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**Neural Mechanisms of Executive Control during Cognitive
Conflict and Competition: A Functional Neuroimaging
Investigation**

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TO MY FATHER, ERICH MELCHER.

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Summary / Abstract

The general purpose of the present neuroimaging work was to investigate the neural mechanisms of cognitive control that are recruited in situations of cognitive interference or competition. To address this issue, an oddball variant of the Stroop paradigm was created and applied. Thereby, participants responded to the font size of presented word stimuli by either a left or right button press. Nine neurologically healthy young subjects underwent functional magnetic resonance imaging (fMRI) while they performed the task. Besides the neuroimaging data, reaction time as behavioral measure was registered and analyzed. Basically, the current work pursued three goals:

(1) First, it was planned to investigate and compare the neural mechanisms of cognitive control that are recruited during two distinct situations (i.e. experimental conditions) of interference or competition between task-relevant and task-irrelevant information: (a) Stroop-incongruity (i.e. when subjects are presented with incongruent word information assumed to produce Stroop-interference) and (b) oddballs (i.e. when subjects are presented with task-irrelevant but attention-capturing low-frequency events). Thereby, in order to ensure high comparability, incongruity effects (i.e. Stroop-interference) and oddball effects (i.e. oddball interference) should be investigated within the same processing domain, that means incongruent and low-frequent task-irrelevant information should occur in the same stimulus dimension. Accordingly, besides Stroop-incongruent trials, a ‘Word-oddball’ condition was created that comprised rarely occurring words, so that in both compared conditions interference emanated from the word dimension, including incongruent information in the one case and rarely occurring information in the other. Based on prior studies’ findings, the related hypothesis was that the neural mechanisms that underlie the resolution of Stroop-interference (i.e. the overriding of a prepotent response tendency, in the present case to read and react to word meaning) are, at least in part, the same as those that underlie the processing of task-irrelevant low-frequency events (i.e. the overriding of an involuntary attentional orienting response).

(2) Second, it was planned to elucidate domain-specific effects in interference processing. For this purpose, oddball events that occurred in different stimulus dimensions – corresponding to different processing domains – were compared to each other. Specifically, in addition to Word-oddballs, a Color-oddball condition comprising of rarely occurring red colored stimuli was created, and subsequently the two low-frequency conditions were compared to each other. Either oddball condition was expected to evoke an involuntary orienting response to the

respective dimension, either word or color, in which the oddball event occurs, which consequently would require subjects to reconfigure the current attentional set.

(3) Third and finally, the current work sought to trace back Stroop-interference to the influence of circumscribed properties of task-irrelevant word information that can be conceived as “conflict factors”. In particular, it was planned to delineate the neural substrates of three conflict factors: (A) *response-incompatibility* (i.e. word identity indicates an opposed response), (B) *semantic incongruency* (i.e. word identity is semantically incongruent, i.e. conceptually contradictory, independent of its response-mapping), and (C) *task-reference* (i.e. word identity is semantically related to the task-set, independent of its semantic match with the relevant dimension).

Generally, all interference conditions (i.e. incongruity or oddballs trials) exhibited substantially prolonged reaction times as compared to non-interference conditions (i.e. baseline trials), demonstrating that the experimental manipulation of the adopted task paradigm was indeed effective. Accordingly, the neuroimaging data revealed definitive patterns of results allowing for meaningful conclusions regarding the presented issues of this work.

Ad (1) The comparison of Stroop-interference and interference emanating from Word-oddballs revealed two distinct patterns of neural activation that exhibited only sparse overlap. Therefore, the data did not corroborate the expectation that the two interference effects exhibit a marked activation overlap that could be construed to reflect or represent a core neural mechanism in cognitive control. Rather, the two different activation patterns can be conclusively interpreted to represent two distinct and complementary (sub-)components (i.e. aspects or levels) of cognitive interference that refer to distinct control functions. First, the analyses revealed a motor component of interference that is related to Stroop incongruity or Stroop-interference, and that reflects the occurrence of (response-)conflict emanating from incongruent word meaning. Second, an attentional component was isolated that reflects the ability of low-frequency, task-irrelevant information to efficiently distract attentional resources (i.e. to evoke an involuntary orienting response to which one may refer as ‘oddball interference’). While the first component was associated with activity mainly in regions that are implicated in motor control and response preparation (comprising e.g. premotor cortices, the basal ganglia and cerebellum), the second component was represented by a frontoparietal “attention network” that most probably reflects top-down attentional control to focus on task-relevant information (i.e. to select task-relevant over task-irrelevant information), as suggested by numerous studies of the cognitive neuroscience literature.

Ad (2) Word- and Color-oddballs exhibited a broad overlap of activations, mainly in prefrontal areas but also in posterior processing regions. Findings are consistent with the assumption that attentional selection mainly works through manipulating, i.e. boosting, processing of task-relevant information in posterior processing areas. Color-oddballs compared to Word-oddballs exhibited the stronger behavioral effect as well as stronger and more widespread neural activation. This latter finding may be attributed to the task context and to a greater inherent saliency of color compared to word information. Furthermore, in line with prior studies' findings, the current data emphasized a prominent role of a region in the posterior lateral PFC – referred to as inferior frontal junction area (IFJA) – in implementing top-down attentional control. In this context, both oddball conditions of the current study exhibited the bilateral IFJA as one main site of activation.

Ad (3) Finally, the 'factorial decomposition analysis' revealed definitive activation patterns related to the defined conflict factors that allowed for meaningful conclusions. Response-incompatibility was related to activation in the left ventral premotor cortex which can be reasonably interpreted as indicator for or neural substrate of response conflict (i.e. motor competition). Semantic incongruency exhibited specific activation in the posterior frontomedian cortex, the bilateral insula, the basal ganglia and thalamus, as well as in the left postcentral gyrus corresponding to the somatosensory cortex. These activations presumably underlie strengthened motor control efforts to prevent false responding. Finally, task-reference exhibited activation in the left inferior prefrontal cortex, right superior prefrontal cortex, and left temporo-polar cortex. Due to prior studies' findings that relate these regions to semantic processing of lexical tokens, one may conclusively assume that this neural activation pattern underlies increased lexico-semantic processing of task-irrelevant (but task-associated) word information.

The most notable feature of the current work is that it isolates subcomponents of neural mechanisms that underlie interference processing (i.e. interference resolution) which supposedly have been intermingled in analyses of prior Stroop or interference studies. In particular, the distinction between a motor and an attentional component may contribute to a refined comprehension of cognitive interference and related control mechanisms. Similarly, the conducted factorial decomposition analysis may provide a more fine-grained conceptualization of Stroop-interference as it pointed to the existence of different cognitive sub-processes during interference processing which have their distinct neural substrates (i.e. activation patterns).

Zusammenfassung (deutsche Fassung)

Untersuchung der neuronalen Mechanismen exekutiver Kontrolle in Situationen von kognitivem Konflikt und Konkurrenz unter Verwendung funktioneller Hirnbildgebung

Ziel der vorliegenden Untersuchung war es, mittels funktioneller Hirnbildgebung die neuronalen Mechanismen kognitiver Kontrolle in verschiedenen Situationen kognitiver Interferenz bzw. Konkurrenz zwischen aufgabenrelevanter und aufgabenirrelevanter Information zu untersuchen. Zu diesem Zweck wurde ein spezielles Aufgabenparadigma, eine „Oddball-Variante“ der klassischen Stroop-Aufgabe, entwickelt und eingesetzt. Hierbei war es Aufgabe der Probanden, präsentierte Wortstimuli anhand deren Schriftgröße per (linken oder rechten) Tastendruck (als „groß“ oder „klein“) zu klassifizieren. Neun neurologisch gesunde Probanden nahmen an der Studie teil und unterzogen sich funktioneller Kernspintomographie (fMRT), während sie die beschriebene Aufgabe bearbeiteten. Neben den generierten Bildgebungsdaten, wurden die Reaktionszeiten der Probanden auf die Stimuli registriert und analysiert. Im Wesentlichen verfolgte die Studie folgende drei Ziele:

(1) In erster Linie war es das Ziel, die neuronalen Mechanismen kognitiver Kontrolle in zwei distinkten Situationen (d.h. unter zwei distinkten experimentellen Bedingungen) kognitiver Interferenz zu untersuchen und miteinander zu vergleichen: (a) wenn Stroop-Inkongruenz – d.h. inkongruente Wortinformation von welcher angenommen wird, dass sie sog. Stroop-Interferenz auslöst – auftritt, und (b) wenn „Oddballs“ – d.h. aufgabenirrelevante, jedoch saliente und daher aufmerksamkeitsablenkende Seltenheitsereignisse – auftreten. Um eine gute Vergleichbarkeit zu gewährleisten, sollten Inkongruenz- und Oddball-Effekte in der gleichen Verarbeitungsdomäne untersucht werden, d.h. inkongruente und seltene aufgabenirrelevante Information sollten in der gleichen Stimulusdimension dargeboten werden. Entsprechend wurde neben Stroop-inkongruenten Durchgängen eine sog. „Word-Oddball“ Bedingung gebildet, die aus selten präsentierten Worten bestand. Folglich ging in beiden zu vergleichenden Bedingungen Interferenz von der Wort-Dimension der dargebotenen Stimuli aus, die im einen Fall inkongruente Information und im anderen Fall seltene Information beinhaltete. Aufgrund der Ergebnisse vorausgehender Studien bestand die Hypothese, dass die neuronalen Mechanismen, die der Lösung von Stroop-Interferenz (bestehend in der Überschreibung der vorherrschenden Reaktionstendenz, irrelevante Wortinformation zu lesen) und Oddball-Interferenz (bestehend in der Überschreibung einer

unwillkürlichen attentionalen Orientierungsreaktion) zugrunde liegen, (zumindest teilweise) sich entsprechen.

(2) Zweitens war es geplant, den Einfluss der Verarbeitungsdomäne, in welcher Interferenz auftritt, zu untersuchen, d.h. es sollten mögliche domänenspezifische Effekte der Interferenzverarbeitung bestimmt werden. Zu diesem Zweck wurden Oddball-Ereignisse (d.h. Seltenheitsereignisse), die in verschiedenen Stimulusdimensionen – und entsprechend in verschiedenen Verarbeitungsdomänen – auftreten, miteinander verglichen. Speziell wurde zusätzlich zu den beschriebenen „Word-Oddballs“ eine sog. „Color-Oddball“ Bedingung, bestehend aus selten auftretenden rotfarbigen Stimuli, realisiert, um anschließend die beiden Seltenheitsereignisse miteinander zu vergleichen. Von beiden Oddball-Bedingungen wurde erwartet, dass sie eine attentionale Orientierungsreaktion, hin zu der jeweiligen Stimulusdimension, in der das Seltenheitsereignis auftrat, auslösen, was eine Rekonfiguration der Aufmerksamkeit notwendig machen würde.

(3) Schließlich war es das Ziel der vorliegenden Arbeit, Stroop-Interferenz auf den Einfluss umschriebener Merkmale aufgabenirrelevanter Wortinformation, die als „Konfliktfaktoren“ („conflict factors“) betrachtet werden können, zurückzuführen. Speziell sollte das neuronale Substrat bzw. Korrelat der folgenden drei Konfliktfaktoren bestimmt werden: (A) Antwortinkompatibilität („*response incompatibility*“; heißt, dass Wortinformation eine nicht vereinbare oder entgegengesetzte motorische Reaktion indiziert), (B) semantische Inkongruenz („*semantic incongruency*“; heißt, dass Wortinformation in semantischem bzw. konzeptuellem Widerspruch steht, unabhängig von deren Reaktions-/Antwortbezug) und (C) Aufgabenbezug („*task-reference*“; heißt dass Wortinformation mit der aktuell zu bearbeitenden Aufgabe in semantischem Bezug steht, unabhängig von deren semantischen Übereinstimmung mit der aufgabenrelevanten Information).

Allgemein zeigten alle realisierten Interferenz-Bedingungen (d.h. Inkongruenz- und Oddball-Durchgänge) im Vergleich zu den Kontrollbedingungen erhöhte Reaktionszeiten, was die Wirksamkeit der experimentellen Manipulation in dem verwendeten Aufgabenparadigma belegt, bzw. dieses als „Interferenz-“ oder „Konflikt-Paradigma“ validiert. Entsprechend zeigten auch die Bildgebungsdaten plausible und aussagekräftige Ergebnisse in Bezug auf die vorgestellten Fragestellungen und Ziele der Untersuchung.

Ad (1) Der Vergleich zwischen Stroop-Interferenz und Interferenz, die von Word-Oddballs ausgeht, zeigte zwei distinkte Aktivierungsmuster, die nur geringfügig überlappten. Entsprechend wurde die Hypothese, dass die beiden Interferenzeffekte eine deutliche Aktivierungsüberlappung aufweisen, die im Sinne eines gemeinsamen neuronalen

Mechanismus kognitiver Kontrolle zur Interferenzlösung interpretiert werden kann, nicht bestätigt. Vielmehr kann plausibel angenommen werden, dass die Aktivierungsmuster zwei distinkte und komplementäre Subkomponenten bzw. Aspekte kognitiver Interferenz widerspiegeln, die auf verschiedene neuronale Mechanismen kognitiver Kontrolle (d.h. Mechanismen der Interferenzlösung) rekurren. Erstens zeigten die Analysen eine „motorische Subkomponente“ von kognitiver Interferenz, die sich auf Stroop-Interferenz bezieht und im Wesentlichen das Auftreten von Antwortkonflikt, ausgehend von inkongruenter Wortinformation, widerspiegelt. Zweitens zeigten die Analysen eine primär „attentionale Subkomponente“ von Interferenz, die die Fähigkeit aufgabenirrelevanter Information, effektiv Aufmerksamkeit auf sich zu ziehen (d.h. eine attentionale Orientierungsreaktion auszulösen), widerspiegelt. Während die erste Subkomponente hauptsächlich durch Aktivierungen in Hirnarealen, die mit motorischer Kontrolle und Vorbereitung in Verbindung stehen (z.B. dem prämotorischen Kortex, den Basalganglien und dem Kleinhirn), charakterisiert war, zeigte die attentionale Subkomponente Aktivierung in einem fronto-parietalen „Aufmerksamkeits-Netzwerk“, das in der kognitiv-neurowissenschaftlichen Literatur konsistent mit top-down Steuerung von Aufmerksamkeit, und speziell mit der Selektion aufgabenrelevanter Information, in Verbindung gebracht wird.

Ad (2) Die Aktivierungsmuster von Word-Oddballs und Color-Oddballs zeigten eine starke Überlappung, die vornehmlich in präfrontalen Arealen, jedoch auch in posterioren Regionen der visuellen Verarbeitung auftrat. Dieser Befund ist sehr gut mit der Annahme vereinbar, dass Aufmerksamkeitsselektion grundlegend über Manipulation, d.h. Verstärkung, der Verarbeitung aufgabenrelevanter Information in posterioren Verarbeitungsregionen neuronal funktioniert. Color-Oddballs zeigten im Vergleich zu Word-Oddballs den deutlicheren behavioralen Effekt sowie eine stärkere und umfangreichere neuronale Aktivierung. Dieser Befund kann zum einen mit dem Aufgabenkontext und zum anderen mit einer größeren Salienz (d.h. Prägnanz oder Auffälligkeit) von Farbinformation im Vergleich zu Wortinformation erklärt werden. Ein Hauptfokus der Aktivierungen war in beiden Oddball-Bedingungen eine Region im posterioren präfrontalen Kortex, die in früheren Arbeiten „inferior frontal junction“ genannt wurde. In Einklang mit früheren Studien sprechen die vorliegenden Ergebnisse dafür, dass diese Region eine zentrale Rolle bei der „top-down“ Steuerung der Aufmerksamkeit spielt.

Ad (3) Schließlich zeigte die Analyse zur „faktoriellen Zerlegung“ von Stroop-Interferenz Aktivierungsmuster, die aussagekräftige Schlussfolgerungen in Bezug auf die definierten „Konfliktfaktoren“ erlaubten. Antwortinkompatibilität war mit Aktivierung im ventralen

prämotorischen Kortex (linkshemisphärisch) verbunden, welche in diesem Zusammenhang als Indikator für bzw. als neuronales Substrat von Antwortkonflikt interpretiert werden kann. Semantische Inkongruenz zeigte spezifische Aktivierung im posterioren frontomedianen Kortex, im bilateralen insulären Kortex, in den Basalganglien und Thalamus sowie im linken postzentralen, d.h. somatosensorischen, Kortex. Es ist sehr plausibel, dass diese Aktivierungen mit verstärkter motorischer Kontrolle zur Vorbeugung falscher manueller Antworten in Verbindung stehen. Schließlich zeigte Aufgabenbezug signifikante Aktivierung im linken inferior-frontalen Kortex, im rechten superioren präfrontalen Kortex sowie im linken temporo-polaren Kortex (Temporalpol). Aufgrund zahlreicher Studien, die diese Hirnregionen mit lexikalisch-semantischer Verarbeitung in Verbindung gebracht haben, kann plausibel angenommen werden, dass dieses Aktivierungsmuster inkrementeller (d.h. verstärkter) semantischer Verarbeitung der aufgabenirrelevanten (jedoch aufgabenbezogenen) Wortinformation zugrunde liegt.

