, but not in AS blocks (cI – cC) – (iI – iC) = 15 ms, $t(29) = 1.16$, $p > .25$.

The Accessory Stimulus × Current Trial Congruency interaction was close to the statistical threshold, $F(1, 29) = 4.04$, $p < .06$, $\eta_p^2 = .122$, suggesting a tendency toward a larger Stroop effect in the AS (216 ms) relative to the no-AS condition (202 ms). However, this effect may result from the reduced post-conflict adjustments in the AS, compared to the no-AS, condition. To examine whether accessory stimuli affected the Stroop effect independently of the reduction of post-conflict adjustments, we compared the Stroop effects between AS and no AS-blocks for trials that directly followed a congruent trial; this comparison failed to reveal a significant difference, $t(29) < 1$, $p > .44$ (Figure 2).

Error Rates

A repeated-measures ANOVA including the same factors as the RT analysis revealed only a significant main effect of current trial congruency, $F(1, 29) = 22.90$, $p < .001$, $\eta_p^2 = .441$: participants committed more errors in incongruent (6.3%) than in congruent trials (2.9%) (Table 2).

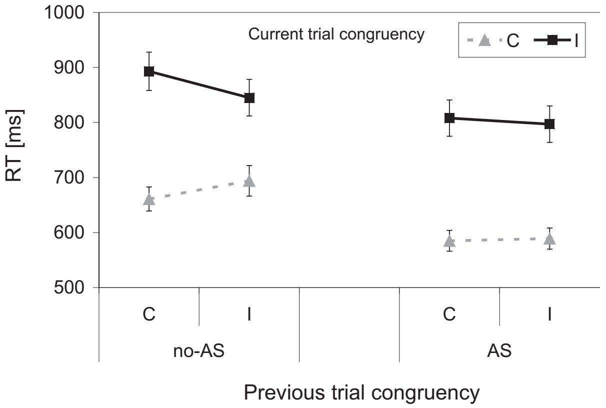

Figure 2. Mean reaction times (RTs) for the Stroop task conditions in Experiment 2. Error bars indicate the standard error of mean. *Notes*. C/c = congruent; I/i = incongruent; AS = accessory stimulus.

Between-Experiment Analysis

To test whether accessory stimuli have differential effects on post-conflict adjustments between the Stroop and the Simon task, we combined the data of Experiments 1 and 2 and calculated a 2 × 2 × 2 × 2 mixed-measures ANOVA including the within-subject factors Accessory stimulus, Previous trial congruency, and Current trial congruency, and the between-subject factor experiment (Experiment 1 vs. Experiment 2). To avoid redundancies with previous analyses, we report only significant effects involving the factor experiment. The main effect of experiment, $F(1, 50) = 70.97$, $p < .001$, $\eta_p^2 = .587$, indicated that mean RTs were overall faster in the Simon task than in the Stroop task. Moreover, the magnitude of the congruency effect differed between the two experiments, $F(1, 50) = 51.84$, $p < .001$, $\eta_p^2 = .509$: the Simon effect was smaller than the Stroop effect. Most importantly, the four-way interaction Experiment × Accessory Stimulus × Previous Trial Congruency × Current Trial Congruency was significant, $F(1, 50) = 6.60$, $p < .05$, $\eta_p^2 = .117$, power = 71%, indicating that the effects of the accessory stimuli on post-conflict adjustments differed

Table 2. Error rates for the Stroop task of Experiment 2. In parentheses are the standard errors of mean

Previous trial congruency	c		i	
Current trial congruency	C	I	C	I
no-AS	2.8 (.4)	7.1 (1.3)	2.5 (.7)	7.3 (1.3)
AS	3.3 (.6)	6.7 (1.3)	2.2 (.9)	4.0 (.8)

Notes. C/c = congruent; I/I = incongruent; AS = accessory stimulus.

between Experiments 1 and 2. This result supports our previous analyses which showed that accessory stimuli lead to decreased post-conflict adjustments only in the Stroop task but not in the Simon task.

Discussion

Experiment 2 examined the effects of accessory stimuli on cognitive control in the Stroop task. We found significant post-conflict adjustments only in the no-AS, but not in the AS, condition. This is in contrast to the Simon task in which accessory stimuli did not interact with post-conflict adjustments. Thus, accessory stimuli appear to have dissociable impacts on cognitive control in the Stroop and the Simon paradigms.

There are two potential explanations for the reduced post-conflict adjustments in the Stroop task. First, it is possible that conflict-triggered control was suppressed in AS relative to no-AS blocks (distraction account). Previous research has already shown that post-conflict adjustments are inhibited by the attentional demands of a task (Fischer, Dreisbach, & Goschke, 2008; Fischer, Plessow, Kunde, et al., 2010) or by working memory demands (Soutschek, Strobach, & Schubert, in press). Analogously, accessory stimuli too may exert a "distraction" effect on cognitive control in the Stroop task, for example by capturing attentional resources, preventing the recruitment of enhanced cognitive control following conflicts.

An alternative explanation for the reduced post-conflict adjustments in the Stroop task is that accessory stimuli may reduce the impact of such adjustments by improving the extraction of task-relevant stimulus attributes up to a level at which no additional improvement of conflict processing is possible (optimization account). In more detail, it has been shown that accessory stimuli improve the efficiency of task-relevant perceptual processing (Böckler et al., 2011; Matthias et al., 2010). Since post-conflict adjustments, too, are thought to enhance the processing of task-relevant stimulus attributes (Egner & Hirsch, 2005; Egner et al., 2007), post-conflict adjustments and accessory stimuli may have similar, or at least overlapping, effects on task performance. Hence, it is possible that, when perceptual processing of task-relevant stimulus attributes has already been enhanced to near-optimum level by accessory stimuli, the scope for post-conflict adjustments to improve conflict resolution even further is severely limited. In contrast to the distraction account, the optimization account assumes that the net impact of (exerted) control is reduced in the AS compared to the no-AS condition, rather than the recruitment of control per se.

The data of Experiment 2 do not permit a conclusive decision to be made between the distraction and optimization accounts. However, the distraction account would appear less plausible from a theoretical point of view: given that alertness (induced by accessory stimuli) and executive functions are mediated by independent subsystems of an encompassing attention network (Fan, McCandliss, Sommer, Raz, & Posner, 2002; Posner & Petersen, 1990), it would be unlikely that accessory stimuli directly suppress the operation of cognitive control. In contrast, there is strong evidence that alertness and conflict-triggered control in the Stroop task (despite belonging to different networks) have a similar, facilitatory effect on perceptual processing (Böckler et al., 2011; Egner & Hirsch, 2005; Egner et al., 2007; Matthias et al., 2010). Taken together, existing views of the relationship between accessory stimuli and cognitive control support the assumption that accessory stimuli would impair the impact of (exerted) cognitive control, rather than directly suppressing control.

The sensory optimization account also receives support from the finding that the presentation of accessory stimuli yielded faster RTs in all trial sequences of Experiment 2 (*p*s < .001), indicating that accessory stimuli improve the processing of task-relevant information. Thus, given the existing evidence for effects of accessory stimuli on task-relevant information processing, the optimization account presents the more parsimonious explanation as, in contrast to the distraction account, it does not need to postulate an additional suppressive effect of accessory stimuli on cognitive control.

General Discussion

The present study was designed to examine the effects of accessory stimuli on conflict processing in the Stroop and the Simon tasks. The results revealed that accessory stimuli affected post-conflict adjustments only in the Stroop task, but not in the Simon task. Such a dissociation was expected based on the assumption of conflict-specific control mechanisms operating in the two types of tasks. In the Simon task, enhanced cognitive control following conflicts is thought to be mediated by inhibition of direct-route processing (Egner et al., 2007; Stürmer et al., 2002). The present Experiment 1 shows that this control mechanism does not interact with the level of alertness. By contrast, post-conflict adjustments in the Stroop task were significantly reduced in blocks with, as compared to blocks without, accessory stimuli. Although the aim of the current study was not to decide between the distraction and the optimization account but to test for conflict-specific effects of accessory stimuli on control, theoretical considerations would favor the optimization account, according to which accessory stimuli impair the efficiency of post-conflict adjustments in the Stroop task. By implication, our findings also support the proposal of Egner et al. (2007) that post-conflict adjustments in the Stroop task are based on a stimulus-biasing, rather than a response-biasing, strategy: While accessory stimuli did not affect control-triggered direct-route suppression in the Simon task (Experiment 1), they did interfere with the conflict-triggered focusing on task-relevant stimulus attributes in the Stroop task (Experiment 2), probably because accessory stimuli improve perceptual processing of task-relevant stimulus attributes to optimum level. Thus, taken together, the present results provide further support for the hypothesis of conflict-specific control processes in the Stroop and the Simon tasks, by showing that these control processes can be dissociated also on a functional level.

Note that accessory stimuli can improve task performance in two conceivable ways: by inducing arousal and/or by reducing temporal uncertainty. Although our data do not permit these alternatives to be disentangled, the relatively low intensity (~ 50 dB) and the long tone-stimulus interval suggest that accessory stimuli might rather have led to increased predictability than to increased arousal (Stahl & Rammsayer, 2005). For our conclusions, though, it is only important that accessory stimuli have dissociable effects in the Stroop and the Simon tasks, whether these are attributable to increased arousal or improved temporal predictability. Note, however, that our findings cannot be explained in terms of a stimulus-priming account of post-conflict adjustments (Hommel et al., 2004; Mayr et al., 2003), as we excluded repetition trials. Besides, a stimulus-priming account would have difficulty explaining the observed dissociation between the Stroop and the Simon task.

Challenging our interpretation of the data, one might surmise alternatively that acoustic accessory stimuli suppress conflict control in the Stroop task because the tones transiently strengthen the phonological processing pathway (on which distractor processing in the Stroop task may depend), increasing the impact of the conflicting word semantics on task performance. At variance with this alternative, however, Salamè and Baddeley (1987) found that task-irrelevant acoustic noise has no effect on processing in the phonological loop. In addition, this account would also predict the Stroop effect to be larger in blocks with, compared to blocks without, accessory stimuli after both previously congruent and previously incongruent trials – but, in fact, there was no difference between the Stroop effect in AS and no-AS blocks after congruent trials.

Another alternative account might surmise that the processing demands are higher in the Stroop compared to the Simon task, so that accessory stimuli (assuming that they draw on limited mental resources) are more likely to interfere with performance in the Stroop task. However, this explanation can be considered as a variant of the distraction account – which we cannot definitely rule out, but which (for reasons outlined above) appears less plausible than the optimization account.

The present study emphasizes the importance of differentiating between distinct kinds of conflict engaging specific control mechanisms. Although previous studies have suggested that distinct control processes are involved in different conflict paradigms, the present study is, to our knowledge, the first one to show that these control processes interact with a further cognitive process in a conflict-specific way. Moreover, our results have implications for currently still prevalent notions of a domain-general architecture of cognitive control (Botvinick et al., 2001), which do not take into account the conflict specificity of control mechanisms – for instance, that Stroop-type conflicts are resolved by stimulus biasing, in contrast to Simon-type conflicts which are resolved using response biasing. On this background, the present findings underscore the need for elaborating conflict-specific models that incorporate such conflict-specific control mechanisms.

In sum, the present study provided further insights into the determinants of conflict processing and cognitive control. We established that accessory stimuli have dissociable effects on post-conflict adjustments in the Stroop and the Simon tasks, and explained this dissociation in terms of the notion that differential conflict resolution mechanisms are involved in these tasks. Consequently, the present study emphasizes the necessity of differentiating between different kinds of conflicts and their conflict-specific resolution strategies.

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Behavioral/Cognitive

Dissociable Networks Control Conflict during Perception and Response Selection: A Transcranial Magnetic Stimulation Study

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Current models of conflict processing propose that cognitive control resolves conflict in the flanker task by enhancing task-relevant stimulus processing at a perceptual level. However, because conflicts occur at both a perceptual and a response selection level in that task, we tested the hypothesis of conflict-specific control networks for perceptual and response selection conflicts using transcranial magnetic stimulation (TMS). TMS of the presupplementary motor area selectively disrupted the processing of response selection conflict, whereas TMS of the posterior intraparietal sulcus/inferior parietal lobule interfered with perceptual conflict processing. In more detail, the presupplementary motor area seems to resolve response selection conflict mainly when no conflicts have occurred in the previous trial. In contrast, the posterior intraparietal sulcus/inferior parietal lobule may resolve perceptual conflicts selectively when a conflict has occurred in the previous trial. The current data show the need for revising models of cognitive control by providing evidence for the existence of conflict-specific control networks resolving conflict at different processing levels.