Wesentliches Merkmal der vorliegenden Arbeit ist, dass diese verschiedene Subkomponenten neuronaler Mechanismen, die der Verarbeitung (d.h. der Lösung) von Interferenz zugrunde liegen und mutmaßlich in früheren Interferenzstudien miteinander konfundiert wurden, isoliert. Speziell die Unterscheidung zwischen einer motorischen und einer attentionalen Komponente kann zu einem verbesserten Verständnis kognitiver Interferenz und darauf bezogener Kontrollmechanismen beitragen. Entsprechend kann auch die durchgeführte Analyse zur faktoriellen Zerlegung zu einer detaillierteren und präziseren Konzeptualisierung von Stroop-Interferenz beitragen, da diese Evidenz für das Vorhandensein verschiedener Subprozesse während der Interferenzverarbeitung, die ihre distinkten neuronalen Substrate (d.h. neuronalen Aktivierungsmuster) aufweisen, erbrachte.

1 Introduction

1.1 The subject area: executive function(s) and cognitive control

1.1.1 The construct: terms and descriptions

The term '*executive function(s)*' subsumes a class of mental activities (i.e. higher cognitive processes) that allow for goal-directed, intentional and flexible actions as opposed to reflexive, impulsive reactions to sensory information. In that, executive functions enable individuals to engage in independent, purposeful, and self-serving behaviors (see e.g. Barkley, 1996, 1997; Pennington et al., 1996). The mental regulation and coordination of behavior in accordance with goals or intentions is also unified under the term '*cognitive control*' or '*executive control*' which has been conceptualized as emanating from an executive system as a basic neurocognitive control device or instance (e.g. Baddeley, 1986, 1990; Norman & Shallice, 1980). Executive control has been associated with multiple and dissociable cognitive processes, among the major ones are *response inhibition* permitting impulse control, *attentional selection* which is essential for resistance to distraction, *verbal* and *non-verbal working-memory*, *mental calculation*, and *delay of gratification*.

Deficits in executive control have been classically associated with acquired damage to the prefrontal cortex. Baddeley (1986) coined the term '*dysexecutive syndrome*' (DES) to describe dysfunctions of the central executive in patients who suffered prefrontal lesions. The classic frontal syndrome is characterized by attentional and comprehension deficits, increased distractibility, and problems to master new types of task, i.e. to pursue goal-directed action in new or unexperienced situations (Rylander, 1939). In other words, patients suffering from DES lack flexibility and the ability to control their processing resources which becomes obvious in disorganized actions and strategies for everyday tasks. Important to note, more recent findings strongly suggest that executive dysfunctions are not specific to frontal lobe damage, as it may likewise arise from damage to interconnected cortical and subcortical brain structures or from more diffuse brain damage.

Closely related to the concept of cognitive or executive control is the frequently used term "*task-set*". The appropriate accomplishment of a task – i.e. the pursuit of a given behavioral goal – requires an adequate configuration of mental resources. The adequate mental configuration state has been called "*task-set*" or "*procedural schema*" (Monsell, 1996). In a

similar sense, the term “*attentional set*” comprises all cognitive representations involved in the attentional selection of task-relevant stimuli and/or responses (Corbetta & Shulman, 2002).

1.1.2 Top-down vs. bottom-up processing

“Top-down” and “bottom-up” have become widespread expressions for two basic and antagonistic levels of cognition. While top-down processing comprises higher levels of cognitive functioning mainly corresponding to executive control (see [1.1.1](#)), bottom-up processing primarily reflects lower levels of cognitive functioning mainly related to sensation and perception. Top-down cognitive processes are commonly described as goal- or conceptually driven and accordingly mainly depend on cognitive representations. Bottom-up cognitive processes, on the other hand, are conceived as sensory- or data-driven and accordingly to primarily depend on incoming perceptual information.

Important to note, adaptive human behavior in a changing environment requires both kinds of cognitive processing, “top-down” and “bottom-up”, and therefore imposes antagonistic requirements on agents’ control system. While conceptually-driven top-down processes should promote attentional selection and behavioral stability, bottom-up processing should provide agents with behavioral flexibility and responsivity to significant changes in the environment that occur outside the current focus of attention. Hence, top-down and bottom-up processes fulfill complementary roles in the control of adaptive behavior. Taken together, effective cognition requires a context-sensitive “just-enough” calibration of endogenous control that is sufficient to protect an ongoing goal-directed action from distraction (e.g. not looking up at every little noise in the environment), that however does not compromise the flexibility allowing the rapid execution of another behavior when appropriate (e.g. when the sound appears to be a cry for help or a warning) (see Monsell, 2003).

1.1.3 Dilemmas in cognitive control

Thomas Goschke (e.g. Goschke, 2003) described the antagonistic requirements on action control – i.e. the complementary roles of top-down and bottom-up processes – during goal-directed action in terms of two control dilemmas.

(1) *The selection-monitoring dilemma*. When pursuing a certain behavioral goal, agents have to select task-relevant information and inhibit distracting task-irrelevant information in order to prevent crosstalk and interference (Allport, 1989). On the other hand, however, it would

not be adaptive if attentional selection operated so rigorously as to suppress irrelevant information completely. Rather, it is equally important to monitor the environment for potentially significant information, even if this information is not relevant for an ongoing action. This “background monitoring” attentional function is highly adaptive as it enables an organism to process irrelevant information to a degree that allows to recognize threats or opportunities outside the current focus of attention that are related to its goals and needs.

(2) *The maintenance-switching dilemma.* Goals and goal-directed actions have to be maintained and shielded from competing responses, so as to promote behavioral stability and the pursuit of long-term goals (Kuhl, 1985). On the other hand, however, an organism has to stay able to interrupt an ongoing action in the case of significant changes in the environment. For instance, people have to be capable to respond to the unexpected appearance of smell of burning with a fast switch from an ongoing behavior (e.g. doing crossword puzzles) to a totally different behavior (e.g. using a fire drencher or flight).

1.2 Interference in cognitive processing: cognitive conflict and attentional competition

1.2.1 The construct: descriptions and working definitions

One central purpose of the executive control system is to overcome crosstalk or interference in cognitive processing and thereby to enable the agent to maintain adequate performance in the face of effective distraction (see e.g. van Veen & Carter, 2005). Accordingly, in order to investigate control processes, it is a major strategy to collect behavioral and neurobiological measures of cognitive performance during situations of interference that are construed to evoke the processes (i.e. the neurocognitive mechanisms) of interest. Regarding the experimental implementation (i.e. operationalization) of cognitive interference, different task paradigms have been developed (see [1.2.2](#)). The following working definition should provide a theoretical conception of cognitive interference and thereby outline commonalities of different tasks or operationalizations of cognitive interference.

*Working definition: **cognitive interference** consists of interference from task-irrelevant information occurring in the attentional background on the processing of task-relevant information that occurs in the current focus of attention.*

According to the given definition, to select task-relevant over task-irrelevant information – as an essential aspect of attentional functioning – may be thought of as core process in the resolution of cognitive interference. Specifically, during the resolution of cognitive interference or conflict, top-down attentional control provides a bias favoring the processing of task-relevant information over that of task-irrelevant information (see MacDonald et al., 2000; Weissman et al., 2005).

According to the processing level at which cognitive interference occurs, one can distinguish three basic kinds of cognitive interference:

(1) **Response-conflict.** Response-conflict – also referred to as motor conflict – denotes interference at the motor level of cognitive processing, and is defined as the co-activation of incompatible response tendencies, or similarly, as competition between a correct and an incorrect response (e.g. Botvinick et al., 2001; Brown & Braver, 2005). In other words, during response-conflict task-irrelevant information induces incongruent, conflicting motor tendencies. For instance, response conflict may comprise interference between a required and a prepotent but inadequate response (i.e. motor action), or a stop-go conflict.

(2) **Semantic conflict.** Semantic conflict, as inherent in the term itself, occurs at the semantic level of cognitive processing and comprises interference or crosstalk between simultaneously occurring diverging or incongruent (i.e. contradictory) mental representations. In other words, during semantic conflict task-irrelevant information induces incongruent, conflicting semantic representations. Important to note, conflicting semantic representations are not necessarily associated with incompatible motor actions so that semantic conflict can occur independently of motor conflict. For instance, semantic conflict may comprise conflict between different color representations, different shapes, different terms, different numbers, or other contradictory semantic units.

(3) **Competition.** The term competition denotes an “early” interference effect that occurs at the attentional level of cognitive processing. Thereby, task-irrelevant information draws attentional resources away from task-relevant information, and thus competes with task-relevant information for priority in processing (e.g. Milham et al., 2003a). As discussed by others (e.g. Frith, 2001; Milham et al., 2003a), the perceptual features of a task-irrelevant stimulus or stimulus aspect (e.g. its brightness or color) can increase its salience relative to a task-relevant stimulus or stimulus aspect, thereby favoring its processing and allowing associated representations to effectively compete for priority in processing. Noteworthy, during competition, task-irrelevant information interferes without necessarily being

incongruent at either the semantic or motor level, so that competition can occur independently of conflict.

[For an experimental distinction between response-conflict and semantic conflict see e.g. van Veen & Carter (2005), and for a distinction between conflict and competition see e.g. Milham et al. (2002) and Milham & Banich (2005)].

The presented kinds of interference may be arranged in an hierarchical order – with response-conflict on first place, semantic conflict on second, and competition on third/last – wherein “higher” interference effects comprise “lower” ones. Specifically, task-irrelevant information that is associated with an incompatible motor action (i.e. that induces an incompatible response-tendency), as a rule, is also or primarily associated with (i.e. induces) an incongruent semantic representation. Hence, response-conflict can be conclusively conceptualized as to imply semantic conflict. Similarly, to induce incongruent semantic representations, task-irrelevant information, in the first place, has to effectively draw attention (i.e. has to interfere at the attentional level), so that conflict conclusively premises competition. In other (simple) words, if task-irrelevant information remains unnoticed, it won't be able induce conflict.

Whether task-irrelevant information induces (any kind of) interference or not, may be conclusively attributed to circumscribed properties of task-irrelevant information. Accordingly, in the present work, properties of task-irrelevant information that potentially lead to cognitive interference are conceived as so-called ‘*conflict factors*’.

*Working definition: **conflict factors** are properties of task-irrelevant information that potentially lead to cognitive interference.*

With the latter definition, two further assumptions are associated:

- (1) different conflict factors may lead to different interference effects, and
- (2) different conflict factors can occur simultaneously and hence may lead to different interference effects simultaneously.

The current work focuses on three conflict factors: (**A**) *response-incompatibility* (denotes that task-irrelevant information indicates an incompatible or opposed motor response), (**B**) *semantic incongruency* (denotes that task-irrelevant information is semantically incongruent, i.e. conceptually contradictory, independent of its response-eligibility), and (**C**) *task-reference* (denotes that task-irrelevant information is semantically related to the task-set, independent of its semantic concordance with the relevant information). These conflict factors can be conclusively related to different interference effects. Response-incompatibility can be thought

to induce response-conflict whereas semantic incongruency can be construed to produce semantic conflict. Finally, as task-irrelevant information that is semantically related to the task at hand assumably draws attention to a higher degree, task-reference as conflict factor can be conceived to lead to attentional competition between task-relevant and task-irrelevant information.

Generally, as a theoretical construct, cognitive interference is no observable entity. In the study of interference, two behavioral performance measures are generally conceived as hallmark or indicator for the occurrence of cognitive interference:

- (a) prolonged reaction times (RTs), construed to reflect the time costs associated with the implementation of additional control processes as remediate action, and
- (b) enhanced error rates (ERs), construed to reflect incomplete or deficient control processes that failed to resolve interference.

The following subsections present experimental task paradigms that allow for an operationalization (i.e. experimental implementation) of the presented theoretical constructs, and therefore to investigate the behavioral and neurobiological correlates of interference so as to characterize and understand cognitive control .

1.2.2 Experimental-psychological paradigms of cognitive control and interference: the tasks, their basic findings and theoretical concepts

1.2.2.1 Task-switching paradigm: interference due conflicting task-sets

Task-switching paradigms are applied to experimentally model the frequent shifts between different (cognitive) tasks as they are required in every day life. Accordingly, task-switching paradigms are well suited to investigate (the behavioral and neurobiological correlates of) cognitive processes that underlie the configuration and reconfiguration of task-sets. In a task-switching experiment, subjects perform two (or more) alternating tasks. Each of the implemented tasks requires subjects to focus attention on one certain aspect or attribute (i.e. dimension) of the presented target stimuli (e.g. color, size, or shape of geometric objects), while values of the dimensions are mapped with different responses, mostly button presses. Basically, with respect to the response that has to be given on a trial at hand, the currently irrelevant dimension can be congruent (i.e. mapped to the same response), incongruent (i.e. mapped to the opposite response) or neutral (i.e. non-mapped) which yields three basic experimental conditions: congruent, incongruent and neutral trials. Importantly, the two (or

more) tasks of a task-switching paradigm impose antagonistic requirements on participants' attention as the attribute or aspect that has to be focused in the one task has to be inhibited in the other task, and vice versa. Consequently, attentional sets (i.e. task-sets) get into conflict or competition and have to be shielded against each other which forces subjects to retain a consecutive high level of cognitive control. For instance, Monsell and collaborators (Monsell et al., 2003) presented subjects with single digits while they had to classify the targets by a left or right button press as odd or even in the one task (odd-even task), and as greater or smaller than five in the other (high-low task). Gruber and collaborators (e.g. Gruber & Goschke, 2004; Gruber et al., 2006) adopted a task-switching paradigm in which subjects are presented with colored tube figures while they have to focus on either color or shape of the target stimuli in order to select the correct response (left or right button press). There are several methods to indicate a subject which task has to be performed on the current or upcoming stimulus (see e.g. Rogers and Monsell, 1995; Monsell, 2003). In the *alternating-runs paradigm*, tasks alternate every N trials, where N is constant and predictable so that the trial sequence tells the subjects when to switch to the other task. In *cued task-switching paradigms*, tasks (i.e. task switches) are unpredictable, and a task cue that appears either immediately before or simultaneously with the target indicates the relevant stimulus dimension. This paradigm allows for manipulating the cue-target interval (CTI) – also referred to as stimulus-onset asynchrony (SOA) – and thus to investigate preparation effects in task switching (e.g. Gruber et al., 2006).

The major behavioral finding in task-switching paradigms are *switch costs*, also called *task repetition benefit* (e.g. Wylie & Allport, 2000; Schneider & Logan, 2005). Generally, responses after a task switch (i.e. responses on so-called “switch trials”) take longer and are more error-prone as compared to responses after a task repetition (i.e. responses on so-called “repeat trials”). Interestingly enough, switch costs after incongruent trials appeared to be prolonged as compared to switch trials after congruent trials (e.g. Goschke, 2003). This finding can be explained by the conflict-triggered control hypothesis of Botvinick and colleagues which assumes that response conflict leads to enhanced inhibition of the distracting stimulus dimension and the corresponding task-set, referred to as “conflict-triggered goal-shielding” (Botvinick et al., 2001). The inhibition of the competing task-set might still persist on the subsequent trial, and accordingly following task-switches should be additionally challenging in that they require to overcome the persisting inhibition (see also Goschke, 2003).

Generally, task repetitions are considered to benefit from the fact that the relevant task-set is already in place. Specifically, switch costs in terms of RT prolongation (i.e. the difference in RT between task repetitions and task alternations) are commonly construed as direct measure of the duration of the executive control process to implement the appropriate (and to disable the “other”) task-set (Monsell, 1996; Monsell, 2003). In a comprehensive series of studies, Allport and colleagues (e.g. Allport et al., 1994; Allport & Wylie, 1999; Wylie & Allport, 2000) provided strong evidence for switch costs being essentially influenced by proactive interference or priming effects, and thereby contradicted, at least in part, the common interpretation of switch costs as representing task-set reconfiguration (see also Schneider & Logan, 2005). Main findings suggestive of a significant contribution of priming effects to switch costs comprise enhanced and instable RTs on repetition trials (which gradually decay back to baseline in sequences of consecutive repetition trials), (increased) “reverse Stroop interference” (i.e. interference from incongruent color on word reading) after task switches, “residual switch costs” (i.e. switch costs that still occur after a extensively long preparation interval), asymmetrical switch costs in the Stroop paradigm (in terms of higher switch costs for the word task, which is the “easier” task, compared to the color task; see [1.2.2.2](#)), and enhanced switch costs when the preceding task uses incongruent stimuli or the same stimuli as the task to which participants have to switch. The listed findings have in common that they strongly suggest that proactive interference (i.e. persisting activation) in terms of priming of the inadequate task-set (also called ‘task-set inertia’) or inadequate responses (due to established short-term stimulus-response bindings) essentially contributes to the emergence of switch costs.