Introduction

Cognitive control enables successful goal-directed behavior by adjusting information processing in response to changing task demands. Research on cognitive control has often focused on control adjustments in interference paradigms in which conflicts between task-relevant and distracting information occur. A parsimonious and elegant model of the role of cognitive control in conflict resolution is the conflict-monitoring account (Botvinick et al., 2001). However, whereas this model assumes that conflicts in interference paradigms occur at the response selection stage, empirical studies using the Stroop or flanker paradigm found that conflicts occur at both a perceptual and a response selection level (De Houwer, 2003; van Veen and Carter, 2005). Findings from neuroimaging studies suggest that perceptual conflict is correlated with superior/middle frontal and posterior parietal cortex (PPC) activity, whereas response selection conflict is associated with medial and inferior frontal activity (van Veen and Carter, 2005; Liston et al., 2006; Nigbur et al., 2012). However, because the results of neuroimaging studies are correlative in nature, it remains unclear whether these regions are *causally* involved in the active resolution (instead of passive processing) of conflict. Using transcranial magnetic stimulation (TMS), the present study tested the hypothesis of conflict-specific control networks for perceptual and response selection conflict. Because the existence of conflict-specific control networks is still a matter of controversy (Egner, 2008), the potential finding that the resolution of perceptual and response selection conflict can be impaired selectively by TMS of dissociable brain regions would not only clarify the roles of these regions in conflict processing, but would also provide evidence for the existence of distinct control networks for the resolution of perceptual and response selection conflict.

Resolution of response selection conflict may be related to the presupplementary motor area (pre-SMA). A combined TMS-EEG study by Taylor et al. (2007) showed that pre-SMA TMS modulates the lateralized readiness potential in incongruent trials of a flanker task, suggesting that the pre-SMA exerts top-down control over the motor cortex to resolve response selection conflict. Consistent with this interpretation, other studies reported a causal role of the pre-SMA in action reprogramming and response inhibition (Mars et al., 2009; Neubert et al., 2010). Based on these findings, we hypothesized that pre-SMA TMS interferes selectively with the processing of response selection conflict.

In contrast, resolution of perceptual conflict may be linked to the PPC. Although previous studies suggesting PPC involvement in conflict control did not distinguish between different conflict-processing levels (Egner et al., 2007; Luks et al., 2007; Wang et al., 2010), subregions of the PPC close to the intraparietal suclus (IPS) and the inferior parietal lobule (IPL) have been related to top-down regulation of attention (Rushworth and Taylor, 2006; Green and McDonald, 2008) and may thus contribute selectively to resolving perceptual conflict.

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We tested the hypothesized roles of pre-SMA and IPS/IPL in resolving perceptual and response selection conflict in two separate experiment using a flanker task that permits these different types of conflicts to be dissociated.

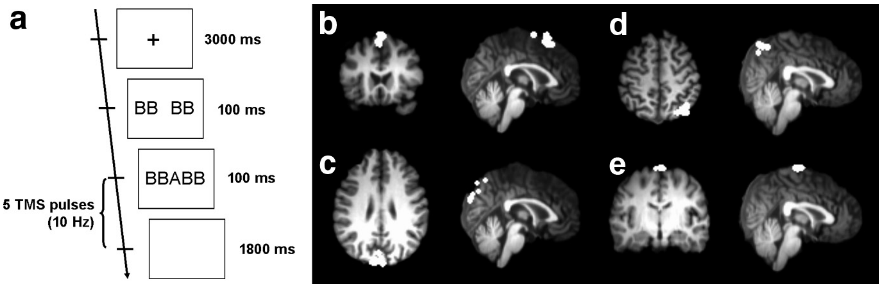

Figure 1. ***a***, Schematic illustration of a flanker task trial in which participants had to respond to the central target letter of an array of five letters. On TMS trials, five TMS pulses were applied with a frequency of 10 Hz starting with target onset. Stimulation sites in the pre-SMA (***b***) and the control (***c***) condition of Experiment 1 and in the IPS/IPL (***d***) and control (***e***) condition of Experiment 2. Each white circle represents the stimulated site in one participant.

Materials and Methods

Experiment 1: pre-SMA TMS

Participants. Thirty-one right-handed volunteers (mean age, 24.03 years; range, 20–29; 22 female) who were recruited at the Ludwig-Maximilians-Universität participated in Experiment 1. All volunteers had normal or corrected-to-normal vision, gave informed consent before participating in the study, and were paid 10 Euros per hour for their participation.

Task design. Participants performed a letter variant of the Eriksen flanker paradigm that allowed dissociating conflicts at the perceptual and at the response selection stage. Participants had to decide whether a centrally presented target letter surrounded by four distractor letters was either a vowel (“A” or “E”) or a consonant (“B” or “K”). We instructed them to respond to the target letter by pressing the left control key on a keyboard for vowels and the right control key for consonants, using the left and right index finger, respectively. The targets and distractors were either congruent (C), stimulus-incongruent (SI), or response-incongruent (RI). In C trials, target and distractor letters were identical (e.g., “AAAAA”). In SI trials, target and distractor letters were different but linked to the same response alternative (e.g., “EEAEE”), resulting in conflict at the perceptual processing level. In RI trials, target and distractors were additionally associated with different response alternatives (e.g., “BBABB”). Therefore, conflicts occurred both at the perceptual and the response selection stage in RI trials because targets and distractors were represented by different stimuli (perceptual conflict) and were also associated with different response alternatives (response selection conflict). Using subtraction logic, we defined perceptual conflict as the difference between SI and C trials and response selection conflict as the difference between RI and SI trials (van Veen and Carter, 2005). Hereafter, the terms “perceptual conflict” and “response selection conflict” will refer to the SI-C and RI-SI contrasts, respectively.

Every block contained 60 trials that were divided into equal numbers of C, SI, and RI trials. In every block, TMS was applied in half of the trials of each condition. Trial order was randomized, with the only constraint that we never applied more than three consecutive TMS trials.

Procedure. On each trial, first a white fixation cross was presented for 3000 ms on a black background, followed by a stimulus array comprising only the four distractors for the flanker task (Fig. 1*a*). After 100 ms, the target stimulus was also presented in addition to the distractors and the whole stimulus array disappeared after 100 ms. Participants had to respond within an interval of 1800 ms after stimulus presentation.

TMS. We applied TMS in half of the trials of a block, starting with target onset and ending 300 ms after target offset (five pulses at 10 Hz and 110% resting motor threshold) using a figure-eight coil with an internal diameter of 7 cm (MagPro R30 machine with MC-B70 Butterfly Coil; Medtronic). On TMS trials, TMS was applied blockwise either to the pre-SMA or to a control site to test our hypothesis that the pre-SMA plays a causal role in resolving response selection conflict. The pre-SMA TMS site was 4 cm anterior to the vertex, whereas the control TMS site was at electrode position Pz according to the 10–20 international system (Taylor et al., 2007). Previous studies have shown that this procedure provides reliable stimulation of the pre-SMA (Rushworth et al., 2002; Taylor et al., 2007; Mars et al., 2009). After the recording session, coil positioning was confirmed for six subjects by using optical tracking via the Brainsight frameless stereotaxy system (Rogue Research) to determine Montreal Neurological Institute (MNI) coordinates of the stimulation sites based on their structural magnetic resonance images. Mean MNI coordinates for the pre-SMA TMS ($x = 0$, $y = 21$, $z = 62$) and the control TMS ($x = 1$, $y = -79$, $z = 40$) condition suggested that the coil was placed over the pre-SMA and over the parietooccipital cortex, respectively, for active and control sites (Fig. 1*b*,*c*).

Analysis. We analyzed reaction times (RTs) and error rates. For the RT analysis, we excluded error and posterror trials from the dataset. Note that cognitive control may resolve conflicts both on a within-trial and a trial-by-trial level (Boy et al., 2010). Because TMS may affect within-trial and/or trial-by-trial control processes, we conducted separate within-trial and trial-by-trial analyses (for details, see below). For tests of significance, we calculated ANOVAs and paired-samples t tests with a significance threshold of 5%. The p values of the ANOVAs were adjusted using Huynh-Feldt corrections (Huynh and Feldt, 1976).

Experiment 2: IPS/IPL TMS

Participants. Twenty-seven right-handed volunteers (mean age, 24.85 years; range, 19–29 years; 22 female), who were recruited at the Ludwig-Maximilians-Universität and had normal or corrected-to-normal vision, participated in Experiment 2 after having given informed consent. Eight of these volunteers had also participated in Experiment 1.

TMS. We applied TMS blockwise either to the IPS/IPL or to a control site. Our hypothesis was that IPS/IPL TMS should interfere selectively with the resolution of perceptual conflict. The IPS/IPL TMS site was at electrode position P4 to target the posterior IPS/IPL region previously found to affect tasks requiring attentional reupdating (Rushworth and Taylor, 2006). Following previous studies that had stimulated the IPS/IPL region, we used electrode position Cz as the control TMS site (Muggleton et al., 2008; Silvanto et al., 2009). After the recording session, coil positioning was confirmed for six subjects using frameless (optical-tracking) stereotactic registration of individuals’ structural MRIs into standard space (Brainsight; Rogue Research). Mean MNI coordinates for the IPS/IPL TMS ($x = 39$, $y = -67$, $z = 54$) and the control TMS ($x = 1$, $y = -16$, $z = 76$) condition suggested that the coil was placed over the posterior IPS/IPL in the vicinity of the right angular gyrus in the IPS/IPL condition (Fig. 1*d*,*e*).

Task design and analysis. We used the same task design and statistical analyses as in Experiment 1.

Results

Experiment 1: pre-SMA TMS

Within-trial effects

First, we tested the effects of pre-SMA TMS on perceptual and response selection conflict processing in the present trial. If our hypothesis is correct and the pre-SMA is causally involved in the resolution of response selection, pre-SMA TMS should increase the magnitude of response selection conflict selectively (i.e., the RT difference between RI and SI trials). We analyzed congruency effects in RTs with a 3 × 3 repeated-measures ANOVA including the factors TMS (no TMS, pre-SMA TMS, control TMS) and congruency (C, SI, RI). The significant main effect of TMS ($F_{(2,60)} = 18.01$, $p < 0.001$, $\eta_p^2 = 0.375$) indicated that RTs were speeded in the pre-SMA TMS (429 ms) and control TMS (433 ms) condition

Table 1. Mean RTs and error rates in Experiment 1

	No TMS	Pre-SMA TMS	Control TMS
RT (ms)			
C	416 (11)	393 (12)	396 (12)
SI	444 (12)	421 (12)	433 (12)
RI	488 (11)	472 (12)	471 (12)
Error rate (%)			
C	1.5 (0.4)	2.5 (0.8)	3.0 (0.6)
SI	3.1 (0.5)	4.7 (0.8)	3.8 (0.7)
RI	9.7 (1.2)	18.8 (2.4)	15.9 (1.9)

Numbers in parentheses indicate SEM.

relative to the no TMS (449 ms) condition (both $p < 0.001$; Table 1). In addition, we found a significant congruency effect ($F_{(2,60)} = 235.64$, $p < 0.001$, $\eta_p^2 = 0.887$), indicating that RTs differed between the congruency conditions (i.e., C, SI, and RI trials): RTs were slowest in RI trials (477 ms), followed by SI trials (433 ms) and, finally, C trials (402 ms; all $p < 0.001$). Therefore, both perceptual (SI-C: 31 ms; $p < 0.001$) and response selection conflict (RI-SI: 45 ms; $p < 0.001$) occurred. The congruency effect was modulated by the factor TMS ($F_{(4,120)} = 2.46, p < 0.05, \eta_p^2 = 0.076$), suggesting that the TMS conditions had dissociable effects on perceptual versus response selection conflict. To examine the effects of TMS on perceptual and response selection conflict in more detail, we computed two separate ANOVAs with the factor TMS (no TMS, pre-SMA TMS, control TMS), one on perceptual conflict and the other on response selection conflict. The ANOVA on perceptual conflict did not yield a significant main effect of TMS ($F_{(2,60)} = 1.81$, $p > 0.17$, $\eta_p^2 = 0.057$), indicating that perceptual conflict did not differ among the pre-SMA TMS (28 ms), no TMS (28 ms), and control TMS trials (37 ms) (all $p > 0.1$). In contrast, the ANOVA on response selection conflict revealed the main effect of TMS to be significant ($F_{(2,60)} = 5.42, p < 0.01$, $\eta_p^2 = 0.153$). Consistent with our hypothesis, response selection conflict was increased significantly in the pre-SMA TMS condition (51 ms) compared with the no TMS (44 ms; $t_{(30)} = 2.18$, $p < 0.05$) and the control TMS condition (39 ms; $t_{(30)} = 3.25$, $p < 0.01$), whereas no significant difference was found between the control TMS and the no TMS condition ($t_{(30)} = 1.35$, $p > 0.18$; Fig. 2).