1.2.2.2 The Stroop paradigm: interference due to incongruent lexical word information

The color-word Stroop task (Stroop, 1935/1992; MacLeod, 1991a) is a landmark experimental paradigm in cognitive psychology and cognitive neuroscience and arguably the most widely used and cited demonstration of interference in cognitive processing (MacLeod, 1991b; Roelofs, 2003). Basically, during Stroop task performance, subjects are presented with color-word stimuli that are printed in varying ink color, while their task is to name (or respond to) the color and thereby to ignore the word’s lexical identity. In Stroop’s original task version (Stroop, 1992/1935), subjects dealt with two different cards, an experimental and a control card (representing an experimental and a control condition), each containing 100 target items. The experimental card depicted color words in an incongruent color (e.g. the word BLUE in red ink color) while the control card contained rectangles printed in the same varying ink

colors as the word stimuli. The task instruction was for both conditions the same: to respond as quickly as possible naming the ink color of every item thereby leaving no error uncorrected. The critical measure was the time it took subjects to go through the items of one card. The difference between the condition means – with longer processing times for incongruent words compared to rectangles – was reckoned to be a measure of interference, referred to as *Stroop effect* or *Stroop interference*. The found incremental effect was uncommonly substantial ranging about 70% and has appeared to be highly replicable in terms of both pattern and, interestingly enough, absolute times (MacLeod, 1991a). Basically, Stroop-interference can be adequately described as in the following working definition.

*Working definition: **Stroop-interference** comprises interference from task-irrelevant and incongruent semantico-lexical information on the processing of some other task-relevant information – mostly color – so that agents have to override the predominant response tendency to read and respond to word meaning in order to maintain adequate performance.*

From Stroop's initial work to our days, the primary task version has been extended and modified in several respects. First, the presentation modus is now mostly computerized which allows for a measured consecutive presentation of single items. The major advantage hereby is that reaction times can be taken item-wise, timed from the onset of the stimulus to the subject's response, and that false responses can be easily excluded. In the card version, in contrast, processing time is taken across all items of one condition (i.e. one card) and therefore represents an ambiguous "all in" measure as correct and false responses thereby get intermingled. Furthermore, single-item stimulation avoids distraction from previous or following stimuli that are simultaneously visible in the card version.

Second, in modern task adaptations the response modality is mostly manual rather than verbal, using key presses instead of overt verbal responses. Concretely, in manual tasks different response fingers are defined and each assigned to a certain color, requiring, for instance, a right-hand middle finger key press in response to red stimuli and a right-hand index finger key press in response to blue stimuli. Manual response modality is especially favored in functional neuroimaging studies, because verbal response may yield unfavorable movement artifacts in the imaging data. Moreover, the colored rectangle control stimuli of Stroop's initial task version generally has been replaced by control stimuli made up of keyboard characters, for example rows of colored Xs. Also, in more recent works, scientists did not content themselves with only two experimental conditions as Stroop did, but rather

created further trial types. Klein (1964) was among the first who compared multiple conditions and thereby unleashed the potential of the paradigm. He compared naming the colors of rows of asterisks, meaningless non-words, color-related words (e.g. grass or sky), incongruent color words not among the ink colors to be named (incongruent response-eligible trials) and incompatible color words in the response set (incongruent response-eligible trials). Dalrymple-Alford & Budayr (1966) introduced congruent trials in which ink color and word meaning correspond to each other. It has been argued that Stroop avoided this condition taking into account that subjects may switch to word reading when presented with a series of congruent stimuli which would make this condition incomparable to the others (MacLeod, 2005). The Stroop task has also been adopted as task-switching paradigm in which subjects alternate between color naming and word reading in response to the targets (e.g. MacDonald et al., 2000).

Behavioral findings on the Stroop paradigm and corresponding explanation accounts (for neuroimaging findings see subsection [1.3](#)). Basically, the *Stroop interference effect* denotes the phenomenon that color naming is much slower for incongruent trials as compared to control trials (see above). This effect still persists even after thousands of trials (MacLeod, 1998). Stroop interference is generally thought to be a hallmark of competition or conflict between cognitive processes in which the (highly facilitated) default tendency to read and react to a presented word must be overridden in order to respond to ink color. Most important, interference within the paradigm appears to be asymmetrical with interference from an incongruent color in the word task being negligible or even absent, that means that there is no (or only a small) “*reverse Stroop effect*”. A widespread account, the *relative-speed-of-processing explanation*, attributes this finding to the fact that word information is processed at higher velocity than color information. This account, however, is challenged by several empirical findings. For instance, Glaser and Glaser (1982) compensated for the time advantage of word reading by introducing stimulus onset asynchronies (SOAs) in their experimental design. They observed that even if an incongruent color patch is presented sufficiently before a to be read color word, still no reverse Stroop effect occurs. Dunbar and MacLeod (1984) took an inverse approach and delayed word reading by presenting subjects with word stimuli in upside down position or in backward order. Stroop interference, however, was unmodified by these manipulations. Taken together, the reported findings suggest that processing velocity is not the crucial factor in the emergence of interference asymmetry during Stroop task performance.

Another account, the *differential practice explanation*, attributes interference asymmetry during Stroop-performance to the extensive training of reading skills during socialization. However, several studies showed that extensive training on color naming does not yield a reverse Stroop effect. Furthermore, young children and older adults exhibit the largest interference scores (e.g. Schiller, 1966), suggesting that control ability rather than reading automation plays a major role. Besides interference, several studies also observed facilitation due to congruent words within the color task, while facilitation in general does not reach the extent of interference (e.g. MacLeod, 1998; Glaser & Glaser, 1982). Of note, color-related words (e.g. sky or grass) also yield interference, but not as much as real color words (e.g. blue or green), commonly referred to as *semantic gradient* (Dalrymple-Alford, 1972). Studies which used the manual task version showed a *response* or *task set effect* in that response-eligible color words (i.e. words that denote response-mapped colors) yielded stronger interference (a stronger effect on RT) compared to response-ineligible color words (e.g. Proctor, 1978; van Veen & Carter, 2005).

1.2.2.3 Oddball tasks: interference due to low-frequency events

During oddball tasks, cognitive interference emanates from unexpected low-frequency events, so called oddballs. Specifically, oddballs – as investigated in the current work – consist of infrequent task-irrelevant deviations that occur outside the current focus of attention, that therefore may be referred to as ‘task-irrelevant oddballs’.

Note: The use of the term ‘oddball’ in the context of cognitive interference might be somehow ambiguous, as originally low-frequency events have been investigated as targets rather than distractors in vigilance or so-called target detection tasks. Low-frequency events in target detection tasks might be adequately termed ‘task-relevant oddballs’ as opposed to ‘task-irrelevant oddballs’ to which the present work refers. For an unambiguous, clear distinction between task-relevant and task-irrelevant oddballs, target detection experiments and their findings will be presented below in this subsection.

If salient enough, unexpected low-frequency events capture attention and lead to an orienting response that results in an unintended attentional switch. It has been repeatedly shown that when task-irrelevant information occurs infrequently it attracts attentional resources to a greater extent and thereby impairs the processing of task-relevant stimulus information (e.g. Schröger & Wolf, 1998; Berti & Schröger, 2001). Important to note, oddball events yield

interference (in terms of performance deterioration) without necessarily being incongruent or incompatible with task-relevant information at either the semantic or motor level. Thus, oddball interference can be expected to occur at a pure attentional level and hence may be conceived a particular kind of attentional competition (see [1.2.1](#)). It has been repeatedly suggested that low-frequency events lead to an involuntary orienting-response which serves to direct attention to potentially important changes in the environment (e.g. Goschke, 2003; Gruber & Goschke 2004). This process may be thought of as part of a highly adaptive function of background monitoring that takes into account possible threats or opportunities occurring outside the current focus of attention (see [1.1.2](#)). On the other hand, however, orienting responses to novel stimuli may interrupt a currently required attentional set, and consequently the agent may have to override the automatic attentional switch in order to maintain goal-directed action.

Orienting responses and the mismatch negativity. Involuntary attention shifts have been originally described and explained by the *orienting-reflex (OR) theory* (Sokolov, 1963). This theory assumes that repetitive sensory features of the environment get represented in a neuronal model while sensory deviations from this model yield the OR. Thus, the theory postulates a neural stimulus-change detection mechanisms. Näätänen with collaborators (e.g. Näätänen, et al., 1978; Näätänen, 1990/1992) investigated stimulus-change detection for the auditory domain. He found a frontocentral negative event-related potential (ERP) component N2 that is reliably elicited by any discernible change in the physical features of a repetitive sound. In accordance with the OR theory, Näätänen interpreted this so-called *mismatch negativity* (MMN) as the neuronal substrate of an automatic cortical change-detection process in which a difference is found between the current input and a memory trace representation of a regularity. Moreover, Näätänen (1990) postulated that the MMN is involved in triggering a signal for attention switching after the perceptual detection. In line with Näätänen's assumption, there is converging evidence that the neuronal process eliciting the MMN is associated with involuntary attentional switching (Escera et al., 1998). For instance, Schröger (1996) found substantial performance deterioration after MMN-eliciting task-irrelevant tones, while this effect was strengthened for decreasing frequency of occurrence of the deviant auditory stimuli.

While the MMN is well defined in the auditory domain, the question arose whether it also exists in the visual modality. Pazo-Alvarez and colleagues (Pazo-Alvarez et al., 2003) reviewed relevant studies and provided convincing evidence for a visual MMN homologue.

Task-relevant oddballs. Important to note, the term “oddball” has been initially developed in the study of attentional vigilance, in so-called target-detection paradigms (e.g. Sutton et al., 1965). Here, subjects detect and respond to infrequent target events that are embedded in a series of repetitive distractor events. On the one hand, task-relevant oddballs are not covered by the working definition of cognitive interference given above that basically presumes that interference necessarily emanates from task-irrelevant, unattended events or information (see [1.2.1](#)). Therefore, task-relevant oddballs are actually not part of the current work’s subject matter. On the other hand, however, processing of task-relevant oddballs (targets) and task-irrelevant oddballs (distractors) may plausibly engage common neural mechanisms, as both include the detection of rare events (Bledowski et al., 2004). The detection of infrequent targets consistently appeared to evoke a prominent ERP component – following the target onset after 300-600ms and with its maximum over the parietal scalp – referred to as P300 or P3b (Smith et al., 1970). The P3b is preceded by another small positive component that peaks over the frontal lobe and that has been called the P3a or “novelty P3” (Courchesne et al., 1975; Knight, 1996). P3a has also been found in studies using task-irrelevant oddballs and has been interpreted to reflect an initial automatic orienting response to rare and salient events, independent of their behavioral relevance. Hence, the P3a plausibly reflects the neural substrate of the ‘processional overlap’ of task-relevant and task-irrelevant oddballs, assumably consisting of an attentional orienting response.

Nevertheless, the main interest of the current work are task-irrelevant oddballs that substantially impair task-relevant stimulus processing as indexed by RT prolongation. Studies showed that interference by task-irrelevant oddballs evokes the MMN and the P3a as well as a subsequent negative component in the 400-600ms range, called *re-orienting negativity* (RON; see Schröger & Wolf, 1998). In this context, MMN, P3a and RON may be assumed to reflect a processional succession comprising change detection, attentional switching and subsequent re-orienting to task-relevant information. Thus, in conjunction, the presented ERP components yield an theoretical conceptualization of oddball interference that can be summarized as in the following working definition.

*Working definition: **Oddball interference** denotes an involuntary orienting response (attentional switch) to rare and task-irrelevant events that requires subjects to perform a subsequent re-orienting of attentional resources (to task-relevant information) in order to meet current task requirements and to maintain adequate performance.*

Milham and colleagues (Milham et al., 2003a) were among the first who investigated oddball interference and incongruity effects (i.e. cognitive conflict) in the same experimental paradigm, while they focused in particular on prefrontal cortex's (PFC's) involvement. Specifically, they employed an oddball variant of the Stroop paradigm (see [1.2.3.2](#)) that justified a direct comparison of the influence of low-frequently occurring task-irrelevant word information (i.e. oddball interference) on the one hand, and the influence of response-incongruent task-irrelevant word information (i.e. Stroop-interference) on the other. They report both, an activation overlap as well as an activation dissociation in prefrontal cortices which led them to propose a regional subdivision along the anterior-posterior axes of PFC's attentional control function. According to Milham and colleagues (see also Brass & von Cramon, 2004), the posterior inferior PFC in the vicinity of premotor cortex – which was activated for both oddball and incongruity trials – is primarily involved in manipulating posterior regions to ensure selection of task-relevant information, whereas more anteriorly located regions within inferior PFC – which were exclusively activated for incongruent trials – are primarily responsible for biasing maintenance and selection of task-relevant information in working-memory. [As this study is of special relevance for the current work, it will be presented in more detail in a following subsection (see [1.3.5](#).)]

1.2.2.4 Other interference paradigms

The *Flanker-task* is another quite common cognitive task that involves responding to a centered stimulus that is surrounded by peripheral distracting stimuli, so-called flankers. The original task was introduced by Eriksen and Eriksen (1974) and involved the presentation of a string of five letters while the middle letter served as target and the four lateral letters as irrelevant, distracting flankers. In a suchlike task, subjects might be instructed, for instance, to press a left key if the central letter is a T and a right key if the central letter is an M. Basically, the paradigm allows to operationalize two experimental conditions: during compatible/congruent trials, the four flankers map to the same response as the target (e.g. MMMMM), while during incompatible/incongruent trials the flankers map to a different response (e.g. TTMTT). In another prevalently used version of the paradigm, the centered target stimulus consists of an arrow which is flanked by distracting arrows that point in either the same (i.e. congruent) or other (i.e. incongruent) direction (e.g. Botvinick et al., 2001; Fan et al., 2002).

In the *spatial conflict* or *Simon task*, target stimuli are presented in different locations of the visual field. Thereby, the location of the target could be compatible or incompatible with the

response to be given (i.e. on the same or opposite side as the mapped key press), and also could be neutral (i.e. presented in a center position). The Simon effect involves conflict between target location and the direction of the matching response as it becomes obvious in prolonged RTs on incompatible trials of spatial tasks (Simon & Berbaum, 1990; Gerardi-Caulton, 2000).

1.3 Neuroimaging studies on attentional control and cognitive interference: major findings and related theoretical assumptions

The investigation of the neural correlates of cognitive control and attentional selection has become a major research focus in cognitive neuroscience. Numerous fMRI studies using various paradigms have been carried out to delineate the brain regions that govern the detection and resolution of cognitive conflict and interference. In the following subsections, neuroimaging studies' results and related theoretical assumptions that are relevant for the current work's purposes will be presented.

1.3.1 Conflict resolution and neural mechanisms to impose an attentional set for task-relevant information

It is a quite common assumption that neural structures involved in attentional selection form two distinct systems, one anterior and one posterior (Posner & DeHaene, 1994). Thereby, the anterior system is considered to be responsible for executive processes (i.e. the exertion of cognitive control) while the posterior system is primarily involved in the selection of target information according to the anterior system's top-down influence. In the same sense, LaBerge (2005) distinguished the *control* of attention in frontal areas from the *expression* of attention in posterior cortical areas, especially parietal cortices. Accordingly, many studies have suggested that attentional selection basically depends on neural activity in a fronto-parietal network wherein frontal operations of executive control are directed at parietal areas where activity can influence the early processing of incoming sensory stimulation (e.g. Hopfinger et al., 2000; Corbetta et al., 2002; for reviews see Corbetta & Shulmann, 2002; LaBerge, 2005).

It has been repeatedly proposed that attentional selection in general and resolving cognitive conflict or interference in particular works through manipulating, i.e. boosting, activity in those brain areas which are specialized for processing the sensory information which has to be

attended (e.g. Cohen et al., 1990; Desimone & Duncan, 1995; Cohen et al., 1996; Wojciulik et al., 1998; Banich et al., 2001; Weissman et al., 2005; Egner & Hirsch, 2005). In this context, it is generally assumed that prefrontal regions “alert” those posterior processing areas that are involved in processing the task-relevant feature. In a classic study using positron emission tomography (PET), Corbetta collaborators (Corbetta et al., 1991) provide strong support for the existence of a suchlike neuro-attentional mechanism. They consecutively presented subjects with abstract objects that could be distinguished by three visual attributes (i.e. stimulus dimensions): shape, color, and size. Subjects performed three different object matching tasks while in each task they had to refer to one specified dimension and to ignore the two remaining ones. As central finding, neural activity was modulated in different posterior processing regions depending on the visual attribute that has to be attended. For instance, when subjects had to make the matching decision based on color, enhanced brain activation was observed in lingual fusiform regions that previously have been implicated in color perception (e.g. Zeki & Marini, 1998).

While amplification of neuronal responses seems to play an important role in attentional selection, there is likewise evidence for inhibitory suppressive mechanisms that substantially contribute to attention regulation (Kastner et al., 1998; Kastner & Ungerleider, 2000). Thus, both target amplification and distractor inhibition appear to be feasible neural mechanisms of attentional functioning, and the question arose whether neural mechanisms of processing cognitive interference (i.e. conflict resolution) comprise both or solely one of them. Recently, Egner and Hirsch (2005) reported findings of an fMRI study that substantiate the notion of target amplification as primary mechanism in conflict resolution. Specifically, they employed a modified Stroop task using face stimuli as targets and thereby manipulated trial-by-trial levels of conflict and cognitive control. The analyses of the fMRI data showed enhanced activity in the fusiform face area (FFA) – an extrastriate visual region specialized for face processing (Kanwisher et al., 1997) – under high control conditions when faces served as task-relevant information, but not when they served as task-irrelevant distractors. Furthermore, Egner and Hirsch conducted connectivity analyses using the psychophysiological interaction (PPI) approach (Friston et al., 1997; see [4.5.3](#)). The results showed enhanced coupling between FFA and the dorsolateral prefrontal cortex (DLPFC) – a candidate region for the implementation of cognitive control thought to provide neural signals biasing extrastriate visual processing (MacDonald et al., 2000; Kerns et al., 2004; see [1.3.3](#)) – under high control conditions, again only when faces served as targets, but not when they served as distractors. Taken together, the findings strongly suggest that attentional

amplification of target features serves as primary mechanism in conflict resolution, and findings provide no evidence for a mechanism that suppresses interference-inducing distractors.

1.3.2 Segregated but interacting frontoparietal attentional systems for top-down and bottom-up processing

In previous subsections two principle and antagonistic levels of cognitive processing are described which are thought to provide complementary attentional functions: top-down (i.e. conceptually-driven) processing and bottom-up (i.e. sensory-driven) processing (see [1.1.2](#) and [1.1.3](#)). Corbetta & Shulman (2002) reviewed a vast body of neuroimaging studies and thereby came up with a neuroanatomical model that relate these cognitive functions with two segregated but interacting neural systems, represented by a dorsal and a ventral frontoparietal network.

(a) Dorsal frontoparietal network for top-down control

The first system is represented by a largely bilateral dorsal frontoparietal network that includes parts of the intraparietal cortex and superior frontal cortex, specifically the frontal eye fields (FEF). Corporate activation in intraparietal and superior frontal cortices in relation to voluntary attentional orienting have been reported for both spatial attention – i.e. attention to different locations in the visual field (e.g. Gitelman et al., 1999; Kastner et al., 1999) – and feature attention – i.e. attention to different object features like color, shape or motion (e.g. Shulman et al., 1999; Shulman et al., 2001) – and beyond that have been related to motor preparation and motor attention (e.g. Snyder et al., 1997; Kawashima et al., 1995; Rowe et al., 2000). Based on the reviewed findings, Corbetta and Shulman conjecture that top-down (i.e. goal-directed) selection of both stimuli and motor actions is implemented by a dorsal frontoparietal attention network. In particular, this neural system could be construed to implement whole task-sets by relating relevant sensory representations to relevant motor representations.

(b) Ventral frontoparietal network for bottom-up processing

As functional counterpart to the dorsal frontoparietal network, Corbetta and Shulman propose a ventral frontoparietal network, strongly lateralized to the right hemisphere, that mainly comprises the temporoparietal cortex referred to as ‘*temporoparietal junction*’ (TPJ) and the inferior frontolateral cortex. This system is thought to provide an alerting mechanism that detects and orients attention to sensory changes in the environment that are of potential

behavioral relevance. Therefore, the system works as a '*circuit breaker*' for the dorsal system, directing attention to salient events. Accordingly, studies showed activation in the TPJ and inferior PFC in response to unexpected sensory changes across different modalities, while activation was additionally strengthened when sensory changes were task-relevant (e.g. Downar et al., 2000; Downar et al., 2001).

Taken together, Corbetta and Shulman (see Corbetta & Shulman, 2002) carried out a neuroanatomical model of attentional control that relate the complementary mechanisms of top-down and bottom-up processing to circumscribed cortical structures that are organized in segregated but interacting neural networks. In their complementary function, these neural systems may afford to meet the antagonistic requirements on attention as they are imposed during goal-directed action in a changing environment (see sections [1.1.2](#) and [1.1.3](#)).

1.3.3 The anterior cingulate cortex's function in cognitive control: selection-for-action versus conflict detection

The anterior cingulate cortex (ACC), situated on the medial surface of the frontal lobes, is commonly believed to be critically involved in cognitive control and the regulation of attention (Posner & Peterson, 1990; D'Esposito et al., 1995; Posner & DiGirolamo, 1998). Numerous neuroimaging and electrophysiological studies revealed ACC activation during the performance of a variety of cognitive tasks that require selection between stimulus attributes and/or response alternatives. In particular, the ACC appears consistently activated in studies using the Stroop task when incongruent trials are contrasted against neutral or congruent trials (e.g. Pardo et al., 1990; Carter et al., 1995; MacDonald et al., 2000; Fan et al., 2003; Mitchell, 2005). Based on this vast body of evidence, it is widely accepted that the ACC plays a prominent role in cognitive control, however, beyond this consensus, it still remains a matter of discussion how the ACC exactly contributes to conflict processing. Basically, one can distinguish two competing theoretical accounts of ACC's function in conflict processing, the '*selection-for-action*' account and the '*conflict monitoring*' account.

(1) The selection-for-action account

The '*selection-for-action*' account (Posner & DiGirolamo, 1998; Petersen et al., 1999) postulates that the ACC directly exerts top-down attentional control by selecting information or objects in the environment as triggers for action. Thus, according to this account, the ACC is thought to represent an executive neural instance which imposes or implements a required attentional set. In particular, the account presumes that ACC helps to resolve cognitive

conflict or interference by increasing processing resources towards task-relevant information so as to limit interference from task-irrelevant information. In a recent fMRI study, Weissman and collaborators (Weissman et al., 2005) sought to examine the role of the dorsal/caudal ACC in conflict processing, and thereby they wanted to test whether this neural structure actually contributes to conflict resolution in a direct manner by boosting attentional resources towards relevant events. For this purpose, they adopted a cued task-switching paradigm wherein participants had to attend either the local or the global aspect of hierarchical letter stimuli (e.g. a big letter *S* composed of smaller letters *H*), referred to as ‘*global/local task*’. The authors report that greater ACC activity during distraction was associated with reduced behavioral measures of interference. Furthermore, greater ACC activity was associated with cues to attend local features compared to cues to attend global features, while attentional demands are enhanced when subjects have to attend local features (Weissman et al., 2003). Weissman and colleagues interpreted their results in line with the selection-for-action account as indicating that ACC is basically involved in focusing attention on behaviorally relevant stimuli, especially when behavioral goals are threatened by interfering distractors.

(2) *The conflict monitoring account*

Against the selection-for-action account, other authors have put forward the ‘*action-monitoring theory*’ or ‘*conflict-monitoring account*’ (Botvinick et al., 1998; Carter et al., 1998). This theory is based on the general assumption that cognitive control has not only a regulative dimension by which top-down influence is exerted, but also to comprise an evaluative function that monitors information processing for current control demands and that thus allows for appropriate, context-sensitive control adjustments (Botvinick et al., 2001). The theoretical assumption of a complementary evaluative mechanisms in cognitive control appears to be necessary because without it, control conceptions remain “humuncular” assuming an independent, self-guided instance to implement control (Botvinick et al., 2001; van Veen & Carter, 2002). Importantly, the regulative function and the evaluative function are thought to be represented by distinct but interacting neural structures. Specifically in the conflict monitoring account, neural activity in the ACC is construed as neural substrate of the evaluative function. Hence, according to this account, the ACC does not exert top-down control but instead detects and signals the occurrence of conflict in information processing. Importantly, the ACC response to conflict is thought to trigger subsequent shifts in cognitive control (i.e. to trigger enhanced control efforts), which serve to reduce conflict in subsequent performance. Thereby, the adaptation of control efforts as proper executive control activity is attributed to other neural systems, primarily located in the frontolateral cortex, that refer to

ACC's signal. MacDonald and colleagues (MacDonald et al., 2000) provided key evidence for the conflict monitoring account. Using a task-switching version of the Stroop task, MacDonald and colleagues observed a double dissociation of activity in ACC and dorsolateral prefrontal cortex (DLPFC). While ACC was selectively engaged by conflict emanating from incongruent stimuli, DLPFC was selectively engaged in task-preparation, especially in response to color cues indicating the more demanding color task. Importantly, there was no enhanced instruction-related activity in ACC for color cues and no enhanced response-related activity in DLPFC for incongruent stimuli. Based on their findings, the authors argue that DLPFC translates ACC's signal into the implementation of executive control.

The study, however, was strongly criticized for the extremely long (12.5 sec) cue-target interval – included to clearly separate preparation-related from response-related processes – that precludes a straightforward interpretation of the reported results. Weissman and colleagues (see Weissman et al., 2004; Weissman et al., 2005) convincingly argued that the long cue-target interval putatively reduced the likelihood that participants oriented their attention at the time of cue presentation and, in turn, the probability of observing activity in ACC which was related to focusing attention during the cue presentation. Hence, from this perspective, the conflict-related ACC activity in the MacDonald study may still reflect processes that focus attention on task-relevant stimuli. Generally, long trial durations arguably lower the overall task difficulty and the level of conflict which, in turn, reduces the degree to which control execution is necessary to achieve an adequate level of performance. Hence, the long cue-target interval (i.e. long trial duration) in the MacDonald study might have significantly diminished the probability of observing greater (control-related) ACC activity for color cues (that indicate the putatively more difficult task) as compared to word cues.

The conflict monitoring hypothesis builds up on an earlier 'performance monitoring' account that assumes that ACC activation represents the neural substrate of an error detection system or mechanism. It is a well-established finding that ACC transiently activates in association with the commission of errors. Error-related ACC activation has been investigated initially in ERP studies where it takes the form of a transient negative potential referred to as '*error-related negativity*' (ERN) (e.g. Falkenstein et al., 2000). Later, fMRI studies corroborate neurophysiological findings and likewise reported error-related ACC engagement (e.g. Kiehl et al., 2000; Menon et al., 2001). Studies led to the postulation of a neural error-detection system that gets activated when a comparison between representations of the appropriate (i.e. correct, intended) and the actual response yields a mismatch. This system has been localized

in the frontomedian wall leading to the error detection hypothesis of the ACC. The error detection model was challenged by an fMRI study which demonstrated ACC activation during error trials as well as during correct trials involving high response competition (Carter et al., 1998), while this study marks the origin of the conflict monitoring account.

As an integrative account, Brown & Braver (2005) put forward the '*error-likelihood hypothesis*' which accounts conflict and error detection as special cases of a more general performance monitoring mechanism. In this model, the ACC does not detect errors or conflict per se but more generally provides a prediction signal of error probability as an anticipation of a reduction in reward. In a quite similar sense, it has been proposed that the ACC monitors for the earliest indication for increased attentional demands in order to prompt additional control efforts to prevent negative future outcomes (Holroyd & Coles, 2002).

1.3.4 Common neural activations across different situations of cognitive interference

Prior to the current investigation, Oliver Gruber and collaborators conducted a study running under the working title "Perseus" (see Gruber & Goschke, 2004; Melcher et al., 2004) that has been created within the scope of the same research program as the current investigation (priority program "executive functions" of the German Research Foundation (DFG); project title: "Dynamic interactions between complementary components of executive control"). Important to note, the findings of this fMRI study substantially inspired and influenced the development of the current investigation that in part builds up on the results and associated interpretations that will be reported in this subsection.

Essentially, the study was set out to investigate the neural mechanisms that enable humans to meet the antagonistic requirements on attentional control as imposed during goal-directed action in a changing environment (see [1.1.3](#)). For this purpose, Gruber and collaborators adopted a cued task-switching paradigm using colored geometrical objects (tube figures) as target stimuli. Thereby, subjects were to classify targets according to either color or shape (providing a color task and a shape task) by either a left or right manual response consisting of button presses with the right index and middle finger, respectively. The experimental design included three basic conditions – congruent, incongruent, and neutral trials – that equally appeared in the color and the shape task. On congruent trials, color and shape were mapped to the same manual response while on incongruent trials color and shape indicated opposed responses. On neutral trials, the currently irrelevant dimension was not mapped to either

response. The behavioral data showed reliable switch costs (i.e. significantly longer RTs on switch-trials compared to repeat-trials) and a substantial effect of incongruency (i.e. significantly prolonged RTs on incongruent trials compared to neutral trials). Both behavioral effects are quite common findings in the investigation of task switching performance (see [1.2.2.1](#)) and therefore were perfectly in line with the study's prior expectations. Beyond this, however, congruent trials exhibited significantly longer RTs compared to neutral trials in the shape-task, whereas congruent trials have been expected to produce facilitation rather than interference. Retrospectively, the prolonged RTs have been conclusively interpreted to represent a mismatch-like or oddball effect, as congruent trials occurred rarely in the experimental stimulation (i.e. represented low-frequency events) as compared to the prevalent neutral trials. This difference in frequency of trial types resulted from a special design feature that had been implemented for fMRI-methodological reasons. Specifically, trials that entered into the statistical analyses – referred to as ‘critical trials’ – should be preceded by a baseline period in order to minimize the protracted effects of preceding trials on the fMRI signal, taking into account the inertia of the BOLD response. The baseline period over which the fMRI signal should recover was created by a sequence of three consecutive neutral trials that did not enter in the statistical analyses. As a side effect, this arrangement of trials caused a disproportionateness between congruent and incongruent trials on the one hand and neutral trials on the other, while the latter represented the vast majority (five-sixths of the trials were neutral and only one sixth congruent or incongruent). With regard to the shape-task, the described disproportionateness took form in a superior number of white colored stimuli, as white represented the neutral color value. Due to this, response-mapped red or blue colors on congruent or incongruent trials in the shape-task represented low-frequency events in the currently task-irrelevant dimension and therefore may be conceived as ‘task-irrelevant oddballs’ (see [1.2.2.3](#)). Accordingly, with regard to the behavioral findings, Gruber and collaborators argued that the rare occurrence of a rarely congruent color within the shape-task involuntarily captured participants' attention and led to an orienting response (i.e. attentional switch) towards the currently irrelevant color dimension. Consequently, the currently appropriate attentional set (or task set) was disrupted and had to be reestablished in order to meet the task requirements.

The analysis of the neuroimaging data revealed likewise a rather interesting finding: both the described mismatch-like effect due to rarely occurring congruent colors (represented by the contrast ‘congruent vs. neutral’) and response-conflict due to incongruent colors (represented by the contrast ‘incongruent vs. neutral’) enhanced brain activity in virtually the same cortical

network. The corresponding left-hemispherically accentuated activation pattern comprised the lateral PFC, especially loci along the inferior frontal sulcus (IFS) and precentral sulcus, the pre-supplementary motor area (pre-SMA), cortices along the intraparietal sulcus (IPS), as well as occipito-temporal cortices (see Figure 1 and Figure 2). Differences between incongruent trials and congruent trials were only quantitative in nature, with incongruent trials exhibiting stronger activations but no additional foci.

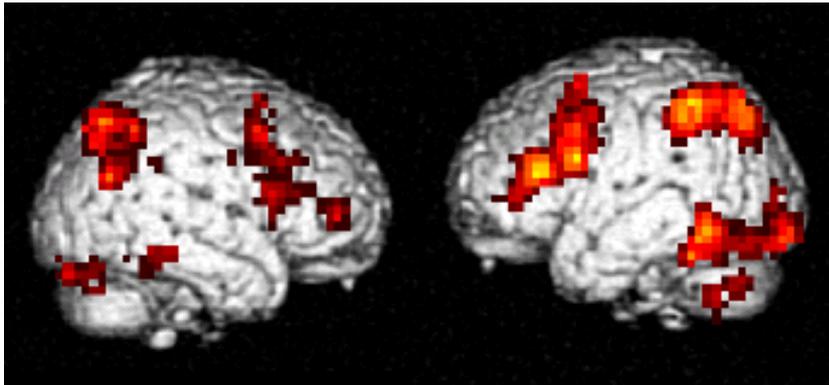


Figure 1: Neuroimaging results of the fMRI study “Perseus”. Activations evoked by rarely occurring irrelevant, incongruent colors (response-conflict). Contrast: incongruent vs. neutral.

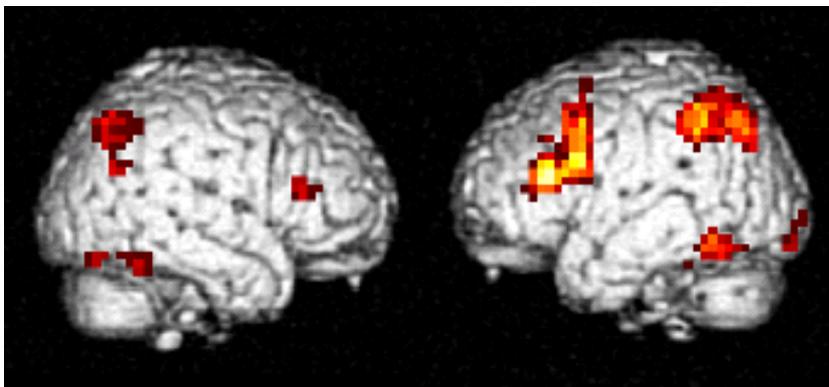


Figure 2: Neuroimaging results of the fMRI study “Perseus”. Activations evoked by rarely occurring irrelevant, congruent colors (oddball effect). Contrast: congruent vs. neutral.