The ANOVA on the error rates revealed a significant main effect of congruency ($F_{(2,60)} = 56.79$, $p < 0.001$, $\eta_p^2 = 0.654$), with the highest error rate in RI trials (14.8%), followed by SI (3.9%) and C (2.3%) trials (all $p < 0.01$). The main effect of TMS was also significant ($F_{(2,60)} = 19.03$, $p < 0.001$, $\eta_p^2 = 0.388$): participants committed more errors in pre-SMA TMS (8.7%) and control TMS (7.6%) compared with no TMS (4.8%) trials ($p < 0.001$). The significant TMS × C interaction ($F_{(4,120)} = 8.16$, $p < 0.001$, $\eta_p^2 = 0.214$) suggested that, similar to the RT analysis, the size of perceptual and/or response selection conflict was modulated by TMS. An additional ANOVA on perceptual conflict with the factor TMS yielded no significant result ($F_{(2,60)} = 1.08$, $p > 0.34$, $\eta_p^2 = 0.035$), indicating that the magnitude of perceptual conflict did not differ among the pre-SMA TMS (2.1%), no TMS (0.8%), and control TMS trials (1.3%) trials (all $p > 0.17$). In contrast, the ANOVA on response selection conflict proved the main effect of TMS to be significant ($F_{(2,60)} = 8.96$, $p < 0.001$, $\eta_p^2 = 0.230$). Planned comparisons revealed a larger response selection conflict in the pre-SMA (14.1%) and the control TMS condition (12.0%) compared with the no TMS condition (6.6%; both $p < 0.01$), whereas the difference between the pre-SMA and the control TMS condition was not significant ($p > 0.16$).

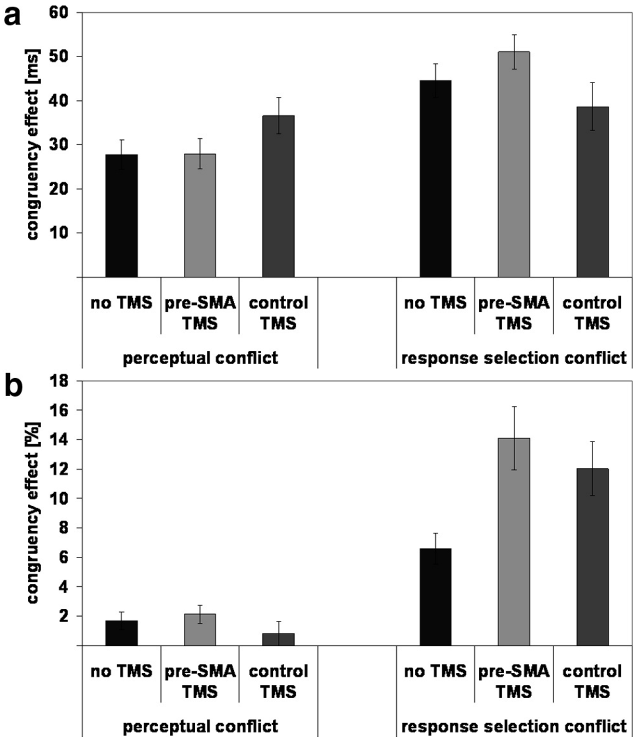

Figure 2. pre-SMA TMS effects on perceptual and response selection conflict in RTs (in ms; ***a***) and error rates (in %; ***b***). Error bars indicate SEM.

Trial-by-trial effects

In addition to the previous analyses, we also tested for potential effects of pre-SMA TMS on trial-by-trial modulations of the congruency effects. Several previous studies had found that congruency effects in the current trial are reduced after the occurrence of a conflict in the previous trial (Kerns et al., 2004; Ullsperger et al., 2005; Verbruggen et al., 2006; Egner, 2007). Because this sequential modulation of congruency effects is thought to reflect the activation of enhanced cognitive control processes, we investigated whether the observed effects of pre-SMA TMS on response selection conflict would relate to this mechanism. There is evidence that conflict adaptation improves conflict processing at the perceptual, rather than the response selection, level (Verbruggen et al., 2006). Therefore, we expected the effects of pre-SMA TMS on response selection conflict not to be related to the reduction of conflict after previously incongruent trials (which should affect conflict at the perceptual processing level). For the analysis of sequential modulations, we removed all repetition trials from the dataset to control for priming effects on conflict adaptation (Mayr et al., 2003; Hommel et al., 2004), leaving a mean total trial number of 487 per subject. We computed two separate ANOVAS involving the factors TMS (no TMS, pre-SMA TMS, control TMS) and previous trial congruency (C, SI, RI) on perceptual and response selection conflict (Fig. 3). The analysis of perceptual conflict revealed only a significant main effect of previous trial congruency ($F_{(2,60)} = 3.74, p < 0.05, \eta_p^2 = 0.112$), suggesting the occurrence of conflict adaptation. Perceptual conflict was significantly reduced after previous encounters of SI (19 ms) compared with C (33 ms) trials ($t_{(30)} = 3.17, p < 0.01$), whereas the reduction of perceptual conflict after RI (27 ms) compared with C trials failed to reach statistical significance ($t_{(30)} < 1$). Similarly to the results of the within-trial analysis, we found no effect of pre-SMA TMS on the sequential modulation of perceptual conflict: the TMS × previous trial congruency interaction ($F_{(4,120)} = 2.07, p >$

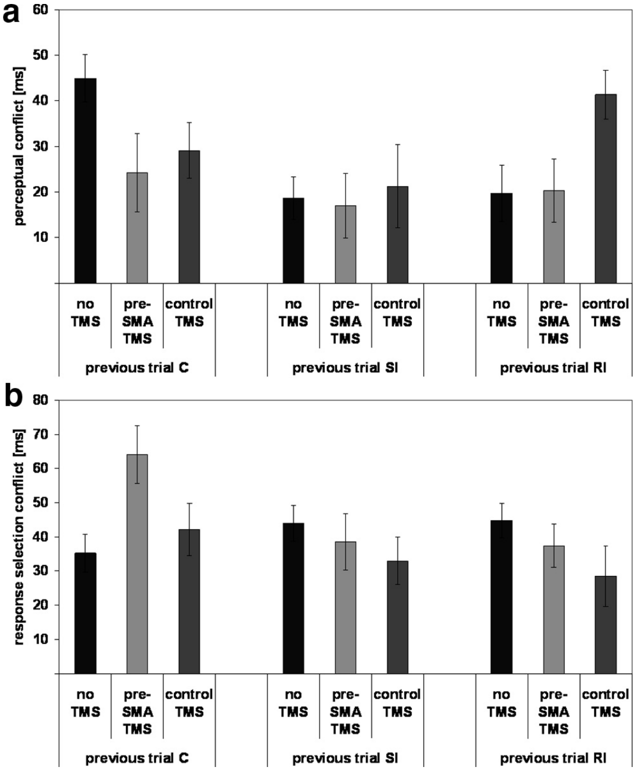

Figure 3. pre-SMA TMS effects on perceptual (***a***) and response selection conflict (***b***) separately for after previously congruent (C), stimulus-incongruent (SI), and response-incongruent trials (RI). Error bars indicate SEM.

Table 2. Mean RTs and error rates in Experiment 2

	No TMS	IPS/IPL TMS	Control TMS
RT (ms)			
C	430 (12)	403 (12)	409 (13)
SI	450 (11)	444 (16)	436 (13)
RI	497 (10)	475 (13)	480 (13)
Error rate (%)			
C	1.9 (0.6)	2.6 (0.8)	2.7 (0.8)
SI	3.2 (0.7)	4.0 (0.9)	4.1 (0.6)
RI	10.4 (1.9)	16.7 (2.7)	18.2 (2.7)

Numbers in parentheses indicate SEM.

0.09, $\eta_p^2 = 0.064$) and the main effect of TMS ($F_{(2,60)} = 1.54, p > 0.22, \eta_p^2 = 0.049$) were not significant.

In contrast, the ANOVA on response selection conflict revealed a significant effect of TMS ($F_{(2,60)} = 3.92, p < 0.05, \eta_p^2 = 0.115$). Because the main effect of previous trial congruency was not significant ($F_{(2,60)} = 1.92, p > 0.15, \eta_p^2 = 0.060$), no conflict adaptation effect occurred at the response selection level. However, the significant TMS × previous trial congruency interaction ($F_{(4,120)} = 2.74, p < 0.05, \eta_p^2 = 0.084$) indicated that the effects of pre-SMA TMS on response selection conflict depended on the congruency of the previous trial. Planned comparisons revealed that response selection conflict was significantly increased in the pre-SMA TMS compared with both the no TMS and the control TMS condition only after previous C trials (both $t_{(30)} > 3.31, p < 0.01$), whereas no significant differences manifested after SI and RI trials (all $p > 0.11$). Therefore, the effects of pre-SMA TMS on response selection conflict were most pronounced when no conflict had occurred in the preceding trial.

Conflict monitoring

Whereas the previous analyses suggest that the pre-SMA is engaged in resolving response selection conflict, an alternative account of pre-SMA functioning claims an involvement of pre-SMA in conflict-monitoring processes. According to this account, pre-SMA activity may be related to the detection of response selection conflicts in the stream of information processing, which results in adjustments of cognitive control and improved conflict resolution in subsequent trials (Ullsperger and von Cramon, 2001; Garavan et al., 2003). If this assumption is correct, then pre-SMA TMS in incongruent trials should interfere with conflict-monitoring processes, and thus with conflict adaptation in subsequent trials. To test this alternative account, we conducted two separate ANOVAs on perceptual and response selection conflict involving the factors previous trial TMS (no TMS, pre-SMA TMS, control TMS) and previous trial congruency (C, SI, RI). We excluded repetition trials and, importantly, because we intended to test the effects of TMS in incongruent previous trials on conflict resolution in current trials, we analyzed only trials in which currently no TMS had been applied. This allowed us to avoid possible interaction effects between the delivery of TMS in the previous and the current trial on the sequential modulation of congruency effects. On average, 244 trials per participant were entered into this analysis. Consistent with the above reported trial-by-trial analysis, the ANOVA on perceptual conflict revealed a main effect of previous trial congruency ($F_{(2,60)} = 4.93, p < 0.01, \eta_p^2 = 0.141$), indicative of the occurrence of conflict adaptation at the perceptual level. Neither the main effect of previous trial TMS nor the previous trial TMS × previous trial congruency interaction was significant (both $F < 1.41$); that is, the conflict adaptation effect was not modulated by the application of TMS in the previous trial. The ANOVA on response selection conflict did not reveal any significant effects (all $F < 1.43$, $p > 0.22$). This pattern does not tally with the conflict-monitoring hypothesis of the pre-SMA, because we failed to find an effect of pre-SMA TMS in the previous trial on the sequential modulation of congruency effects.