In conclusion, in the study’s data, response conflict (i.e. interference at the motor level) and interference from task-irrelevant oddballs (i.e. interference at the attentional level / competition) appeared to engage the same neural activation pattern or network. A preliminary interpretation of the finding was that the neuro-attentional system may possess a background monitoring mechanisms for the occurrence of *potential* behavioral conflict (see Melcher et al., 2004). Because oddballs may indicate a potential behavioral conflict, the putative monitoring mechanisms may recruit the same control mechanisms (i.e. neural activations) in response to low-frequency events as can be observed in relation to response-incongruent trials thought to

evoke proper response conflict. However, this interpretation is somewhat compromised by the fact that the incongruent trials were equally rare as congruent trials. Consequently, incongruent trials may also have led to oddball interference in addition to response conflict, while this putative ‘procedural overlap’ between incongruent and congruent trials may have contributed to some degree to the observed activation overlap. In any case, independent of the latter objection, it is important to emphasize that response conflict during incongruent trials in the presented study did not recruit additional neural activation compared to rarely occurring congruent trials, representing ‘color oddballs’. This finding strongly suggests the existence of a general or core neural mechanism of interference processing (i.e. resolution) that is recruited across different kinds of interference occurring at various levels of cognitive processing.

Consistent with this conclusion, Zysset and colleagues reported neural activation related to Stroop-interference in a cortical network that broadly overlaps with the one that was found related to interference due to color oddballs in the above presented task-switching study. Specifically, Zysset and colleagues (Zysset et al., 2000) adopted a special version of the Stroop paradigm, the ‘Matching Stroop Task’, that was introduced by Treisman and Fearnley (Treisman & Fearnley, 1969). In this paradigm, on each trial subjects are presented with two color word stimuli simultaneously while they have to match the ink color of the first (i.e. above-standing) word – whose lexical meaning could be incongruent, congruent, or neutral with respect to the attended color, providing three experimental conditions – to the lexical meaning of the second (i.e. below-standing) word. This second word is always printed in neutral black. Accordingly, Stroop-interference takes place during the processing of the first item and is separated from response-related processes taking place during the subsequent matching decision. Therefore, response-related processes can be kept constant across all experimental conditions and hence Stroop-interference in this paradigm is investigated at a purely semantic level. Specifically, the Stroop interference contrasts (i.e. “incongruent against congruent” or “incongruent against neutral”) in this paradigm do not intermingle semantic conflict and response/motor conflict as it might be the case in more traditional task versions [for a distinction between (i.e. a separation of) response conflict and semantic conflict in the Stroop paradigm, see van Veen & Carter, 2005]. Essentially, Zysset and colleagues reported neural activation related to Stroop-interference (revealed by the contrast “incongruent vs. neutral”) in a (fronto-parietal) cortical network (comprising of the pre-SMA, posterior IFS, IPS, and occipitotemporal cortices) that largely corresponded to the one that was found in relation to color oddballs in the task-switching study of Gruber and colleagues. Thus, considering the two presented studies in conjunction, Stroop-interference and oddball

interference – as two distinct operationalizations of interference implemented in two different studies – appear to produce essentially the same patterns of neural activation. The observed broad activation overlap conclusively suggests that both kinds of interference – Stroop-interference and oddball-interference – engage the same neurocognitive control mechanism of interference resolution. This assertion motivated the current investigation that, in part, represents a synthetic combination of the fMRI study “Perseus” and the study of Zysset and colleagues, as it examines both Stroop-interference and oddball interference simultaneously. In particular, one aim of the current work was to directly compare Stroop-interference and oddball-interference, this time operationalized within the same experimental paradigm and including the same subjects, so as to ensure high comparability (see [1.4.1](#)).

1.3.5 The inferior frontal junction area: a prominent activation focus in cognitive control

One prominent focus of the described shared activation pattern was situated in the posterior inferior frontolateral cortex, in the vicinity of the junction of the inferior frontal sulcus and precentral sulcus. Due to its anatomical location within the transition zone of premotor and prefrontal cortex, this region has been previously termed the ‘*inferior frontal junction area*’ (IFJA) (Brass & von Cramon, 2004). A recent series of brain imaging studies converge to strongly suggest that the IFJA plays a pivotal role in cognitive control (for review, see Derrfuss et al., 2005). Thereby, it is important to note that the IFJA, given its posterior location within frontolateral cortex, is not part of the mid-dorsolateral PFC (mid-DLPFC) to which the previous literature pointed most consistently as the crucial fronto-lateral area in cognitive control (e.g. Petrides, 2000; MacDonald et al., 2000). One may assume that the special interest in the mid-DLPFC during the last few years may have led to a neglect of the IFJA and even sometimes to an inappropriate labeling of the IFJA as DLPFC. In other words, the primary role attributed to the mid-DLPFC in cognitive control may be due to the fact that consistent activation in the IFJA has been ignored (see Brass et al., 2005).

The neuroanatomical location of the IFJA has been well defined both in terms of its coordinates in the standard stereotactic space (Derrfuss et al., 2004) as well as in terms of its cytoarchitectural structure (Amunts et al., 2004). In contrast, the use of the term DLPFC appears ambiguous and inhomogeneous and hence can not be referred to a distinct neural structure (Gruber, 2005).

Neural activity in the IFJA has been reported for a wide range of attentionally demanding cognitive tasks and conditions (for review, see Derrfuss et al., 2005). For instance, the inferior lateral PFC has been related to task-set preparation (Brass and von Cramon, 2004; Gruber et al., 2006), cognitive set shifting (e.g. Konishi et al., 1998; Dove et al., 2000; Pollmann et al., 2000; Braver et al., 2003; Brass and von Cramon, 2004), and response inhibition (Konishi et al., 1999; Konishi et al., 2003). Furthermore, and most interestingly for the current investigation, the IFJA has been related in particular to the processing of Stroop interference (e.g. Leung et al., 2000; Banich et al., 2000/2001; Zysset et al., 2000; Milham et al., 2003a) and task-irrelevant oddballs (e.g. Milham et al., 2003a; Gruber & Goschke, 2004).

Taken together, studies provide strong evidence that the IFJA plays a crucial role in cognitive control involving task-set management, i.e. the activation of task-representations (see Derrfuss et al., 2004/2005) and the selection of task-relevant over task-irrelevant information (see Milham et al., 2003a), the putative core process in the resolution of cognitive conflict and interference (see [1.2.1](#)). Moreover, studies not only help to describe the IFJA's putative cognitive function, but also show that the IFJA can be functionally separated from other frontolateral areas, specifically from mid-DLPFC. For instance, Milham and collaborators (Milham et al., 2003a) provided evidence for a functional dissociation along the anterior-posterior axis in attentional functioning of the lateral PFC. In particular, they conducted an event-related fMRI study in which they sought to delineate the influence of rare and task-irrelevant word information – i.e. task-irrelevant word oddballs – on prefrontal cortex's involvement in cognitive control. Furthermore, they wanted to determine whether response-incongruent word meaning (i.e. Stroop-interference) produces activation in areas similar or distinct from those sensitive to word oddballs (i.e. oddball interference). As a main result, both word oddball trials and Stroop-incongruent trials enhanced brain activity in the posterior frontolateral cortex corresponding to the IFJA. More anterior areas referring to the mid-DLPFC, on the other hand, were selectively activated by Stroop-incongruent stimuli, and not by oddballs. Based on these results, Milham and colleagues concluded that the posterior inferior PFC (i.e. the IFJA) is primarily involved in manipulating posterior regions to ensure the selection of task-relevant information. The latter assertion is additionally supported by the fact that the posterior lateral PFC is anatomically strongly interconnected with posterior processing regions (Barbas & Mesulam, 1981; Petrides & Pandya, 1984; Petrides & Pandya, 1999). In contrast, more anterior regions within inferior lateral PFC are thought to be primarily responsible for biasing maintenance and selection of task-relevant information in working-memory. Brass and von Cramon (Brass & von Cramon, 2004) proposed a functional

dissociation along the anterior-posterior axis within lateral PFC that is quite similar to the one of Milham colleagues that has been presented above. Brass and von Cramon conducted an fMRI study on task-set preparation and based on their findings conjectured that while more anterior prefrontal regions might be mainly involved in maintaining and manipulating working memory content, the posterior frontolateral cortex, i.e. the IFJA, would provide context-related updating of task representations, i.e. the implementation of relevant task-sets.

1.4 Aims and hypotheses of the current investigation

Generally, the current work sought to investigate behavioral and neurobiological correlates of cognitive performance during conditions of interference and conflict in order to elucidate neural mechanisms of cognitive control. Thereby, the main interest was in two situations of interference, Stroop-interference and oddball interference, which should be examined as operationalized within the same task paradigm. The following subsections present related aims and expectations in more detail.

1.4.1 Behavioral effects of interference

Primarily, it was expected that conditions of cognitive interference produce substantial behavioral effects, i.e. that interference trials exhibit prolonged reaction times (RTs) as compared to non-interference or baseline trials. Specifically, RTs should serve as validation criterion to demonstrate that the implemented experimental manipulation was indeed effective in inducing the processes of interest, Stroop-interference and oddball interference. Thereby, during trials of Stroop-interference, participants would have to overcome the predominant tendency to respond to incongruent word meaning as response-eligible but task-irrelevant dimension (see [1.2.3.2](#)). On the other hand, oddball conditions were expected to evoke an attentional orienting response which participants would have to override in order maintain adequate performance (see [1.2.3.3](#)). Both types of interference were expected to incur time costs that become obvious in prolonged RTs of the respective trial types.

1.4.2 Neural effects of interference

Generally, regarding the neuroimaging data, it was expected that experimental conditions of interference evoke activations in neural structures that have been previously related to

cognitive conflict and interference (see [1.3](#)). Moreover, it was explicitly expected that different interference conditions exhibit a striking activation overlap as hallmark or indicator of a common or core neural mechanism in cognitive control to resolve interference (see [1.3.4](#)). Activation overlap was expected for both anterior, prefrontal areas (thought to underlie ‘attentional control’) and posterior, parietal and temporo-occipital areas (thought to underlie ‘attentional expression’), forming an anterior and posterior attentional system, respectively (see [1.3.1](#)). In particular, the inferior frontal junction area was expected to exhibit prominent activation across all interference conditions, as this structure has been shown to play a pivotal role in the implementation of task-sets as well as in the selection of task-relevant over task-irrelevant information (see [1.3.5](#)). Expectations may be summarized as in the following general hypothesis:

General hypothesis: While different kinds of cognitive interference can be well distinguished – both conceptually as well as operationally – they may share a common neural mechanism (i.e. core process) of interference resolution and accordingly may share common neural substrates.

This assumption was motivated by prior studies’ findings showing the same pattern of frontoparietal activation to occur across different paradigms and conditions of interference involving Stroop-interference, oddball interference and response incongruency during task-switching (see [1.3.4](#)). This observation of common activation suggests the existence of a core neural process in interference processing that is recruited across multiple conflict situations or levels of interference. Generally, during interference processing top-down attentional control provides a bias favoring the processing of task-relevant information over that of task-irrelevant information. Hence, to select task-relevant over task-irrelevant information – as a central aspect of attentional functioning – may be thought of as core process in the resolution of cognitive conflict (Weissman et al., 2005; see [1.2.1](#)).

Considered in more detail, the current investigation pursued three circumscribed goals that will be presented in the following subsections. Thereby, associated predictions in terms of experimental hypotheses will be stated.

1.4.2.1 Direct comparison of Stroop-interference and oddball-interference

First, the current investigation was set out to directly compare Stroop-interference (see [1.2.3.2](#)) and oddball interference (see [1.2.3.3](#)). Thereby, the following hypothesis was specified:

Hypothesis: The neural mechanisms that underlie the overriding of a sensory orienting response to low-frequency events (i.e. oddballs) are – at least in part – the same as the neural mechanisms that allow to resolve Stroop-interference, i.e. to override a prepotent behavioral response.

In particular, Stroop-incongruent trials, thought to evoke Stroop-interference, should be compared with word oddball trials comprising rarely occurring word-meaning. The comparison between Stroop-interference and interference from word oddballs was assumed to ensure good comparability as in both cases interference emanates from the same stimulus attribute (word meaning, including incongruent information in the one case and rarely occurring information in the other) and therefore occurs within the same processing domain.

1.4.2.2 Investigation of the influence of the processing domain from which interference emanates: color vs. word meaning

Second, the current investigation was planned to elucidate domain-specific effects in interference processing, i.e. the influence of the processing domain of the task-irrelevant information from which interference emanates. Thereby, the following hypothesis was specified:

Hypothesis: Different interference effects although occurring in distinct processing domains engage overlapping neural activation that reflects a common neural mechanism of interference resolution.

To test this hypothesis, oddball events in two different attribute dimensions referring to distinct processing domains – color and word meaning – should be created. The comparison between word oddballs and color oddballs was also assumed to ensure good comparability as the compared conditions would only differ in the dimension from which interference emanates (word vs. color) but not in the actual kind of interference (oddball interference in both cases). According to the comparison between Stroop-interference and interference from

word oddballs, it was expected that a putative common executive core process in interference processing would take form in an overlapping activation pattern.

It is a wide-spread assumption that in interference processing prefrontal areas – forming an anterior executive system – alert those posterior cortical regions that are specialized for processing the task-relevant information (see [1.3.1](#)). Accordingly, it was expected to find common activations in posterior processing areas across the compared oddball conditions reflecting the (amplified or boosted) processing of the common task-relevant attribute. However, oddball interference is conceived as orienting response to the task-irrelevant attribute in which the low-frequent event occurs (see [1.2.3.3](#)). Therefore, dissociations in posterior regions between different oddball conditions, if present, were expected to reflect the orienting response to and incremental processing of the respective irrelevant oddball dimension.

1.4.2.3 Decomposing interference during Stroop performance into different conflict factors

Finally, the current work was set out to trace back Stroop interference to circumscribed properties of task-irrelevant information that can be conceived as ‘*conflict factors*’ that trigger different interference effects (for an explanation and working definition of the term ‘conflict factor’, see [1.2.1](#)). In particular, the investigation sought to delineate the neural substrates of three conflict factors that refer to circumscribed properties of (task-irrelevant) lexical word meaning during Stroop performance: (A) ***response-incompatibility*** (i.e. word identity indicates an opposed response), (B) ***semantic incongruency*** (i.e. word identity is incongruent/contradictory, independent of its response-eligibility), and (C) ***task-reference*** (i.e. word identity is semantically related to the task-set, independent of its semantic concordance with the relevant dimension). These properties can be conclusively related to distinct kinds of interference that have been previously distinguished, specifically for Stroop-performance (see [1.2.1](#)): response-incompatibility may induce response-conflict while semantic incongruency may lead to semantic conflict, and finally task-reference may lead to competition between task-relevant and task-irrelevant information. It was expected that the neural correlates of the conflict factors reflect the occurrence of the related kinds of interference. Important to note, different conflict factors can occur simultaneously in an experimental condition, and thus single experimental conditions may intermingle different kinds of interference. For instance, it has been argued that Stroop interference contrasts, in particular the contrast “incongruent against congruent”, may intermingle conflict or

interference at the semantic level and at the motor level. In other words, as word meaning on incongruent trials is both semantic incongruent and response-incompatible, the contrast “incongruent against congruent” involve two incremental components and thus may intermingle semantic conflict and response conflict (see e.g. Zysset et al., 2001; van Veen & Carter, 2005). Following this notion, the current study sought to split activations of the Stroop contrast “incongruent against congruent” into two subgroups: (a) activations due to response-incompatibility (reflecting response conflict) and (b) activations emanating from semantic incongruency (reflecting semantic conflict). For this, it was planned to adopt the statistical principle of ‘*cognitive conjunction*’ in order to disentangle intermingled factors.

Some authors have discussed that attentional demands might be already enhanced whenever task-irrelevant information is semantically related to the current task-set due to competition between task-relevant and task-irrelevant information for priority in processing (e.g. Milham et al., 2002; see [1.2.1](#)). The current study also set out to delineate the neural substrate of this third conflict factor – here referred to as task-reference – which is inherent in both incongruent and congruent Stroop trials and might essentially contribute to the overall Stroop interference effect.

2 Methods

2.1 Data acquisition

2.1.1 Subjects / Participants

Twelve healthy and right-handed young adults have been recruited. The participant group comprised six men and six women with a mean age of 25,67 years (standard deviation: 1.88). They received a monetary payment for participating. All subjects were pre-trained a day before they underwent fMRI so as to ensure high accuracy levels in the task performance. After the preprocessing of the fMRI data three participants had to be excluded from the statistical analyses due to uncorrectable motion artifacts.