Experiment 2: IPS/IPL TMS

Within-trial effects

As for Experiment 1, we first tested for effects of IPS/IPL TMS on perceptual and response selection conflict processing in the current trial. A 3 (TMS) × 3 (C) ANOVA on the RTs revealed a significant main effect of TMS ($F_{(2,52)} = 14.15, p < 0.001, \eta_p^2 = 0.352$): RTs were faster in both IPS/IPL TMS (441 ms) and control TMS (442 ms) relative to no TMS (459 ms) trials ($p < 0.001$; Table 2). The main effect of C ($F_{(2,52)} = 118.38, p < 0.001, \eta_p^2 = 0.820$) showed that RTs were slowest in RI trials (484 ms), followed by SI trials (443 ms) and, finally, C trials (414 ms; all $p < 0.001$). Because congruency effects were modulated by the factor TMS ($F_{(4,104)} = 4.36, p < 0.01, \eta_p^2 = 0.143$), we performed, as in Experiment 1, two separate ANOVAs with the factor TMS on perceptual and, respectively, response selection conflict. The ANOVA on perceptual conflict revealed the main effect of TMS to be significant ($F_{(2,52)} = 8.63, p < 0.001, \eta_p^2 = 0.249$). Consistent with our hypothesis, perceptual conflict was significantly increased in the IPS/IPL TMS condition (40 ms) compared with the no TMS condition (19 ms; $t_{(26)} = 3.78, p < 0.001$) and with the control TMS (27 ms) condition ($t_{(26)} = 2.24, p < 0.05$; Fig. 4). Therefore, IPS/IPL TMS interfered with the resolution of perceptual conflict. In addition, perceptual conflict was larger in control TMS than in no TMS trials ($t_{(26)} = 2.16, p < 0.05$). Likewise, the ANOVA on response selection conflict yielded a significant effect of TMS ($F_{(2,52)} = 4.28, p < 0.05, \eta_p^2 = 0.141$). The response selection conflict

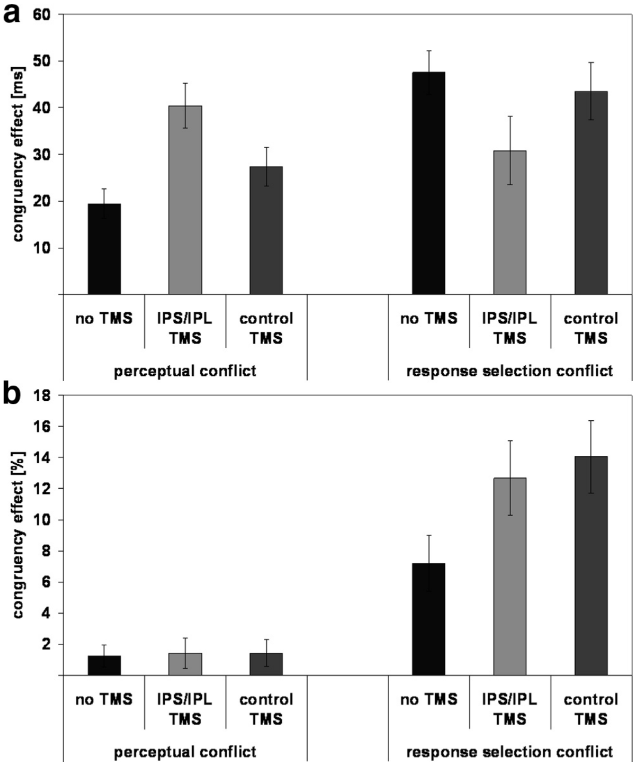

Figure 4. IPS/IPL TMS effects on perceptual and response selection conflict in RTs (in ms; ***a***) and error rates (in %; ***b***). Error bars indicate SEM.

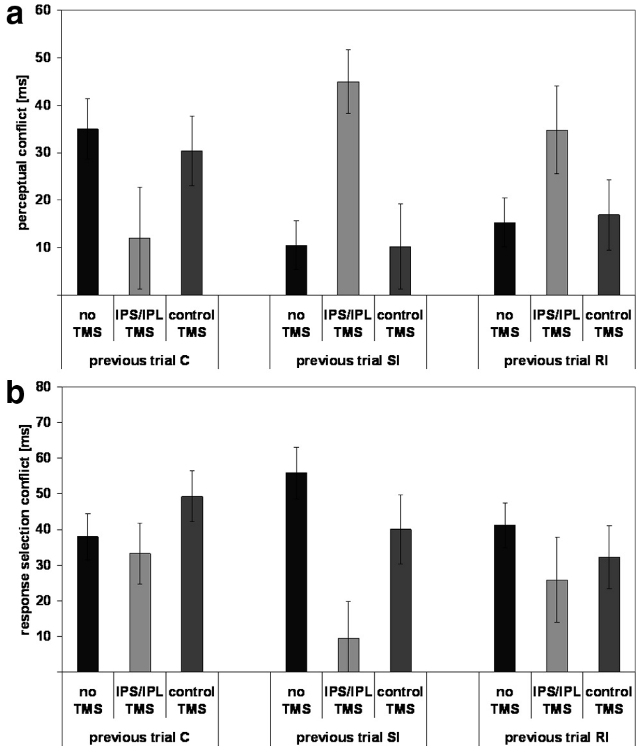

Figure 5. IPS/IPL TMS effects on perceptual (***a***) and response selection conflict (***b***) separately for after previously congruent (C), stimulus-incongruent (SI), and response-incongruent trials (RI). Error bars indicate SEM.

was significantly decreased in the IPS/IPL TMS (31 ms) relative to the no TMS condition (48 ms; $t_{(26)} = 2.69$, $p < 0.05$) and to the control TMS condition (44 ms; $t_{(26)} = 2.17$, $p < 0.05$). No difference was evident between the no TMS and the control TMS condition ($t_{(26)} < 1$).

The ANOVA on the error rates revealed a significant effect of TMS ($F_{(2,52)} = 14.37$, $p < 0.001$, $\eta_p^2 = 0.356$), indicating that more errors were committed in the IPS/IPL TMS (7.8%) and control TMS (8.3%) trials relative to no TMS trials (5.2%; $p < 0.001$). We also found a significant congruency effect ($F_{(2,52)} = 33.71$, $p < 0.001$, $\eta_p^2 = 0.565$). Participants showed the highest error rate in RI trials (15.1%), followed by SI trials (3.8%), and the lowest error rate in C trials (2.4%; all $p < 0.01$). This error congruency effect was modulated by the factor TMS ($F_{(4,104)} = 9.50$, $p < 0.001$, $\eta_p^2 = 0.268$). Although an additional ANOVA on perceptual conflict did not yield a significant result ($F_{(2,52)} < 1$, $p > 0.98$), an ANOVA on response selection conflict revealed the main effect of TMS to be significant ($F_{(2,52)} = 12.43$, $p < 0.001$, $\eta_p^2 = 0.323$): Response selection conflict was significantly larger in both the IPS/IPL TMS (12.7%) and the control TMS (14.0%) relative to the no TMS (7.2%) condition ($p < 0.01$), whereas response selection conflict did not differ between the IPS/IPL TMS and the control TMS condition ($t_{(26)} < 1$). Given that similar effects of TMS on response selection conflict on the error rates had also been observed in Experiment 1, these unspecific TMS effects on response selection conflict may, like the TMS effects on response speed, be attributable to the alerting effects of TMS (Marzi et al., 1998).

Trial-by-trial effects

Next, we tested for potential effects of IPS/IPL TMS on sequential trial-by-trial modulations of the congruency effects. Because conflict adaptation in the flanker paradigm appears to affect mainly the perceptual processing level (see Experiment 1), it is possible that the effects of IPS/IPL TMS on perceptual conflict are related to the modulation of conflict processing after incongruent trials. For that analysis, we again excluded all repetition trials, resulting in a mean trial number of 486 per subject. As for Experiment 1, we analyzed perceptual and response selection conflict in two separate ANOVAs involving the factors TMS and previous trial congruency (Fig. 5). The ANOVA on perceptual conflict revealed only a significant TMS × previous trial congruency interaction ($F_{(4,104)} = 4.26$, $p < 0.01$, $\eta_p^2 = 0.141$), suggesting that the sequential modulation of perceptual conflict (i.e., the conflict adaptation effect) differed between the TMS conditions. To specify this interaction, we calculated the conflict adaptation effect in each TMS condition separately for the reduction of perceptual conflict after previous encounters of SI trials (i.e., perceptual conflict after C trials − perceptual conflict after SI trials) and after RI trials (i.e., perceptual conflict after C trials − perceptual conflict after RI trials). We found that conflict adaptation after SI trials was significantly reduced in the IPS/IPL TMS compared with both the no TMS condition ($t_{(26)} = 4.48$, $p < 0.001$) and the control TMS condition ($t_{(26)} = 3.39$, $p < 0.01$). In addition, conflict adaptation after RI trials was also significantly reduced in the IPS/IPL TMS relative to the no TMS condition ($t_{(26)} = 2.08$, $p < 0.05$), whereas the difference between the IPS/IPL TMS and the control TMS condition was only marginally significant ($t_{(26)} = 1.91$, $p < 0.07$). These findings suggest that IPS/IPL TMS interferes with the sequential modulation of perceptual conflict—that is, with conflict adaptation.

The trial-by-trial analysis of response selection conflict revealed a significant main effect of TMS ($F_{(2,52)} = 6.93$, $p < 0.01$, $\eta_p^2 = 0.210$), reflecting the fact that response selection conflict was decreased in IPS/IPL TMS (23 ms) relative to both no TMS

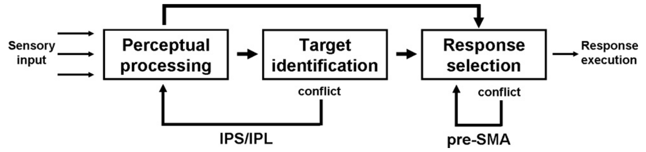

Figure 6. Architecture of control suggested by the current findings. Conflicts at the response selection level are resolved by the pre-SMA. If the cognitive system detects the occurrence of perceptual conflict in the previous trial, the IPS/IPL improves perceptual processing by directing increased attention to task-relevant stimuli.

(45 ms) and control TMS trials (41 ms; both $p < 0.01$). Neither the effect of previous trial congruency ($F_{(2,52)} < 1.05$, $p > 0.35$, $\eta_p^2 = 0.039$) nor the TMS × previous trial congruency interaction was significant ($F_{(4,104)} = 2.13$, $p > 0.08$, $\eta_p^2 = 0.076$). Therefore, our results again provide no evidence of conflict adaptation at the response selection level.

Between-experiment analysis
The results of Experiments 1 and 2 suggested dissociable roles of the pre-SMA and the IPS/IPL in resolving response selection conflict and perceptual conflict, respectively. To provide additional support in favor of this hypothesis, we entered the data of both experiments into a common, mixed-design ANOVA with the magnitude of the congruency effect as the variable and with conflict (perceptual vs response selection), TMS (no TMS, active TMS, control TMS), and experiment (between-subject factor: Experiment 1 vs Experiment 2) as independent variables. The factor level "active TMS" represented a combination of the conditions pre-SMA TMS and IPS/IPL TMS from Experiments 1 and 2, respectively. The only significant effect involving the factor experiment was the experiment × conflict × TMS interaction ($F_{(2,112)} = 8.68$, $p < 0.001$, $\eta_p^2 = 0.134$), indicating that the conflict-specific effects of TMS on perceptual and response selection conflict did differ between Experiment 1 and Experiment 2. In addition, to examine whether the TMS conditions had dissociable effects in the two experiments on perceptual and response selection conflict, we conducted two additional ANOVAs with the factors experiment and TMS, one on perceptual and the other on response selection conflict. Both ANOVAs revealed a significant experiment × TMS interaction (both $F_{(2,112)} = 5.46$, $p < 0.01$). The results of these between-experiment analyses support the findings of the previous single-experiment analyses, suggesting that the effects of TMS on perceptual and response selection conflict differed between Experiment 1 and Experiment 2.

Discussion

The present study provided evidence for the hypothesis of conflict-specific control networks selectively resolving conflicts at the perceptual processing and response selection levels, respectively. Whereas TMS of the pre-SMA interfered selectively with the processing of response selection conflict, IPS/IPL TMS disrupted the processing of perceptual conflict. Therefore, we conclude that the pre-SMA is causally involved in the resolution of conflict at the response selection level, whereas the posterior IPS/IPL is part of a control network adjusting attentional processes to resolve conflicts at a perceptual level. Interestingly, our data also suggest that these networks resolve conflicts at different time scales. Pre-SMA TMS disrupted response selection conflict only after previously congruent trials, that is, when—according to the conflict-monitoring account of Botvinick et al. (2001)—the level of conflict-triggered control could be assumed to be low. In contrast, IPS/IPL TMS disrupted perceptual conflict processing only when a conflict had occurred in the previous trial. Note that one of the core assumptions of the conflict-monitoring account proposes that the detection of a conflict leads to improved perceptual processing in subsequent trials (Botvinick et al., 2001; Egner and Hirsch, 2005; Verbruggen et al., 2006). The current data support this assumption and additionally suggest that the posterior IPS/IPL represents a central part of this reactive control network that enables attention to be focused on the task-relevant stimulus dimension.

The current data are consistent with previous findings on pre-SMA and PPC functioning. Several studies have related pre-SMA activity to conflict resolution (Taylor et al., 2007; Forstmann et al., 2008) and action reprogramming (Mars et al., 2009; Neubert et al., 2010). Our results specify the role of the pre-SMA in conflict processing by showing that it is causally involved in the resolution of conflict specifically at the response selection level. The pre-SMA may support response selection under conflict by facilitating the processing of the task-relevant response alternative (Mars et al., 2009; Neubert et al., 2010). Moreover, the pre-SMA resolves response selection conflict predominantly when the level of activated cognitive control is low—that is, when no conflict has arisen in the previous trial. Therefore, the pre-SMA is mainly active when conflicts have to be resolved under circumstances in which the cognitive system is not prepared for the occurrence of a conflict.

Furthermore, the current data do not support the conflict-monitoring hypothesis of pre-SMA functioning, because disrupting pre-SMA activity had no significant impact on conflict processing in subsequent trials (note, though, that this non-significant result does not necessarily imply that the conflict-monitoring hypothesis of pre-SMA functioning must be rejected). The conflict-monitoring hypothesis of the pre-SMA has been tested in functional imaging studies that found a correlation between pre-SMA activity and the occurrence of conflict in the current trial (Ullsperger and von Cramon, 2001; Garavan et al., 2003). In contrast to these correlation studies, the present study provides causal evidence for an active role of the pre-SMA in conflict resolution, because disrupting pre-SMA activity resulted in increased response selection conflict, but not in impaired conflict adaptation.

An involvement of the posterior IPS/IPL in conflict resolution has already been suggested by previous studies (Egner et al., 2007; Luks et al., 2007; Wang et al., 2010). Our findings specify current accounts of the role of the IPS/IPL region in conflict processing and show that the posterior IPS/IPL resolves conflict selectively at a perceptual processing level. This conclusion is consistent with previous results suggesting that parts of the PPC, including the posterior IPS/IPL and the right angular gyrus, are related to the top-down regulation of attentional processes (Rushworth et al., 2001; Chambers et al, 2004; Rushworth and Taylor, 2006; Green and McDonald, 2008; Silvanto et al., 2009; Taylor et al., 2011). Posterior IPS/IPL activity appears to be related to attention-regulated biasing of perceptual processing to facilitate target identification. In addition, our findings also suggest that the posterior IPS/IPL is mainly active when the level of cognitive control is enhanced after the detection of a conflict, because IPS/IPL TMS suppressed conflict adaptation. This proposal is supported by a study of Egner et al. (2007), which found that IPS/IPL activity was correlated with conflict adaptation in the Stroop task. Therefore, when the cognitive system is prepared for the potential occurrence of a conflict, it may inhibit the impact of distracting information by focusing on task-relevant stimulus attributes.

An unexpected finding was that disrupting posterior IPS/IPL activity resulted in reduced response selection conflict. Therefore, although IPS/IPL TMS impaired the resolution of perceptual conflict, it seemed to facilitate the processing of response selection conflict. However, this finding can be accounted for by assuming that perceptual target identification and response selection processes are performed in parallel (Hübner et al., 2010). Target and distractors may activate the corresponding response alternatives at the response selection level before the task-relevant target has been fully identified, on the basis of a preliminary draft of perceptual processing. Therefore, in trials in which IPS/IPL TMS impairs the identification of the task-relevant target, response selection processes might have more time for processing the task-relevant response even before the target identification process has been completed, resulting in the decreased response selection conflict observed. According to this account, the IPS/IPL region is not involved directly in the resolution of response selection conflict (if it were, IPS/IPL TMS should have increased, and not decreased, response selection conflict); rather, it influences the processing of response selection conflict processing in only an indirect manner by increasing the time required to identify the task-relevant target on a perceptual level.

Our data provide further support for the idea of conflict-specific control processes (Egner et al., 2007; Egner, 2008), challenging the assumption of a domain-unspecific general control mechanism (Botvinick et al., 2001; Freitas et al., 2007; Davelaar, 2008; Niendam et al., 2012). For example, the original conflict-monitoring model of Botvinick et al. (2001) assumes that the detection of a conflict at the response selection level activates control processes, which then resolve conflict at a perceptual level. Our data suggest that this correctly describes the mechanism underlying conflict adaptation (but note that conflict adaptation seems to occur also after SI trials, i.e., in the absence of response selection conflict; see also Verbruggen et al., 2006). Conversely, though, the conflict-monitoring model maintains that control processes at the response selection stage are triggered only by performance errors, whereas our data provide evidence for the operation of control mechanisms resolving response selection conflict after trials with correct responses (recall that posterror trials were excluded from the analyses).

Our data suggest that these conflict-specific control mechanisms may operate at different time scales (Fig. 6). When reactive control processes are activated in preparation for potential upcoming conflicts—that is, when a conflict has occurred in the previous trial—the cognitive system allocates enhanced attentional resources to task-relevant stimulus information. Therefore, it can reduce the amount of conflict already at a perceptual processing level and suppress the impact of distracting information on cognition. However, if the probability of a conflict in the next trial is anticipated to be low (e.g., after previously congruent trials), the system is not prepared for upcoming conflicts. In this processing mode, conflicts cannot be resolved at a perceptual, but only at a response selection level, probably due to the time required to activate control processes after the detection of a conflict (Ridderinkhof, 2002). Similar assumptions regarding cognitive control processes operating on different time scales have been formulated within the dual-mechanisms framework of control, which draws a distinction between a proactive and a reactive control mode (Braver, 2012; Jiménez and Méndez, 2013; but note that it is still a matter of debate whether conflict adaptation is triggered by proactive or by reactive control processes). The assumption that within-trial control affects the response selection level whereas between-trial control affects the perceptual level is also supported by a study by Boy et al. (2010), which revealed that subliminal priming affects the flanker congruency effect in the current trial but does not modulate conflict adaptation. From these findings, the authors concluded that there may be a distinction between reactive control mechanisms resolving conflict after its occurrence (poststimulus control) and anticipatory control mechanisms that are modulated on a trial-by-trial basis (prestimulus control). Our present data support this distinction between prestimulus and poststimulus control and also show that these two control mechanisms affect different processing levels, are implemented in dissociable neural networks, and operate at different time scales.

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Interference control in adult ADHD: No evidence for interference control deficits if response speed is controlled by delta plots

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ABSTRACT

Several theoretical accounts assume that interference control deficits belong to the core symptoms of adult ADHD. However, findings of increased interference effects in adult ADHD patients compared with healthy adults may be confounded with the simultaneous finding of generally slower responses in the patient group. The current study compared the magnitude of the interference effect in the Stroop task between a group of adults with ADHD and a healthy adult control group in a procedure that accounted for differences in overall response speed by using delta plots. The amount of interference did not differ between patient and control group at comparable reaction time levels. These results challenge the conclusions of the previous studies, in that they indicate that interference control is not impaired in adult ADHD.

1. Introduction

Attention deficit hyperactivity disorder (ADHD) in adults represents a disorder which has been related to deficits in various cognitive domains, including attention and executive functions (e.g., Barkley, 1997; Boonstra, Oosterlaan, Sergeant, & Buitelaar, 2005; Faraone et al., 2000; Nigg, 2005). Several theoretical accounts consider impaired interference control to be one of the core deficits in adult ADHD patients (e.g., Barkley, 1997; Nigg, 2005). One important source of evidence is the finding of enhanced interference effects in the Stroop task. In this task, participants have to respond to the ink color of a color word and ignore its semantic meaning; the task-irrelevant semantics can either be congruent (e.g., "RED" written in red) or incongruent (e.g., "RED" written in blue) with the relevant ink color (Stroop, 1935). The reaction time (RT) difference between incongruent and congruent color-word combinations is referred to as "Stroop effect" and represents a widely used measure of resistance to interference. Increased interference effects displayed by adult ADHD patients in the color-word Stroop task (King, Colla, Brass, Heuser, & von Cramon, 2007; Taylor & Miller, 1997; Walker, Shores, Trollor, Lee, & Sachdev, 2000) and in other interference paradigms such as the counting Stroop (Bush et al., 1999) or the Flanker task (Lundervold et al., 2011) are commonly interpreted as an indicator of impaired cognitive control (for a review, see Boonstra et al., 2005), even though they are not always replicated (e.g., Banich et al., 2009; Marchetta, Hurks, Krabbendam, & Jolles, 2008).

Critically, however, the majority of studies that actually replicated larger interference effects also found adult ADHD patients to show slower overall mean RTs than healthy adults (Bush et al., 1999; King et al., 2007; Lundervold et al., 2011; Walker et al., 2000), whereas only one study reported a larger interference effect despite the absence of general performance slowing (Taylor & Miller, 1997). Importantly, the Stroop effect is known to be generally increased with longer overall RT levels (Bub, Masson, & Lalonde, 2006; Pratte, Rouder, Morey, & Feng, 2010). Therefore, larger interference effects in ADHD patients may not reflect impaired interference control, but rather be a by-product of their slowed overall RT performance (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Sergeant, 2005). In line with this possibility, one of the rare studies in which an ADHD and a healthy control group showed a comparable general RT level failed to reveal a significant difference between the interference effects in these groups (Banich et al., 2009). A similar discussion is on-going in the literature about executive function impairments in child ADHD: In particular, some studies reporting deficits in interference control (Homack & Riccio, 2004; Mullane, Corkum, Klein, McLaughlin, & Lawrence, 2011) and motor

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inhibition (Lijffijt, Kenemans, Verbaten, & van Engeland, 2005) found that the general performance level, too, was impaired in children with ADHD compared to controls. In contrast, a study in which interference effects in an auditory Stroop task and a Simon task did not differ between a group of children with ADHD and a control group found only marginally significant or non-significant differences in general performance speed, respectively (Van Mourik et al., 2009). Thus, in both adult and child ADHD, interference control deficits appear to be correlated with general performance speed.

Clarification of whether specific interference deficits or more generalized RT slowing underlie the performance deficits of ADHD adults in the Stroop task is of particular significance from a theoretical point of view because it permits the notion of a cognitive control deficit in ADHD to be evaluated against alternative views. The notion of cognitive control impairments (Barkley, 1997; Nigg, 2005) would predict that, in adult ADHD patients, specific interference effects manifest over and above those explicable solely by overall RT slowing compared to healthy subjects. By contrast, if changes in RT behavior alone could explain the changes in Stroop task performance, this would suggest that the underlying impairments are not related to cognitive interference control in particular, but to more general deficits. Potential candidates that have been proposed in adult ADHD and that may play a role in any RT-based task are deficits in arousal adjustment (Sergeant, 2005), in response selection (Barkley, 1997; Castellanos et al., 2006), and/or in working memory processes (Finke et al., 2011). In fact, some accounts even consider the cognitive deficits in ADHD to be only “by-products” of underlying motivational or energetic dysfunctions (see Sonuga-Barke, Wiersema, van der Meere, & Roeyers, 2010, for a review).

Although the review of Boonstra et al. (2005) surmised that the increased Stroop interference effect in adult ADHD may be confounded by slower overall RTs because interference control deficits in ADHD appear to be positively correlated with slower response speed, the mere finding of a correlation between general RT speed and Stroop interference effects does not conclusively show that the slower mean RTs are the *cause* of the larger Stroop effect. For such a conclusion to be valid, it would be necessary to demonstrate that the amount of interference does not differ at equal RT levels between ADHD patients and healthy control subjects. Given this, the present study was designed to investigate whether adult ADHD patients would show a larger Stroop interference effect than demographically matched healthy control subjects when comparing performance at similar RT levels. If ADHD patients do show a larger effect, then this would provide further, conclusive support for the assumption of cognitive control deficits in ADHD. If not, this would suggest that larger Stroop effects in the ADHD group are brought about by the generally slower mean RTs, rather than by cognitive control deficits.