2.1.2 Neuroimaging: Functional Magnetic Resonance Imaging (fMRI)

To meet the current work's purposes, functional brain imaging should be applied. The term '*functional brain imaging*' embraces the full range of techniques by which physiological changes that accompany brain activity are ascertained or measured. Specifically, the current investigation used '*functional magnetic resonance imaging*' (fMRI), which among all functional brain imaging techniques is reckoned an especially flexible one that offers a wide range of potential applications. Furthermore, unlike other imaging techniques as '*positron emission tomography*' (PET) or '*single photon emission computed tomography*' (SPECT), fMRI is absolutely noninvasive so that a person can be imaged repeatedly without concern. Generally, the functionality of brain imaging techniques is intimately connected to the physiology that underlie neuronal activity, comprising electrophysiological, biochemical, and metabolic processes. In particular, fMRI is based on hemodynamic changes, specifically on local increases of blood oxygen (i.e. oxygenated hemoglobin) – commonly referred to as the *BOLD* (blood oxygenation level dependent) response – that follow brain activity.

2.1.2.1 Physiological basis: local increases of blood oxygenation

Brain activity broadly consists of neurotransmitter release that is accompanied by metabolic changes in neurons and glia that require energy. Energy production in the brain ultimately

depends on oxidative metabolism. Therefore, neuronal activity is accompanied by an increased local demand for delivery of oxygen that is generally met by an increased local blood flow, occurring seconds later. An increase in local blood flow following brain stimulation was firstly shown in 1890 by Charles Sherrington, who beyond this found that the relative proportion of oxygen extracted from this blood was significantly increased. In other words, the increase in oxygen delivery exceeds the increase in oxygen utilization. This disproportionate increase of oxygenated hemoglobin is especially important for the oxygen supply – i.e. the oxidative metabolism and glucose substrate utilization – of the working brain, as vascular oxygen diffusion capacities are significantly restricted (Buxton & Frank, 1997). By increasing the relative proportion of oxygenated hemoglobin in blood, the oxygen gradient between capillaries and circumjacent cells is increased and thereby helps to adapt the diffusion-limited transport to the rate of utilization. However, the thereby accompanying increase in blood flow leads only to a small increase in local blood volume. In brief, changes in the oxygenation level of the blood occur as a consequence of neuronal activity and therefore can be used as an indirect measure of excitatory input to neurons which is closely related to the cell firing rate (Logothetis et al., 2001).

2.1.2.2 Physical basis: nuclear magnetic resonance

As already evident in the term itself, MRI techniques acquire magnetic resonance. Magnetic resonance is a physical phenomenon arising from the interaction of atom nuclei that have a magnetic moment with an applied magnetic field. Nuclei of many atoms with a nuclear “spin” can behave as magnetic dipoles and accordingly can assume either a high-energy state if oriented against the applied magnetic field, or a low-energy state if aligned with the applied magnetic field. Transitions between the two energy states are associated with absorption or emission of energy in the radiofrequency range. The frequency of the energy emitted by an excited nucleus is proportional to the magnetic field at the nucleus which is primarily determined by the magnetic field applied in the imaging experiment. Generally, hydrogen nuclei perform spins around their axis which give them an angular momentum. Furthermore, as protons are positive charges, a current loop perpendicular to the rotation axis is created so that the proton generates a magnetic field. The joint effect of the angular momentum and the generated magnetic field is that protons get a magnetic dipole moment. Importantly, normally one will not experience any magnetic field from a volume of nuclei, because the magnetic dipole moments of the single protons are oriented randomly and in average equalize one another. If an external magnetic field (B_0) is applied, protons are forced to align their spins in

parallel (or anti-parallel) to the applied magnetic field with an angular frequency ω_0 , referred to as Larmor frequency. The Larmor frequency is defined as

$$\omega_0 = \gamma * B_0,$$

where γ is a constant called gyromagnetic ratio, whose value depends on the type of nucleus. That means that under a given magnetic field (B_0), the resulting resonance frequency (ω_0) is specific to the present kind of nucleus, a phenomenon which is used in ‘*spectroscopic*’ MR techniques. In MRI one apply a stationary magnetic field in order to obtain some control over the single protons which is necessary to create resonance that one can record. On the static magnetic field, magnetic pulses are superimposed that tip the net magnetization vector of the nuclear spins away from the equilibrium alignment with the applied magnetic field. Thereby, protons get from a low- to a high-energy state by absorbing energy. When a magnetic pulse ends (i.e. the energy source is switched off), a relaxation process will start immediately during which protons return to the equilibrium state by emitting the afore absorbed energy. Emitting and absorbing radiofrequency energy – which is magnetic resonance – if recorded can be processed into a MR image. The relaxation process in resonance can be described by different time constants which are used to generate contrast in MRI. The biological parameters T1 and T2 are tissue dependent and therefore yield the possibility to separate different tissue types in the human brain. During BOLD-fMRI, T2* effects are recorded which are associated to the fact that deoxyhemoglobin is magnetic whereas oxygenated hemoglobin is not. Following, the three time parameters used to generate MRI contrasts are presented in a bit more detail.

(A) T1 period: spin-lattice relaxation time

How efficient the spin relaxation occurs is determined by the interaction of the spins with their surrounding environment referred to as ‘*lattice*’. During the spin-lattice relaxation, the high-energy state protons exchange energy with circumjacent protons which results in thermal energy. This process has a rate constant $1/T_1$, where T1 is the so-called ‘*spin-lattice relaxation time*’ and represents an exponential process. If excitation pulses are applied more rapidly than allows for full relaxation, then the proportion of spins that can be excited is lower and the resonance signal decreases. This provides one source of imaging contrast, as the T1 for a water molecule depends on the chemical environment, which varies for different parts of the brain, for instance is longer for water in cerebrospinal fluid (CSF) than for water in tissue. By shortening the inter pulse delay (or TR = time of repetition) in a pulse sequence, signal from parts of the brain with a shorter T1 relaxation time will increase relative to signal from parts of the brain with longer T1 relaxation time. Excited spins regain 66% of their

equilibrium magnetization over one T1 period (and 95% over three T1 periods). In principle, if one could observe the signal from an single resonating nucleus, it would decay with a time constant equal to T1.

(B) T2 period: spin-spin relaxation time

Generally, during MRI one is observing emissions from huge numbers of spins simultaneously while single nuclei continuously experience small local changes in magnetic field. These shifting fields allow an exchange of energy between nuclei which leads to a loss of coherence in the phases of their resonance emissions. This loss of coherence leads to an exponential loss of intensity for the summed resonance signal from all of the nuclei together, which is described by the so-called ‘*spin-spin*’ or T2 relaxation time. The T2 is an intrinsic property of nuclei in a particular chemical environment. By increasing the delay before signal detection in a pulse sequence (i.e. lengthening the TE = echo time), signal from tissue with a longer T2 (e.g. gray matter) will be increased relative to tissues with shorter T2 (e.g. white matter).

(C) T2 relaxation time*

The rate of decay of signal is faster if there are local field gradients that the molecules can diffuse through over the time course of a single TE. As molecules move into regions of different local fields, their resonance frequencies change slightly, lowering the coherence of the nuclear spins. This leads to a more rapid decay of the net signal. In the presence of local magnetic field inhomogeneities, the rate of signal decay is expressed by the T2* relaxation time. In regions of rapidly changing local magnetic fields, the T2* can be substantially shorter than the T2. This provides yet another mechanism for generating contrast that is especially important for functional imaging. T2 refers to changes of the signal inside a vessel whereas T2* refers to changes of the signal in the tissue immediately surrounding a vessel. Changes in both T2 and T2* relaxation times for intra- and extravascular water become greater with higher imaging magnetic field strength. However, for intravascular water the increase is linear and for extravascular water the increase is exponential (Ogawa et al., 1993). Consequently, at higher magnetic field strength the contribution of contrast change in the brain tissue increases relative to that from blood in vessels (Gati et al., 1997).

2.1.2.3 Linking hemodynamic changes to magnetic properties

In blood oxygenation level dependent (BOLD) fMRI, the imaging contrast arises as a consequence of changes in the local magnetic susceptibility following the higher ratio of oxyhemoglobin to deoxyhemoglobin in local draining venules and veins that accompanies

neuronal activation (Ogawa et al., 1993). In contrast, during perfusion MRI – a method much less sensitive as BOLD fMRI – there is a direct measuring of the blood flow response. Oxyhemoglobin has no substantial magnetic properties, i.e. is diamagnetic, but deoxyhemoglobin is strongly paramagnetic (Pauling & Coryell, 1936). Thus, variation in the relative proportion of oxyhemoglobin leads to changes in magnetic susceptibility. In BOLD fMRI, deoxyhemoglobin serves as intrinsic paramagnetic contrast agent that has only little effect on T1. Accordingly, in case of local increases of oxygen level, T2 weighted gradient-echo EPI (*‘echo planar imaging’*) sequences and T2* weighted spin-echo EPI sequences, which are both highly susceptibility sensitive, will show an increase in signal (see below [2.1.2.5](#)).

2.1.2.4 Relevant parameters of an MR-sequence

The nature of a signal from an uncontrolled relaxation process would make it impossible to separate the influence of the different parameters, and accordingly different hemodynamic states or tissue types could not be distinguished. Therefore, one exerts control over the relaxation process by introducing a dependency of one of the biological parameters in the recorded signal. In other words, the MR-signals are *weighted* upon one of the biological parameters. To create controlled relaxation processes one changes the way in which the spins are excited and observed using different *‘pulse sequences’*, e.g. a T2-weighted spin-echo sequence or the Inversion-Recovery method for T1-weightened images. There are three principle parameters of pulse sequences that can be varied to generate contrast:

- (a) the *‘flip-angle’* (extent to which the net magnetization vector of the nuclear spins is tipped away from the equilibrium alignment with the applied magnetic field, varied by the energy per pulse put into the sample),
- (b) the rate at which pulses are applied (the *‘pulse rate’*) which increases as the TR (*‘time of repetition’*) interval becomes shorter (the shorter the TR, the less time is allowed for T1 relaxation), and
- (c) the time that is waited before the resonance is detected after excitation, referred to as TE (*‘echo time’*) (nuclei that have a shorter T2 will relatively less signal, the longer the TE value used).

2.1.2.5 EPI: Echo planar imaging

‘Echo planar imaging’ (EPI) is a data acquisition strategy that allows for a very rapid data acquisition. The EPI method was originally described by Mansfield (1977). The basic concept

of this method is that multiple rather than single image lines are acquired after spin preparation. Conventional imaging sequences record one slice of a volume each phase encoding step so that the time required to acquire a complete volume is determined by the product of TR and the number of slices. In contrast, during EPI sequences all slices of a volume are acquired in a single TR period. Hence, what distinguishes the EPI sequence from other sequences is that all the signal information needed to reconstruct an entire image is obtained in a “single shot”. Therefore, successful EPI requires that the time take to read a single image line is significantly smaller than $T2^*$ which necessitates strong gradient fields with rapid switching capability. There are two principal EPI sequences, ‘*gradient-echo*’ EPI and ‘*spin-echo*’ EPI. In both sequences, the readout of multiple slices occurs from a single ‘*free induction decay*’ (FID), while the signal decay occurs with the time constant $T2$ for gradient-echo EPI and with the time constant $T2^*$ for spin-echo EPI.

2.1.2.6 Imaging location: the generation of MR-images from MR-signals

In order to generate MR-images, it is necessary to assign defined MR-signals to circumscribed locations in the brain. Methods to image the location of resonating nuclei in a sample in principle all use the same idea of “spatial frequency encoding”. Thereby, one employs small magnetic field gradients that are superimposed on the larger homogeneous static magnetic field of the imaging magnet. The relative positions of molecules along the smaller gradient field are measured simply from differences in resonance frequency, as a given point in space is equivalent to a given frequency.

2.1.2.7 Time course of the BOLD response

Generally, the time course of the BOLD response in a given region of activation is complex, and different time points of the time course may provide distinct information. BOLD time course is best defined for the primary visual cortex (Ernst & Hennig, 1994). Generally, there is an initial small decrease referred to as ‘*early dip*’ that evolves over the first second. The early dip is hypothesized to arise from the rapid deoxygenation of capillary blood following the greater oxygen utilization associated with greater synaptic activity. Over the next two till four seconds, there is a progressive increase in signal intensity due to the increase in blood flow which exceeds the increase in local oxygen utilization so that the oxyhemoglobin / deoxyhemoglobin ratio increases. For a simple stimulus that does not cause physiological habituation, the signal change is maintained on a relatively constant level for the period of stimulation (Bandettini et al., 1997). After the stimulation stops, both blood flow and the

oxyhemoglobin / deoxyhemoglobin ratio decay. Particularly, after the stimulation stops, the BOLD signal decreases over a few seconds to a level below the initial baseline, referred to as ‘undershoot’, from which it recovers slowly over a further few seconds. Altogether, even for brief stimulus presentations, it takes about 12 to 18 seconds from the onset to the final return of the signal intensity to baseline.

2.1.2.8 FMRI data acquisition in the current investigation

Imaging in the current work was performed on a 3-T MRI scanner (Bruker Medspec 30/100; Bruker BioSpin MRI GmbH, Ettlingen, Germany) with a standard birdcage headcoil. Nineteen axial slices (voxel size 3 X 3 X 5 mm³, distance factor 0.2) were positioned in parallel to the AC-PC plane (AC = anterior commissure; PC posterior commissure), covering the entire brain. Prior to the functional scans, anatomical MDEFT (modified driven equilibrium Fourier transform pulse sequence) slices and EPI-T1 (echo-planar imaging, t1-weighted) slices were obtained. These measurements were followed by three runs of a single-shot, gradient EPI sequence (TR 1.75 s, TE 30 ms, flip angle 90°, field of view 192 mm, 64 X 64 matrix) each acquiring a total of 535 image volumes. Functional brain imaging was synchronized with stimulus presentation by means of ERTS (Experimental Run Time System, Version 3.11, BeriSoft Cooperation, Frankfurt am Main, Germany). In a separate session, a high-resolution structural scan (3D MDEFT) was obtained for each subject. Importantly, there was no whole-numbered or fixed relation between image acquisition and presentation rate, so that the hemodynamic response was sampled at different time points (i.e. was oversampled). Thus, there was no need to insert jittered inter-stimulus intervals for an exact estimation of the hemodynamic response.

2.1.3 Experimental setting and paradigm

2.1.3.1 Stimulation

The stimulation was computer-based using the software package ERTS that run on a PC in the scanner control room. While subjects laid in the scanner tube (supine position; head-first), stimuli have been projected by a video beamer onto a small mirror that was positioned above the subjects’ head in a distance that ensured clear and relaxed vision.

2.1.3.2 Task paradigm

For the current work's purpose, a special version of the Stroop paradigm (see [1.2.2.2](#)) was adopted in which participants classified colored word stimuli according to font size rather than according to ink color as it is the case in most other task versions. Subjects had to classify targets by a forced choice – left or right – button press response using either the middle or index finger of the right hand. They were instructed to make a left response if the word stimuli appeared in big font size and to make a right response for small font size stimuli. Unlike other Stroop paradigms, there was no task related to word meaning, and it was explicitly pointed out to the subjects that they would have to ignore it for good performance. Participants were further instructed to be fast but accurate. Because the current work should be directly linked up with a prior neuroimaging study called 'Perseus' (see [1.3.4](#)), the implementation of a color oddball condition – consisting of a rarely occurring task-irrelevant and response-ineligible stimulus color – was of primary interest. On the other hand, it was impossible to operationalize color oddballs within the commonly used color Stroop task, because here color serves as task-relevant (i.e. response-indicating) dimension and accordingly cannot assume a response-ineligible value. Therefore, the described 'size Stroop task' was created in which all conditions of interest could be implemented and compared. Nevertheless, the experimental task also included color Stroop trials and accordingly consisted of a 'cued task-switching paradigm' (see [1.2.3.1](#)) in order to keep the overall attentional demands on a higher level as during single task performance.

Note: In particular, due to the task switches the cognitive system was expected to keep a higher flexibility and therefore a higher distractibility which should reinforce the oddball effect which actually is a distraction effect. During single task conditions, on the other hand, control efforts to shield the one relevant dimension are sustained and thus, assumably, get very strong so that there is only little distractibility (and hence probably a reduced sensitivity for oddballs) which is achieved at the cost of an attenuated cognitive flexibility.

During the color-task, blue ink color was mapped to a left response and yellow ink color to a right response. It is important to emphasize that color task trials did not enter into the statistical analyses and that hence the current work's results presentation is restricted to the size-task that comprised all conditions of interest (see also below, [2.2.3](#)).

In the beginning of each trial a cue lasting for 500 ms signaled which task had to be performed on the upcoming stimulus. A big letter F for "Farbe" (which is the German translation for "color") indicated the color-task, while a big letter G for "Größe" (which is the German translation for "size") indicated the size-task. Targets appeared after a short delay of

250 ms and lasted for 750 ms. RTs were recorded within a time period of 1500 ms with begin of the target presentation till the onset of the next cue. Thus, the total trial duration was 2250 ms (see Figure 3).