A methodological tool that permits the magnitude of interference effects to be examined as a function of response speed is provided by delta plots. For the construction of delta plots, the interference effect is calculated separately for different percentiles (e.g., deciles) of the RT distribution of a given participant and plotted against the mean RTs of congruent and incongruent trials for the corresponding percentile (de Jong, Liang, & Lauber, 1994). The amount of interference is then taken as dependent variable (y-axis) and the mean RTs for the corresponding percentile as independent variable (x-axis). Previous studies investigating the time course of the Stroop effect with delta plots found that the Stroop effect increases with the RT level, that is: it is minimal for the fastest and maximal for the slowest percentiles within a subject (Bub et al., 2006; Pratte et al., 2010). This relationship has been explained within the framework of information accumulation models, which assume that a response decision is made when the accumulated information determining the response has reached a certain threshold (e.g., Ratcliff & Rouder, 1998; Usher & McClelland, 2001). Congruent stimuli may engender a higher accumulation rate (i.e., reach the response decision threshold faster) than incongruent stimuli because target and distractor information are related to the same response alternative. This in turn results in a larger difference between congruent and incongruent stimuli with increasing accumulation time, or, in other words, with increasing processing time needed to reach the decision threshold (Pratte et al., 2010). Importantly, this positive relationship between the magnitude of the Stroop effect and processing time implies that the increased Stroop effect in ADHD patients compared to controls may be caused by the generally increased RT level, rather than by specific interference control deficits in ADHD. Note that the positive delta plot slope (i.e., larger interference effects with increasing mean RT) in the Stroop task deviates from the shape of delta plots in some other interference paradigms like the Simon task, in which smaller congruency effects at the slowest compared to faster RT levels are found (Pratte et al., 2010; Ridderinkhof, 2002). These different delta plot slopes may be attributable to the different types of conflict and conflict resolution mechanisms engaged in the Stroop and the Simon task (Egner, Delano, & Hirsch, 2007; Soutschek, Müller & Schubert, 2013).

Based on these assumptions about the size of the Stroop effect at different response time levels, the present study aimed at comparing the Stroop effects between ADHD patients and healthy controls under conditions of controlled response time levels between these groups. Importantly, the delta plot technique allowed us to investigate the amount of the Stroop effect in the two experimental groups at comparable RT levels. If we do not find any group differences at comparable RT levels, then this would indicate that adult ADHD may not be related to interference control deficits.

In addition to investigating the Stroop effect in a given (or current) trial, we also examined cognitive control effects manifesting across consecutive trials. Although previous studies investigating interference control in ADHD have mainly focused on the Stroop effect as an indicator of interference control, the so-called “conflict adaptation effect” is often regarded as a more direct measure of cognitive control processes. This effect refers to the observation that the Stroop interference is reduced in the current (incongruent) trial episode n if this trial is preceded by an incongruent, versus a congruent, episode on trial $n-1$. The standard explanation for this effect assumes that the detection of a conflict in trial $n-1$ leads to the enhanced activation of cognitive control, as a result of which a conflict in the subsequent trial n is resolved more efficiently (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Egner, 2007; Kerns et al., 2004). The conflict adaptation effect therefore specifically reflects the reduction of interference resulting from reactive adjustments of cognitive control, rather than indicating only the amount of interference per se (Egner, 2007). To our knowledge, no study thus far has examined the conflict adaptation effect in adult ADHD. We examined the conflict adaptation effect to complement our comprehensive analysis of potential Stroop task indicators of interference control deficits in adult ADHD.

2. Methods

2.1. Participants

Twenty-one non-medicated adult ADHD patients (mean age = 34.14 years, age range 21–54 years, 8 female) were recruited at the Department of Psychiatry of the Ludwig-Maximilians-University Munich. They were tested a few days after the initial diagnostic assessment, which was carried out at a specialized adult ADHD outpatient clinic.

The diagnostic procedure necessary for including a patient in this study comprised different steps: Two psychiatric interviews (according to *DSM-IV*) were carried out independently by two psychiatrists of the ADHD outpatient clinic. Using a conservative criterion, patients were only included when both psychiatrists rated them as ADHD patients. Collateral information from different sources (e.g., school reports and third-party ‘informants’ such as parents or siblings) was obtained by a psychologist trained in ADHD assessment, in order to confirm childhood onset according to the obligatory *DSM-IV* symptoms for childhood ADHD. Patients were only included if descriptions of the respective symptoms were listed in the first elementary school reports (obtained

Table 1

	ADHD ($n = 21$)	Control ($n = 21$)	t
Sex (female/male)	8/13	8/13	
Age	34.14 (10.46) 21–54	32.90 (9.27) 22–50	.41
School (years)	11.86 (1.59) 9–13	11.71 (1.71) 9–13	.28
IQ (MWT-B)	107.33 (10.34) 93–130	113.29 (12.91) 94–136	1.65
CAARS-S subscales			
A	72.29 (8.16) 57–85	49.19 (5.85) 37–59	10.54*
B	63.52 (9.19) 46–84	47.29 (6.59) 34–58	6.58*
C	68.38 (10.59) 41–88	47.90 (6.17) 35–59	7.66*
D	64.86 (8.83) 42–79	44.90 (7.16) 34–60	8.04*
E	82.67 (7.86) 65–90	50.29 (6.22) 38–59	14.80*
F	68.81 (11.27) 48–86	50.14 (7.01) 39–59	6.44*
G	80.81 (9.55) 57–90	50.33 (6.81) 36–58	11.91*
H	74.10 (7.72) 60–88	50.10 (7.92) 34–59	9.45*
WURS	57.57 (13.87) 38–85	20.10 (12.46) 0–42	9.21*

Group demographics: Sex distribution, mean, SD, and range of age, attended school years, IQ. Mean T-values, SD, and range of subjective current symptoms and retrospective childhood symptoms for the ADHD group.

Abbreviations: School: Duration of education (in years); MWT-B: German Multiple-Choice Vocabulary Test (Lehrl et al., 1995); CAARS-S: Connors Adult ADHD Rating Scale Self-Rating (Conners Adult ADHD Rating Scales Self Report, CAARS; Conners et al., 2002); CAARS-subscales: A — inattention/memory problems; B — hyperactivity/restlessness; C — impulsivity/emotional instability; D — problems with self-concept; E — inattentive symptoms according to DSM-IV; F — hyperactive-impulsive symptoms according to DSM-IV; G — total ADHD symptoms according to DSM-IV; H — ADHD Index. WURS: Wender Utah Rating Scale (Wender Utah Rating Scale, WURS; Ward et al., 1993); ADHD: ADHD patients; Con: control participants.

* $p < .001$.

at an age ≤ 7 years) and for a longer-term period in the following reports. In Germany, elementary school reports contain comprehensive descriptions of learning performance (e.g., participation in lessons, diligence with homework, accuracy in written reports), social behavior (e.g., impulsivity and aggression), and daily structure (e.g., forgetfulness and daydreaming), differentiated according to cognition, emotion, and motor behavior. Furthermore, prior psychiatric diagnoses, or third-party 'informants' (siblings), had to confirm that these symptoms were also displayed at home and that there had been no alternative suspected diagnosis. Two patients had already been diagnosed with ADHD in childhood, two had received ADHD medication during childhood (but not in adulthood). Finally, in an assessment of current (Conners Adult ADHD Rating Scales Self Report, CAARS; Conners, Erhardt, & Sparrow, 2002) and retrospective childhood symptoms (Wender Utah Rating Scale, WURS; Ward, Wender, & Reimherr, 1993), self-reports had to indicate ADHD since childhood.

Average ADHD symptom ratings in the ADHD patients (see Table 1) indicated severe subjective current impairments (all T-values > 60) and retrospective childhood ADHD symptoms (all ADHD patient values are above the cut-off value, i.e., ≥46; Ward et al., 1993). In accordance with previous reports on symptoms in adulthood (Biederman, 2005), inattentiveness ratings were especially pronounced (T-values > 70).

German versions of the Minnesota Multiphasic Personality Inventory (MMPI-2; Hathaway, McKinley, & Engel, 2000) and Personality Assessment Inventory (Groves & Engel, 2007) were used to exclude patients with other mental and personality disorders. Furthermore, patients with either prior or comorbid neurological disorders, bipolar disorder, schizophrenia, or other psychotic disorders, substance abuse or addiction other than nicotine within the last three months, or with an IQ below 85 were excluded.

Seven patients had a history of previous cannabis use and two were heavy smokers. Patients whose clinical picture was dominated by depressive symptoms were excluded. However, since depression and anxiety are frequent comorbid disorders in adult ADHD samples (Sprafkin, Gadow, Weiss, Schneider, & Nolan, 2007), secondary diagnoses (in addition to ADHD) had been given to six included patients with recurrent moderate depression (ICD-10 F 33.1; World Health Organization, 1992). Five of these patients took antidepressive medication, but none of them suffered from an acute major depression. Patients and control participants were asked to abstain from nicotine and caffeine at least 1 h prior to the application of the Stroop task. This was meant to ensure that, on the one hand, ADHD patients' performance could not profit from recent nicotine consumption and, on the other hand, that the results of heavy smokers were unlikely to be compromised by withdrawal effects (Heishman, Kleykamp, & Singleton, 2010).

Twenty-one participants with neither neurological nor psychiatric (inclusive drug addiction) history served as control group (mean age = 32.90 years, age range 22–50 years, 8 female) and were paid 8 euro/h for their participation. They were assessed with the Stroop task as well as the CAARS, the WURS, and the WST questionnaire. Age, gender, IQ (German Multiple-Choice Vocabulary Test; Lehrl, Triebig, & Fischer, 1995), and educational level were matched and did not differ significantly between the patient and control groups (all $ps > .1$). In contrast, subjective ADHD symptoms (CAARS — T-value and WURS scores) were significantly higher in the ADHD group than in the control group, all $ps < .001$ (see also Table 1). Informed consent according to the Declaration of Helsinki II was obtained from all participants. All had normal or corrected-to-normal vision.

2.2. Stimuli and apparatus

The experiment was run in a dimly lit sound-proof experimental cabin. The participants sat at a distance of approximately 50 cm from a 17 in. monitor on which stimuli were presented, controlled by Experimental Run Time System (ERTS; Berisoft) run on a standard PC. All stimuli were presented against a black background. We employed a color-word variant of the Stroop paradigm in which we presented three different color words ("BLAU", "ROT", and "GRÜN"; German for blue, red, and green) in blue, red, or green ink, resulting in either congruent (e.g., "BLAU" in blue ink) or incongruent (e.g., "BLAU" in red ink) color-word combinations.

2.3. Task and procedure

The task was to respond to the ink color of the presented words and ignore the semantic meaning. We instructed participants to respond by pressing the keys V (for blue words), B (for red words), and N (for green words) on a QWERTZ keyboard, using their right-hand index, middle, and ring finger, respectively.

Each trial started with the presentation of a white fixation cross on a black screen for 1500 ms, then the color word was presented for 2000 ms. Participants had to respond within stimulus presentation time. The next trial started immediately after the response. A block contained 66 congruent and 24 incongruent trials, which were presented in randomized order. We used a higher number of congruent than incongruent trials because this procedure has been shown to reliably produce strong interference effects (Kerns et al., 2004). We administered three blocks, resulting in a total of 270 trials.

2.4. Statistical analysis

We analyzed RTs and error rates of the Stroop task data. We removed all trials that contained either a repetition of the color or the word from the data set to control for any influence such stimulus repetitions might have on the conflict adaptation effect (Hommel, Proctor, & Vu, 2004; Kerns et al., 2004; Mayr, Awh, & Laurey, 2003). In addition, we conducted further analyses to control for potential negative priming effects (see below). For the RT analysis, we also removed all trials including or following an error.

To calculate the conflict adaptation effect, we differentiated between the effects of current trial congruency (denoted by upper-case C[congruent] vs. I[incongruent]) and previous trial congruency (denoted by lower-case c vs. i). We defined the conflict adaptation effect as the difference between the Stroop effects after previously congruent versus previously incongruent trials ($(cI - cC) - (iI - iC)$; Kerns et al., 2004). We tested the occurrence of conflict adaptation effects in the ADHD and the control group with one-tailed *t*-tests because we expected the congruency effect to be smaller after previously incongruent compared to after congruent trials.

The delta plot analysis was conducted as follows: We rank-ordered all RTs of each participant separately for congruent and incongruent trials and calculated the values for the 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th percentiles (deciles). Next, we calculated the Stroop effect for each decile. The Stroop effect in the first decile, for example, was calculated by subtracting the RT for the first decile in congruent trials from the RT for the first decile in incongruent trials. In order to construct delta plots, we plotted the amount of the Stroop effect for each decile against the mean response speed for that decile, that is, the mean RT of congruent and incongruent trials.

In addition, we also computed a distributional analysis for the error congruency effect. For that purpose, we divided the RT distribution into five bins of equal size (quintiles) and then calculated the congruency effect in the error rates separately in the different RT bins (Ridderinkhof, 2002; Ridderinkhof, Scheres, Oosterlaan & Sergeant, 2005). In detail, we first subdivided the RTs in both correct and incorrect response trials into five bins of equal size, separately for congruent and incongruent trials. Then, we calculated the error congruency effect in each bin by subtracting the error rate in congruent trials from the error rate in incongruent trials in the corresponding bins.

3. Results

3.1. RT analysis

We carried out a 2 × 2 × 2 mixed-design analysis of variance (ANOVA) with the between-subject factor Group (ADHD vs. control) and the within-subject factor Current trial congruency (C vs. I) and Previous trial congruency (c vs. i). Due to the exclusion of stimulus repetition trials as well as error and post-error trials, a mean total trial number of 170 per participant was entered into the RT analysis. Results are illustrated in Fig. 1. This ANOVA yielded a significant main effect of group, with mean RTs being slower overall in the ADHD group (793 ms) than in the control group (597 ms), $F(1, 40) = 20.71$, $p < .001$, $\eta_p^2 = .341$. The main effect of current trial congruency was also significant, due to responses being slower overall in incongruent trials (857 ms) compared to congruent trials (644 ms), $F(1, 40) = 111.75$, $p < .001$, $\eta_p^2 = .736$ — that is, there was a Stroop effect of over 200 ms. Moreover, the Group × Current trial congruency interaction was significant, due to the ADHD group exhibiting a larger Stroop effect than the control group (258 ms vs. 168 ms), $F(1, 40) = 4.65$, $p < .05$, $\eta_p^2 = .104$. The effect of the current trial congruency interacted with the previous trial congruency, $F(1, 40) = 6.35$, $p < .05$, $\eta_p^2 = .137$, which is indicative of a conflict adaptation effect. Importantly, the conflict adaptation effect did not differ in magnitude between the ADHD and the control group, as evidenced by the non-significant Current trial congruency × Previous trial congruency × Group interaction, $F(1, 40) = .19$, $p = .67$, $\eta_p^2 = .005$. That is, there was a significant conflict adaptation effect both in the ADHD group $(cI - cC) - (iI - iC) = 63$ ms, $t(20) = 1.72$, $p < .05$, one-tailed, and in the control group $(cI - cC) - (iI - iC) = 44$ ms, $t(20) = 2.03$, $p < .05$, one-tailed, with no reliable difference in the effect magnitude between the two groups, $t(40) < 1$, $p > .67$.

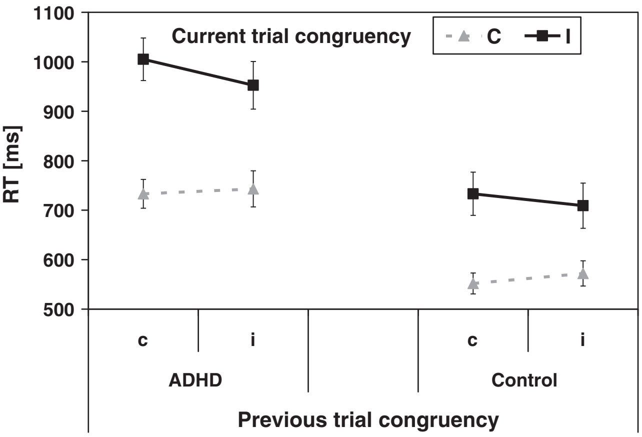

Fig. 1. Mean reaction times (RTs) in the Stroop task for the ADHD and control groups. Error bars indicate the standard error of the mean (C/c, congruent; I/i, incongruent).

For the analyses reported above, we had excluded all trials in which either the color or the word feature had been repeated (within-dimension repetitions) in order to control for potential feature repetition effects on conflict adaptation. Besides within-dimension repetitions, however, conflict adaptation might also be affected by negative priming, i.e. when the target feature becomes the distractor feature in the following trial, or vice versa (across-dimension repetitions). Note that we could not simultaneously control for both within-dimension repetitions and negative priming because this would have resulted in an exclusion of all iI trials in the variant of the Stroop paradigm we used. Therefore, we computed a separate analysis in which we excluded only across-dimension but not within-dimension repetition trials (see Soutschek, Strobach & Schubert, 2012): We found significant conflict adaptation effects both in the ADHD $(cI - cC) - (iI - iC) = 203$ ms, $t(20) = 4.22$, $p < .001$, and the control group $(cI - cC) - (iI - iC) = 67$ ms, $t(20) = 2.77$, $p < .05$, whereas conflict adaptation was more pronounced in the ADHD than in the control group, $t(40) = 2.52$, $p < .05$. The surprising finding of a larger conflict adaptation effect in the ADHD than in the control group may indicate that the benefit from within-dimension repetitions (which were not excluded in this analysis) was more pronounced in the patient than in the control group. Importantly, however, this finding is not compatible with the idea of interference control deficits in adult ADHD. In addition, we also tested whether conflict adaptation occurred when no repetition trials were excluded at all. Again, significant conflict adaptation effects occurred both in the ADHD, $(cI - cC) - (iI - iC) = 92$ ms, $t(20) = 3.11$, $p < .01$, and the control group $(cI - cC) - (iI - iC) = 41$ ms, $t(20) = 2.61$, $p < .05$, whereas we found no significant difference between ADHD and control group, $t(40) = 1.53$, $p > .13$. Taken together, the observed conflict adaptation pattern appears to be robust against the trial types included in the analysis.

3.2. RT delta plot analysis

In line with the previous studies, our analysis revealed a larger Stroop effect in the ADHD group than in the control group. However, the ADHD patients' performance was also characterized by slower mean RTs compared to the control group. As previous studies had shown that the size of the Stroop effect increases with slower responses (Pratte et al., 2010), the differences in Stroop interference between the ADHD and the control group may be attributable to the different RT levels in these groups. To test this hypothesis, we compared the Stroop effects in the ADHD and the control group by means of delta plots, which graph the size of the Stroop effect for different RT levels. To be able to compare similar RT levels between the ADHD and the control group, we calculated the mean Stroop effect for each decile and plotted it against the RT for the corresponding decile. This is illustrated in Fig. 2 in which the size of the Stroop effect (y-axis) for the decile of the two groups is plotted as a function of the mean RTs (x-axis) for the corresponding decile. As can be seen from Fig. 2, the whole distribution of the Stroop effect in the ADHD patient group is shifted to the up and to the right of the distribution of the control group, with the RT distribution being broader in the ADHD than in the control group due to some extremely slow responses occurring in the ADHD group (see also Leth-Steensen, Elbaz, & Douglas, 2000). This observation is corroborated by the results of a 2 (Group) × 9 (Decile) mixed-design ANOVA with the size of the Stroop effect as dependent variable. This analysis revealed a significant main effect of group, $F(1, 40) = 5.95$, $p < .05$, $\eta_p^2 = .129$, reflecting the generally larger Stroop effect in the ADHD group. Furthermore, the main effect of decile was significant, $F(8, 320) = 42.81$, $p < .001$, $\eta_p^2 = .517$, reflecting the fact that the Stroop effect was larger at slower, compared to faster, RTs in both groups. Importantly, the increase of the Stroop effect size with increasing RT levels did not differ between the ADHD and the control group, Group × Decile, $F(8, 320) < 1$, $p > .66$, $\eta_p^2 = .011$. Fig. 2 suggests that ADHD and control group show quite comparable amounts of Stroop interference at similar mean RTs. Importantly, the delta plot technique allowed testing this hypothesis in more detail by calculating post-hoc t-tests between the magnitudes of the Stroop effect in ADHD and control group at comparable RT levels. As it is illustrated by Fig. 2, the mean RTs of the patients in the first (552 ms), second (623 ms), third (677 ms), fifth (772 ms), and seventh deciles (920 ms ms) are comparable to the mean RTs of the controls in the third (536 ms), fifth (608 ms), seventh (694 ms), eighth (757 ms), and ninth deciles (891 ms), respectively (all *ps* > .42 between the corresponding deciles). Independent-samples *t*-tests validated that the size of the Stroop effect did not differ between ADHD and control group at these RT levels (i.e., first decile ADHD — third decile control: $t(40) < 1$, $p > .78$; second decile ADHD — fifth decile control: $t(40) < 1$, $p > .93$; third decile ADHD — seventh decile control: $t(40) < 1$, $p > .58$; fifth decile ADHD — eighth decile control: $t(40) < 1$, $p > .68$; seventh decile ADHD — ninth decile control: $t(40) < 1$, $p > .72$). In other words, ADHD and control group showed similar amounts of the Stroop effect at comparable RT levels.

In order to support the observation reported above which provided no evidence for interference control deficits in ADHD, we additionally compared the slopes of the delta plot curves between patient and control group. If ADHD patients suffered from specific interference control deficits, then the increase of the Stroop effect with slower response speed (that is, the slope of the delta plot curve) should be larger in the patient than in the control group. This is because the delta plot slope is thought to reflect the efficiency of interference control processes (Pratte et al., 2010). To test this prediction, we first computed the slopes of the individual delta plots by conducting a regression analysis for every single participant in which the magnitude of the interference effect and the mean RT in each decile were entered as criterion and predictor, respectively. The resulting beta weights of these regressions represented the delta plot slopes of the individual participants. In the next step, we calculated an independent-samples *t*-test to compare the delta plot slopes between ADHD patients and control subjects. Because the observed delta plot slopes did not significantly differ between the ADHD (mean slope = .49) and the control group (mean slope = .59), $t(40) = 1.03$, $p > .30$, the analysis of the delta plot slopes provided no evidence for interference control deficits in adult ADHD.

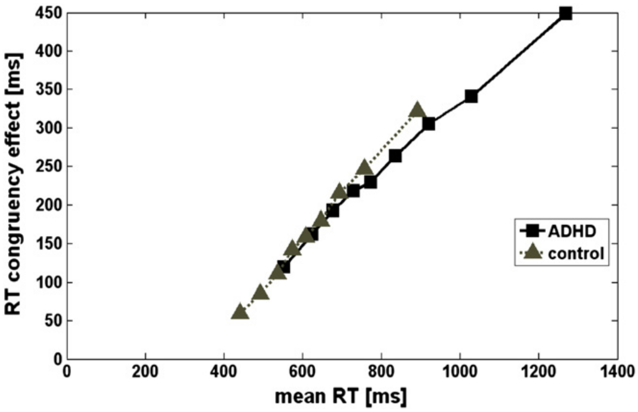

Fig. 2. Delta plot of the reaction time (RT) congruency effect in the ADHD and control groups.

3.3. Error analysis

We also analyzed error rates in a 2 × 2 × 2 mixed-design ANOVA including the same factors as in the RT analysis (for details, see Table 2). On average, 181 trials per participant were entered into the error analysis. ADHD patients tended to make more errors overall than healthy controls, $F(1, 40) = 3.45$, $p = .07$, $\eta_p^2 = .079$. The significant main effect of the Previous trial congruency indicated that error rates were larger after previously incongruent (6.4%) compared to the previously congruent trials (5.8%), $F(1, 40) = 7.14$, $p < .05$, $\eta_p^2 = .141$. In addition, there was a significant congruency effect, with more errors occurring in incongruent (11.6%) than in congruent trials (3.7%), $F(1, 40) = 25.72$, $p < .001$, $\eta_p^2 = .391$. This error congruency effect was modulated by the factor Group, $F(1, 40) = 5.73$, $p < .05$, $\eta_p^2 = .125$, reflecting a larger congruency effect in the ADHD group (11.2%) than in the control group (4.3%). Furthermore, there was a significant conflict adaptation effect in the error rates, $F(1, 40) = 5.69$, $p < .05$, $\eta_p^2 = .125$, indicating a reduced error congruency effect after incongruent (5.7%), compared to congruent (10.1%), trials. Again, the conflict adaptation effect did not differ in magnitude between the ADHD and the control group, $F(1, 40) = .78$, $p > .38$, $\eta_p^2 = .019$.