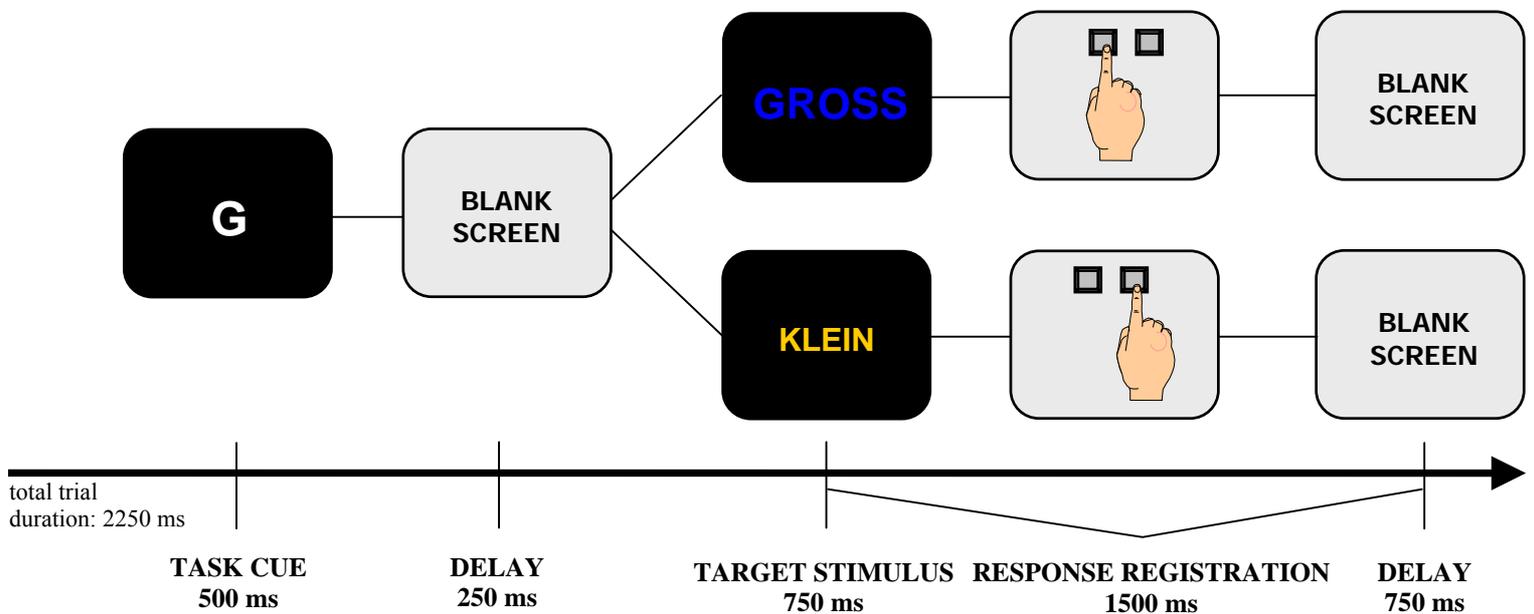


Figure 3: Task paradigm and trial constitution.

2.1.3.3 Design and experimental conditions

Six basic experimental conditions of interest were created that occurred in both tasks equally frequent so that the experimental design was completely symmetrical. During *congruent (CO) trials*, word meaning matched the value of the currently relevant dimension, for instance the word BIG printed in big letters in the size-task, or the word BLUE printed in blue color in the color-task. During *response-eligible incongruent / response-incongruent (RI) trials*, word meaning denoted the opposed-mapped value of the currently relevant dimension, for instance the word SMALL printed in big letters in the size-task, or the word BLUE printed in yellow color in the color-task. During *response-ineligible incongruent / semantically incongruent (SI) trials*, word meaning was likewise incongruent with the currently relevant dimension but – in contrast to the RI condition – was not mapped to any response, i.e. was response-ineligible. Specifically, for the color-task the color word GREEN and for the size-task the size-associated word BROAD were presented, which are both response-ineligible (i.e. not part of the task-set). *Word-oddball (OW) trials* comprised rarely occurring words that were semantically unrelated to the tasks, while the vast majority of trials comprised response-

eligible or response-ineligible color or size words. Ten oddball words were implemented comprising of KALT, WARM, LAUT, BRAV, VOLL, LEER, SPÄT, FRÜH, HELL, and FERN (English translations: cold, warm, good (in terms of “well behaved”), full, empty, late, early, bright, and distal) which were matched for word length and syllable number with the prevalent word stimuli. Each oddball word was presented with a frequency of one in every 112 trials (~0.9%) while each response-eligible and response-ineligible color word or size word appeared with a frequency of one in every six trials (~17%). Furthermore, another low-frequency condition was created in which the oddball event occurred in the currently irrelevant dimension and that therefore differed for the color-task and the size-task. Regarding the size-task, *Color-oddball (OC) trials* consisted of rarely occurring red colored stimuli while the vast majority of stimuli appeared in yellow or blue ink color. Regarding the color-task, *Size-oddball trials* consisted of rarely occurring mid-size stimuli while the vast majority of stimuli appeared in small or big font size. Important to note, the color-task could not include color oddballs (i.e. OC trials), since the oddball color red was response-ineligible and participants consequently could not have given a response on OC trials presented during the color-task. Similarly, the size-task could not include size oddballs because the mid-size value, just like the red color, was response-ineligible. Both, red colored and mid-size stimuli appeared with a frequency of one in every 32 trials (~3%) while each other color and size value (blue and yellow as well as big and small font size) appeared on virtually every second trial (~49%). Noteworthy, while Color-oddballs and Size-oddballs occurred with a different frequency, the frequency ratio (i.e. relative frequency) of rare values (i.e. oddball values) to prevalent values was roughly identical for the color and the word dimension (~1:17). Oddballs were distributed within the stimulation sequence in a pseudorandomized manner that ensured that no oddball trial followed another oddball trial, and furthermore that oddball trials were preceded by every other trial type equally often. Size-oddball trials – just as all other trials of the color-task – did not enter into the statistical analyses (see [2.2.3](#)) and were implemented only to keep the design balanced (i.e. symmetrical) across the two tasks. *Neutral / semantically unrelated (SU) trials* included the normally frequent and response-ineligible color word “GREEN” in the size-task and the normally frequent and response-ineligible size word “BROAD” in the color-task, so that word meaning was semantically unrelated to the task at hand. SU trials should primarily serve as contrast condition for the oddball conditions – Color-oddballs and Word-oddballs – and therefore were also termed ‘*oddball control condition*’.

Important to note, all trial types mentioned so far – with the exception of Color- and Size-oddballs – were ‘*basically congruent*’, i.e. color and size were mapped to the same response. But, there were also ‘*basically incongruent*’ trials during which color and size were mapped to opposed responses. Specifically, basically incongruent trials comprised big font size combined with yellow color or small font size combined with blue color. However, basically incongruent trials were not relevant for the current work’s purposes and had been included for task-strategic reasons only, in order to prevent subjects from focusing on the same dimension in both tasks, which would be a “successful” strategy if only basically congruent trials were presented. Each trial type, with the exception of the oddball trials, appeared 36 times in both the color-task and the shape-task. Word-oddballs trials appeared 10 times in both tasks, while Color-oddballs and Size-oddballs appeared 36 times in the size task and 36 times in the color task, respectively. Switch trials, i.e. the first trials after a task switch, were excluded from the analyses because cognitive (re)configuration processes during task switches are not part of the current work’s purposes. The experimental stimulation was fully counterbalanced in that every color value, size value and word as well as their combinations occurred equally often within the experimental course, while the included low-frequency (i.e. oddball) events represented intended exceptions. Altogether, the experimental stimulation included 1168 trials which participants performed on three separate blocks of equal length. Conditions were presented in a counterbalanced order, generated to ensure that each trial type followed every other trial type equally often. Labelings of the experimental conditions and associated stimuli are depicted in the tables of Figure 4 and Figure 5 for the color-task and the size-task, respectively.

color-task	
experimental conditions	word stimuli (English translation)
Stroop-incongruency (response-eligible)	GELB (YELLOW)
	BLUE (BLUE)
Stroop-incongruency (response-ineligible)	GREEN (GREEN)
	GREEN (GREEN)
Stroop-congruency	BLAU (BLUE)
	GELB (YELLOW)
Word-oddball	LAUT (LOUD)
	KALT (COLD)
Size-oddball	BREIT (BROAD)
	BREIT (BROAD)
Semantically unrelated / Oddball control	BREIT (BROAD)
	BREIT (BROAD)
Basic incongruency	BREIT (BROAD)
	BREIT (BROAD)

Figure 4: Table depicts condition labels and corresponding target stimuli of the color-task.

size-task		
experimental conditions	abbr.	word stimuli (English translation)
Stroop-incongruency (response-eligible)	RI	KLEIN (SMALL)
		GROSS (BIG)
Stroop-incongruency (response-ineligible)	SI	BREIT (BROAD)
		BREIT (BROAD)
Stroop-congruency	CO	GROSS (BIG)
		KLEIN (SMALL)
Word-oddball	OW	LAUT (LOUD)
		KALT (COLD)
Color-oddball	OC	GRÜN (GREEN)
		GRÜN (GREEN)
Semantically unrelated / Oddball control	SU	GRÜN (GREEN)
		GRÜN (GREEN)
Basic incongruency		GRÜN (GREEN)
		GRÜN (GREEN)

Figure 5: Table depicts condition labels and corresponding target stimuli of the size-task.

2.2 Data analysis

2.2.1 Neuroimaging data

2.2.1.1 Preprocessing of the fMRI data

Using the SPM2 software package (<http://www.fil.ion.ucl.ac.uk/spm/>), the functional images acquired were realigned, corrected for motion artifacts, slicetime acquisition differences, global signal intensity variation, and low-frequency fluctuations, normalized into the standard stereotactic space (using the MNI template) and spatially smoothed with a 9 mm and 8 mm full-width-half-maximum Gaussian kernel for group and single subject analyses, respectively. Based on the General Linear Model approach for time-series data, a design matrix was created in which the experimental conditions were modeled as different events in time and convolved with a hemodynamic response function accounting for the delay of the BOLD (blood oxygen level dependent) response.

2.2.1.2 Statistical procedures: cognitive subtraction and cognitive conjunction

Consequent to the preprocessing, the fMRI data were statistically analyzed by adopting two basic statistical principles, cognitive subtraction and cognitive conjunction, that will be presented in the following subsections.

2.2.1.2.1 Cognitive subtraction: condition contrasts

Generally, cognitive subtraction comprises the definition of an experimental condition and a baseline condition so that the two conditions differ in only one cognitive component (i.e. cognitive process), which is the one that is actually sought to be investigated. Consequently, brain regions demonstrating (stronger) increases in vascular activity associated with the experimental compared to the baseline condition are interpreted as neural substrate of the differential (i.e. incremental) component (Price and Friston, 1997). In the current investigation, t-contrasts – corresponding to one sample t-tests – were performed for each subject separately. Thereby, the computed subtractions comprised both single contrasts and interaction contrasts. Generally, single contrasts determine activations that significantly differ between two conditions of an experiment, and in the current work have been defined in order to delineate neural activation related to the different interference (i.e. incongruency and oddball) effects. In a second step, interaction contrasts were performed so as to compare

interference effects against each other. In particular, interaction contrasts consisted of “contrasted contrasts” in terms of chained subtractions. For instance, if one wishes to compare two contrasts A–B and C–D, the subtractive chaining to an interaction contrast would result in (A–B)–(C–D) which corresponds to A–B–C+D, taking into account rules for dissolving mathematical operator brackets. In this way, Stroop-interference was compared against Word-oddball interference and Color-oddball interference against Word-oddball interference. Thereby, each comparison (i.e. interaction contrast) was performed in both directions. Interaction contrasts should reveal areas that significantly differ between the single t-contrasts and thereby help to separate common from unique activations of the respective interference effects. For group statistics, random effect analyses (Holmes & Friston, 1998) were performed on single subject contrast images and were thresholded at $p < .005$, uncorrected. Essentially, random effect analyses identify those brain regions that are consistently activated across different subjects, while subjects are treated as random factors – giving random effect analyses their name – so that results can be generalized to the entire population to which subjects belong.

2.2.1.2.2 Cognitive conjunction: conjoint condition contrasts

In subtraction designs, one may encounter the problem that it is impossible to set an appropriate condition pair that isolates a certain component of interest. Specifically, condition contrasts may intermingle different incremental components (i.e. may confound the component of interest with other ones) so that a valid interpretation of the found pattern of differential activation as reflecting the neural substrate of the component of interest is precluded. Cognitive conjunction is in part designed to resolve this issue (Price & Friston, 1997; Friston et al., 1999). Essentially, cognitive conjunctions identify regions that are commonly activated across two (or more) contrasts. In other words, conjunction analyses identify regions in which each of two (or more) condition pairs yield differential vascular (i.e. BOLD) responses. If the conjoint contrasts share one – and only one – common incremental component (the component of interest), the delineated pattern of common activation is interpreted as reflecting the neural substrate of this component. Incremental components or cognitive operations of the contrasts other than the component of interest (i.e. confounded variables) can be disregarded without concern as long as these components are not shared by the conjoint contrasts.

Regarding the current investigation, conjunction analyses were performed by using a random-effect statistical model in which the single-subject contrast images were entered (see above,

[2.2.1.2.1](#)) and were thresholded at $p < .005$, uncorrected. Specifically, conjunction analyses were applied according to the revised statistical test introduced by Tom Nichols and colleagues (Nichols et al., 2005). This test allows for a valid conjunction interference, i.e. tests for a true logical AND, while older versions refer to an inappropriate null hypothesis for a suchlike straightforward interpretation.

2.2.1.3 Defined contrasts and contrast conjunctions

2.2.1.3.1 Single contrasts to determine interference-related activation

Three different single contrasts have been computed in order to delineate brain activations related to (1) Stroop-interference, (2) Word-oddball interference, and (3) Color-oddball interference. Ad (1): Neural activity related to Stroop-interference was determined by contrasting *response-incongruent trials against congruent trials* (RI-CO). Ad (2): Activations specific for interference emanating from Word-oddballs have been determined by the contrast *Word-oddball trials against neutral (semantically unrelated) trials* (OW-SU). Ad (3): Brain activations associated with interference from Color-oddballs were determined by the contrast *Color-oddball trials against neutral (semantically unrelated) trials* (OC-SU).

Additionally, the contrast *response-incongruent trials against neutral (semantically unrelated) trials* (RI-SU) was computed so that the neural effects of incongruity and oddballs could be compared as derived from the same baseline.

2.2.1.3.2 Interaction contrasts to determine differences between interference effects

In a second step, pairings of the considered t-contrasts have been compared by means of so-called interaction contrasts. Interaction contrasts in the current investigation consisted of subtractive connections of two single contrasts, i.e. of chained subtractions (see [2.2.1.2.1](#)). Interaction contrasts have been computed to reveal areas that significantly differ between the single t-contrasts so as to separate common from unique activations of the respective interference effects. Thereby, subtractions have been conducted in both directions, each, in order to isolate activations that are significantly stronger in one contrast (i.e. for one interference effect) compared to other, and vice versa. Concretely, Stroop-interference has been contrasted against Word-oddball interference (corresponding to $RI-CO-OW+SU$ and $OW-SU-RI+CO$) as well as Color-oddball interference against Word-oddball interference (corresponding to $OW-SU-OC+SU = OW-OC$ and $OC-SU-OW+SU = OC-OW$).

2.2.1.3.3 Conjoint contrasts to determine activations related to conflict factors

Conjunction analyses (see [2.2.1.2.2](#)) have been conducted to delineate the influence of circumscribed conflict factors that may independently contribute to the overall Stroop-interference effect. In particular, set pairings of conjoint contrasts should separate activations of the contrast RI-CO into two subgroups: (a) activations related to response-incompatibility and (b) activations related to semantic incongruency. The table in Figure 6 allocates conflict factors of interest to experimental conditions as well as to condition contrasts respectively contrast conjunctions. Thereby, conditions are arranged in an hierarchical order wherein each next “higher” condition includes only one incremental component, from SU including no factor of interest through RI including all three factors of interest. While the contrast RI-CO arguably intermingles ‘response-incompatibility’ and ‘semantic incongruency’ (see [1.4.2.3](#)), the contrasts RI-SI and SI-CO isolate response-incompatibility and semantic incongruency, respectively. Accordingly, it was expected that activations of the contrast RI-CO that reflect response-incompatibility were also observable in the contrast RI-SI. Similarly, activations of the contrast RI-CO emanating from semantic incongruency should be equally present in the contrast RI-SI. Based on this allocation of conflict factors to condition contrasts, contrast conjunctions have been defined. Thereby, common activations of RI-CO with RI-SI have been attributed to response-incompatibility whereas common activations of RI-CO with SI-CO have been interpreted as emanating from semantic incongruency. To determine activations specific to ‘task-reference’, the third conflict factor of interest, the single contrast CO-SU was computed, that includes no other incremental component.

experimental conditions conflict factors	SU semantically unrelated	CO congruent	SI semantically incongruent	RI response- incongruent	contrasts / conjunction
response- incompatibility	X	X	X	✓	RI-CO \cap RI-SI
semantic incongruency	X	X	✓	✓	RI-CO \cap SI-CO
task-reference	X	✓	✓	✓	CO-SU

Figure 6: Table allocates conflict factors to experimental conditions (✓= included, X= not included) as well as to condition contrasts, respectively contrast conjunctions.