3.4. Distributional analysis of error congruency effects

We conducted a distributional analysis of the error congruency effect in order to examine the magnitude of the error congruency effect at different response time levels (see Fig. 3). For that purpose, we divided the RT distribution into five bins of equal size and calculated the error congruency effect in each RT bin separately for ADHD patients and controls. A 2 × 5 (Group × Bin) ANOVA revealed a tendency to a significant Group × Bin interaction, $F(4, 160) = 2.12$, $p < .08$, $\eta_p^2 = .052$, suggesting that the distributions of the error congruency effect differed between the ADHD and the control group. Comparing the congruency effects between these groups at each RT bin by independent-samples *t*-test, we found that ADHD patients showed a significantly larger error congruency effect than healthy controls only in the first bin (i.e., the fastest RTs), $t(40) = 2.62$, $p < .05$, whereas no significant difference occurred in all other bins, $ts < 1.03$, $ps > .30$. These findings indicate that ADHD patients showed a larger error congruency effect than healthy controls particularly in trials with very fast responses.

4. Discussion

In ADHD research, there is currently a debate as to whether or not adult ADHD patients suffer from deficits in interference control compared to healthy controls (e.g., Boonstra et al., 2005; Bush et al., 1999; King et al., 2007). Interestingly, the increased interference effect in the patient group seems to be correlated with slower overall response speed in this group (for an overview, see Boonstra et al., 2005). In line with these previous findings, the present study replicated both an

Table 2
Error rates in the Stroop task for ADHD and control group. Numbers in brackets denote the standard errors of mean (C/c, congruent; I/i, incongruent).

Previous trial congruency	C		I	
Current trial congruency	C	I	C	I
ADHD group	4.3 (1.0)	18.9 (3.0)	3.1 (1.0)	11.8 (3.2)
Control group	3.5 (1.1)	9.1 (1.7)	4.0 (1.6)	6.8 (2.2)

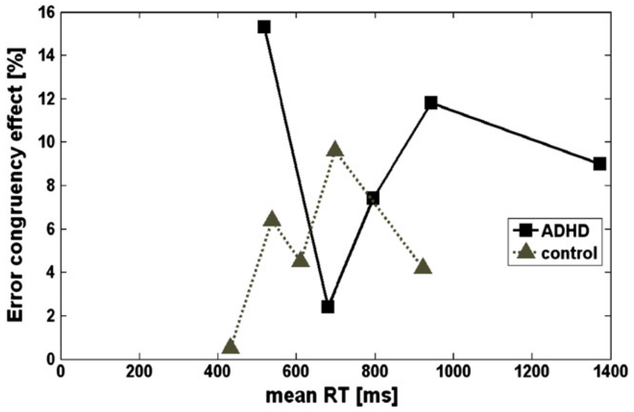

Fig. 3. Delta plot of the error rate congruency effect in the ADHD and control groups.

increased interference effect and slower RTs in the ADHD, compared to the control, group. Importantly, however, the larger Stroop effect disappeared when we compared performance between the ADHD and the control group at similar response speed levels. In particular, the delta plot analysis revealed that the Stroop effect did not differ in magnitude between ADHD patients and controls at comparable RT levels. Since the Stroop effect generally increases with slower mean RTs (Bub et al., 2006; Pratte et al., 2010), we conclude that the generally slower RT performance of the ADHD patients can (at least to a large extent) explain the larger mean Stroop effect in that group. In other words, there is no need to assume that interference control, too, is impaired in ADHD. If the ADHD patients had suffered from deficits in interference control, then this group should have shown a larger Stroop effect, compared to the control group, at comparable RT levels as well. Note that there is evidence that color perception may be impaired in ADHD (Banaschewski et al., 2006). However, although this impairment might have contributed to the slower mean RTs in the ADHD than in the control group, it seemed to have no impact on the Stroop effect itself because the Stroop effect did not differ between ADHD and control group at comparable RT levels.

The current results are in line with the findings of the previous studies that failed to find a larger Stroop effect in ADHD when mean RTs were comparable between the patient and control groups (Banich et al., 2009) or when response speed was controlled for (Boonstra et al., 2005). However, in contrast to the findings of a correlational relationship between the magnitude of the Stroop effect and the general performance level, we directly tested for Stroop effect differences at comparable RT levels by using delta plots. The findings of the current analysis suggest that the increased interference effect in adult ADHD reported in the previous studies may be attributable to the slower overall RTs (Bush et al., 1999; King et al., 2007; Lundervold et al., 2011). A testable hypothesis that directly follows from our conclusion is that ADHD patients should show larger effect sizes than healthy controls in all experimental paradigms with positive-going delta plots (e.g., for word frequency effects in lexical decision tasks; see Rouder, Yue, Speckman, Pratte, & Province, 2010), whereas effects with negative-going delta plots (such as the Simon effect) should be reduced in ADHD relative to control samples.

It is important to note that slower mean RTs can be accounted for larger interference effects in ADHD patients relative to controls only if the delta plot of the applied interference paradigm has a positive slope. While a positive delta plot slope is well established for the Stroop task, the distributional properties of other interference paradigms used in ADHD research such as the counting Stroop task (Bush et al., 1999) have – to the best of our knowledge – not yet been examined. Thus, one should be careful with generalizing the results of our study to interference paradigms with unknown distributional properties.

As a further indicator of unimpaired interference control in the Stroop task, we found that the conflict adaptation effect was not reduced in the ADHD compared to the control group. Since the conflict adaptation effect measures control-triggered adjustments in interference processing, it is assumed to represent a more direct indicator of cognitive control than the Stroop effect itself (Botvinick et al., 2001; Egner, 2007). ADHD patients even showed a larger conflict adaptation effect than controls when only across-dimension repetitions were excluded from the data set, suggesting that the facilitatory effect of stimulus priming (induced by within-dimension repetitions) may have been more pronounced in the ADHD than in the control group. Summarizing our findings for the Stroop effect and the conflict adaptation effect, the present results suggest that interference control may not be impaired in adult ADHD.

The fact that an increased interference effect in adult ADHD is not necessarily indicative of deficits in interference control, but may rather be related to a generally slower RT level, raises the question as to how the slower RT level of the patients can be explained. Currently, several different accounts are discussed as potential explanations for the general performance deficits in ADHD: According to the recent dual-process models, for example, dysfunctional bottom-up factors like alertness/arousal or motivational factors contribute to the behavioral impairments in ADHD (Nigg & Casey, 2005; Sonuga-Barke, Wiersema, van der Meere, & Roeyers, 2010). According to the state regulation deficit account of ADHD, for example, ADHD patients show deficits in the context-dependent attribution of cognitive resources to the motor preparation stage (Sergeant, 2005; van der Meere, 2005), which may result in prolonged overall processing times. Our finding that seeming interference control deficits may be explicable by a general RT slowing would be consistent with such accounts of ADHD according to which the observed cognitive impairments are only secondary deficits originating from more basic motivational or energetic impairments. However, deficits in working memory functions, too, are discussed as causes for the impaired performance level in adult ADHD (Finke et al., 2011). The current data alone do not permit a decision to be made among these accounts of slower response speed in ADHD. For the purpose of the present study, however, the important result is that the increased Stroop effect in ADHD may be attributable to the slower response speed of ADHD patients, whereas the specific mechanisms underlying this slowing require further research.

A somewhat puzzling finding relates to the increased error congruency effect in the ADHD compared to the control group. However, the distributional analysis of the error congruency effects revealed ADHD patients to show a larger error congruency effect than healthy controls only in trials with very fast responses. This is consistent with the idea that errors in interference paradigms occur when the distractor information in incongruent trials automatically activates the wrong response alternative via a fast direct processing route (Ridderinkhof, 2002). Assuming that response activation via the direct route may be more pronounced in ADHD patients than in healthy controls, as suggested by Ridderinkhof et al. (2005), it would appear that the distractor information activated the incorrect response alternative more often in patients than in normal controls; and this in turn would result in an increased error congruency effect in fast trials. Accordingly, the observation of an increased error congruency effect in the patient group can be explained by the assumption of enhanced automatic direct-route activation in the ADHD compared to the control group, which affects the decisions only in trials with fast RTs. In contrast, the findings do not provide evidence for an impairment of interference control processes involved in the active resolution of processing conflicts.

Although the present results question the assumption of interference control deficits in ADHD, our findings do not imply that adult

ADHD patients do not suffer from impairments in the other domains of executive functions. This is so because the concept of executive functions represents a theoretical construct that includes several subcomponents such as interference control, working memory, and set shifting (Miyake et al., 2000); accordingly, ADHD might still be related to deficits in the other domains of executive functions than interference control. In fact, several studies found ADHD-related deficits also for working memory and set shifting processes (Burgess et al., 2010; Finke et al., 2011; King et al., 2007; Marchetta et al., 2008). Consequently, the results of the present study do not question the assumption of deficits in executive functions as a core syndrome of adult ADHD, but only the evidence for impaired interference control deriving from paradigms such as the Stroop task. It should also be noted that dissociable control mechanisms may be involved in resolving the different types of conflicts, e.g. in resolving stimulus-based conflicts in the Stroop task and response-based conflicts in the Simon task (Egner et al., 2007). Hence, despite our findings for the Stroop task, ADHD participants might conceivably still suffer from interference control deficits in the Simon task. In fact, there is evidence that response inhibition is impaired in adult ADHD (Lijffijt et al., 2005). Future research will have to clarify whether ADHD patients suffer of conflict-specific control deficits.

As in adult ADHD, interference control deficits in child ADHD are also often accompanied by a generally slower performance level (Homack & Riccio, 2004; Mullane, Corkum, Klein, McLaughlin, & Lawrence, 2011; Van Mourik et al., 2009). However, a meta-analysis found evidence for impaired interference control even when controlling for performance speed (Lansbergen, Kenemans, & van Engeland, 2007). Another study that investigated interference control in child ADHD by delta plots found that children with ADHD showed worse response inhibition performance than a healthy control group (Ridderinkhof et al., 2005). Despite our divergent findings for *adult* ADHD patients, control deficits may well be among the cognitive symptoms in *childhood* ADHD, given that the evidence for a relationship between interference control deficits and general performance speed in child ADHD is still pending and that cognitive deficits may partly differ between child and adult ADHD (Biederman, Mick, & Faraone, 2000). There is evidence that the development of prefrontal cortical areas (associated with cognitive control) is only delayed in children with ADHD compared to controls (Shaw et al., 2012), such that adults with ADHD may (at least partly) recover from the control deficits exhibited in childhood.

From a methodological point of view, our results underscore the usefulness of distributional analyses such as delta plots for comparing performance between (various) patient groups and healthy control subjects with different mean RT levels. This is of particular importance when comparing an effect whose magnitude is known (or suspected) to depend on general response speed. In such cases, the finding of differential effect sizes between two groups may lead to false conclusions if these groups also differ in their general response speed, owing to, for instance, differences in arousal or motor speed. Delta plots permit the magnitude of the respective effects to be compared between the groups at similar RT levels and so help to avoid false conclusions. Note that delta plots are not only helpful when it is already known that the magnitude of an effect depends on the RT level, but they also provide a useful tool for examining the distributional shape of an effect. In addition, delta plots should also be preferred to the use of performance-matched control groups in clinical research because they do not require the exclusion of control subjects from the data set. Thus, they can be recommended as a standard tool whenever performance in groups with different mean RTs is compared. Importantly, however, they require that the same cognitive processes are involved in slow and fast trials in an experimental task. In the context of the present study, the finding that the slopes of the delta plot segments did not significantly differ from each other suggests that this pre-condition was approximately met in our experiment.

5. Conclusions

Previous studies often considered the finding of a larger interference effect in adult ADHD patients compared to healthy controls as evidence for the interference control deficits in ADHD. The results of the present study reveal that this performance difference disappears when performance is compared at equal response speed levels. In addition, we found that also a more direct measure of cognitive control, namely, the conflict adaptation effect, did not differ between the ADHD and control groups. Our results therefore question the assumption of interference control deficits in ADHD. Moreover, the present study illustrates the importance of comparing cognitive deficits between patient and control groups in reaction time tasks with delta plots, which allow performance to be compared at similar levels of response speed.

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