2.2.2 Behavioral data

Statistical analyses of the behavioral data used SPSS 11.5 for Windows and were conducted after wrong responses had been excluded. Reaction times (RTs) have been aggregated across subjects and conditions. Consequently, based on the GLM (General Linear Model), the data were analyzed by a repeated measures ANOVA (analysis of variance), thresholded at $p < .05$, as omnibus test for estimating the global effect of the experimental variation on the RT data. Consequently, single t-contrasts (using paired t-tests) for pairwise comparisons of the experimental conditions have been conducted to determine single interference effects. Specifically, single comparisons comprised the following five contrasts: RI-CO, SI-CO, SU-CO, OW-SU, and OC-SU. Statistical inferences relied on one-tailed probabilities as the compared conditions (i.e. condition contrasts) were associated with definite a-priori expectancies, assuming prolonged RTs for interference conditions compared to non-interference or baseline conditions (see [1.4.1](#)).

2.2.3 Restriction of the statistical analyses to the size-task

All results that will be presented in the following section exclusively refer to the size-task as color-task trials did not enter into the statistical analyses of either the behavioral or the neuroimaging data. The reason for this was that color oddball trials could only be implemented in the size-task as the color-task, in which color serves as task-relevant dimension, could not include a response-ineligible color value (see also [2.1.2.3](#)). The restriction of the analyses to the size-task, which included all relevant conditions that are needed to address the current work's purposes, should ensure a good comparability among all compared trial types. Besides, size oddballs within the color task were not expected to produce a significant effect at either the behavioral or neural level, because the mid-size value did not represent a salient deviation from big or small font size stimuli whereas red color oddballs clearly contrasted with the prevalent blue or yellow stimuli. Rather, Size-oddballs were created just as 'counterpart' for Color-oddballs in order to keep the design balanced across both tasks.

3 Results

3.1 Behavioral results

All subjects reached high accuracy levels [mean percentages: correct responses 94.9%; wrong responses 3.3%; missing responses 1.8%]. The bar chart in Figure 7 depicts mean RTs and corresponding standard errors of the experimental conditions [means \pm standard error: RI, 471 ms \pm 4.9; SI, 459 ms \pm 4.7; CO, 452 ms \pm 4.3; SU, 456 ms \pm 5.3; OW = 478 ms \pm 12.8; OC, 482 ms \pm 6.2].

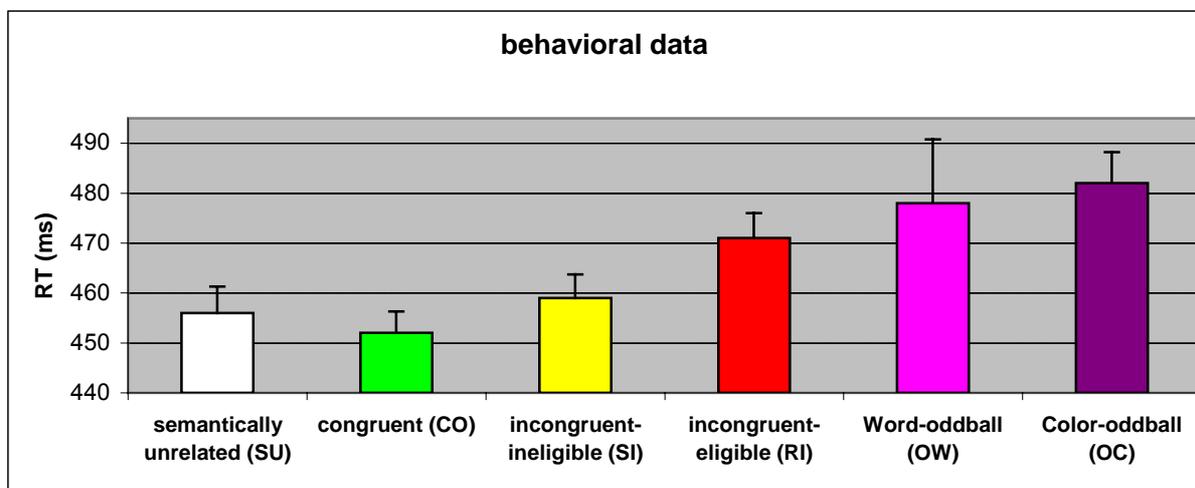


Figure 7: Behavioral data. The bar chart depicts mean reaction times and respective standard errors of the experimental conditions. Data exhibited significant effects (i.e. interference effects) for Stroop-incongruency (response-eligible incongruent trials), Word-oddballs and Color-oddballs. Statistical effects were determined by paired t-tests, thresholded at $p < .05$.

The data showed, primarily at the descriptive level, that RTs on interference trials (i.e. RI, SI, OW, and OC) were generally prolonged as compared to non-interference trials (CO and SU). Then, the omnibus ANOVA across all conditions appeared significant at $p = .017$ (under sphericity assumption) indicating that the descriptive differences were at least in part reliable. T-contrasts appeared significant for the comparisons RI-CO ($p = .025$), OW-SU ($p = .026$), and OC-SU ($p = .004$), indicating a behavioral effect for Stroop-interference, interference from word oddballs, and interference from color oddballs. On the other hand, the contrast SI-CO did not yield a significant result ($p = .149$) and therefore provided no evidence for substantial interference in the SI condition. Finally, the contrast CO-SU was likewise not significant ($p = .352$) and hence yielded no evidence for substantial facilitation by congruent word meaning.

In conclusion, the behavioral data clearly indicated that the experimental manipulation within the adopted task paradigm was indeed effective in inducing interference. The following subsections present how the effects observed at the behavioral level were reflected in the neuroimaging data.

3.2 Neuroimaging results

3.2.1 Neural activations related to different interference effects

3.2.1.1 Activations related to Stroop-interference

Stroop-interference – as represented by the contrast “Stroop-incongruency vs. Stroop-congruency” – elicited activation particularly in the left premotor cortex (BA 6) and left motor cortex (BA 4) along the precentral and central sulcus, in the pre-supplementary motor area (pre-SMA; BA 6/32), in a subgenual portion of the anterior cingulate cortex (ACC; BA 24), as well as in the bilateral anterior insula (BA 13) and in a more posterior part of the left insula (BA 13). Further, a significant signal change was observed in the left postcentral (somatosensory) cortex (BA 1/3), in the bilateral cuneus (BA 19), the right occipito-temporal cortex (BA 37/39), and the cerebellum, as well as in the right basal ganglia and thalamus. The reported activations are listed in Table 1 and depicted in Figure 8A.

The contrast *response-incongruent trials against neutral (semantically unrelated) trials* (RI-SU) revealed significant activation in the right posterior lateral PFC, a region previously referred to as inferior frontal junction area (IFJA) (see [1.3.5](#)) [t-value (coordinates): 3.80 (45 6 18)] as well as in the ventral premotor cortex (BA 6) [t-value (coordinates): 3.80 (-60 6 36) / 3.64 (-54 3 39)].

3.2.1.2 Activations related to interference from Word-oddballs

Activations associated with Word-oddball interference have been determined by the contrast OW-SU. This contrast showed significant activation bilaterally in the frontolateral cortex, including bilateral activations along the posterior part of the inferior frontal sulcus (IFS) belonging to the IFJA, in an anterior portion of the right inferior frontal gyrus (IFG; BA 45), as well as in the right anterior insular cortex (BA 13). Furthermore, the contrast revealed significantly enhanced brain activity in posterior frontomedian cortex (BA 32) in the vicinity

of the cingulate sulcus, in the left precentral or premotor cortex (BA 6), and bilaterally in the temporo-polar cortex (TPC; BA 21/38) as well as in the left posterior insula (BA 13). Finally, word oddball interference was associated with activation in posterior cortical regions including bilateral parietal cortices along the intraparietal sulcus (IPS; BA 7), the left fusiform gyrus (FG; BA 37), the bilateral occipito-temporal cortex (BA 39) as well as bilateral extrastriate visual cortices (BA 18). The reported activations are listed in Table 1 (and Table 2) and depicted in Figure 8B.

3.2.1.3 Activations related to interference from Color-oddballs

Color-oddballs produced neural activation – as revealed by the contrast OC-SU – throughout a largely distributed network of regions, comprising numerous bilateral cortical and subcortical structures. Lateral prefrontal activations were observed bilaterally in the anterior IFG, comprising pars triangularis and pars orbitalis (BA 45, BA 47), and bilaterally in the posterior IFG belonging to the IFJA. Furthermore, color oddball interference produced significantly enhanced activation in the frontomedian wall, particularly in the superior frontal gyrus (SFG; BA 8/9) as well as in a more ventral region in the vicinity of the cingulate sulcus (BA 32). Color-oddballs further elicited strong activation in the bilateral TPC and in parietal cortices bilaterally along the IPS. Finally, Color-oddballs involved mainly left-hemispherically posterior processing regions, specifically the left FG (BA 37), left lingual gyrus (BA 19), left occipito-temporal cortex (BA 39), as well as bilateral extrastriate visual cortices (BA 18) and bilateral precuneus cortex (BA 19). The reported activations are listed in Table 2 and depicted in Figure 8C.

3.2.2 Neural activations differentiating between different kinds of interference

In a second step, pairwise comparisons of the presented single contrasts have been conducted in order to separate common from unique activations of the respective interference effects, i.e. to delineate activations that are specific to single interference effects. For this purpose, bidirectional interaction contrasts (see [2.2.1.3.2](#)) have been computed to delineate activations that are significantly stronger for one of the pairwise contrasts as compared to the other, and vice versa.

3.2.2.1 Comparison between Stroop-interference and interference from Word-oddballs

Basically, Stroop-interference and Word-oddball interference exhibited quite distinct patterns of neural activation. There was only sparse activation overlap observed for the left premotor

cortex, the left posterior insula, and in the more anterior right insular cortex. Furthermore, there was overlapping activation in the postcentral gyrus that, important to note, appeared to be significantly stronger for Stroop-interference as for Word-oddballs. Activations specific to Stroop-interference was observed in the left precentral gyrus (dorsal premotor cortex), in the pre-SMA, in the subgenual ACC, in the left anterior insular cortex, in the bilateral cuneus, in the right cerebellum, as well as in the right basal ganglia and thalamus. Reversely, only Word-oddballs activated the right anterior and posterior inferior frontal cortex and the bilateral IFJA, bilateral TPC, the posterior portions of the right inferior and superior temporal cortex, the left FG, as well as bilaterally the IPS and extrastriate visual cortices. The reported activations are listed in Table 1 and depicted in Figure 8A/B/D.

3.2.2.2 Comparison between interference from Word-oddballs and interference from Color-oddballs

Oddballs in both the word and color dimension produced signal changes in a wide range of cortical areas and thereby exhibited a striking overlap of activation. Both oddball types showed increased activation in prefrontal cortices including the right anterior IFG and bilaterally posterior lateral PFC (i.e. the IFJA), in the left precentral cortex, as well as in the posterior frontomedian cortex. Further common regions of significant activation were observed in parietal cortices, bilaterally along the IPS, as well as in posterior processing areas, specifically in the left posterior inferior temporal gyrus (ITG), left FG, left occipito-temporal cortex, and in bilateral extrastriate visual cortices.

Beyond commonalities, the bidirectionally computed interaction contrast revealed areas that were differentially activated by the two oddball conditions. Activations unique to Color-oddballs were observed in the medial prefrontal cortex, comprising left and right medial SFG as well as in the frontomedian cortex in the vicinity of the cingulate sulcus and further in the lateral PFC, particularly in the left IFG including Broca's area. In addition, Color-oddballs uniquely elicited activation in the left lingual gyrus, bilateral precuneus, bilateral temporal cortices, bilateral thalamus, as well as in the right cerebellum. Areas exhibiting significantly more activation for Word-oddballs were less numerous and comprised cortices along the left central sulcus and in the left posterior insula, as well as the right anterior insula and posterior ITG. The reported activations are listed in Table 2 and depicted in Figure 8 B/C/E.

Of note, both conflict contrasts exhibited significant activations bilaterally within the inferior TPC (BA 38) that, however, did not completely overlap resulting in a double dissociation within this region. Temporo-polar activations in the Word-oddball condition peaked in more

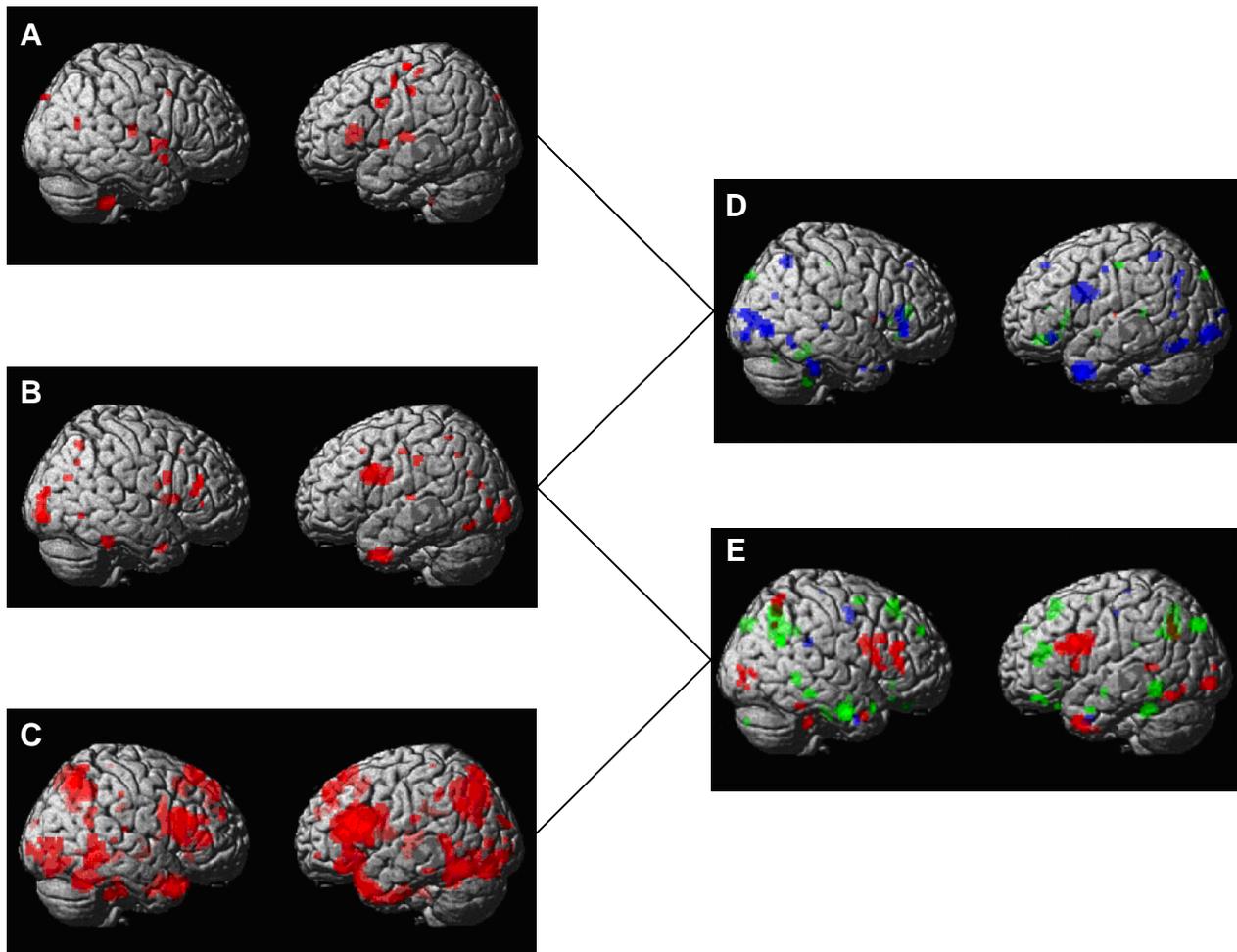
posterior areas in both hemispheres as compared to the Color-oddball condition which exhibited more anterior foci. In the left hemisphere, the activation focus in the Color-oddball condition was more dorsally located as compared to the Word-oddball condition. Activations of both oddball conditions in the TPC are displayed Figure 9.

Table 1: Comparative listing of regions sensitive to Word-oddball interference and Stroop-interference. Common and differential activations associated with interference from Word-oddballs (Word-oddball vs. Oddball control condition / OW-SU) and Stroop-interference (Stroop-incongruency vs. Stroop-congruency / RI-CO). Differential activations were revealed by interaction contrasts. All activations were determined by random effects analyses on single subject contrast images and thresholded at $p < 0.005$, uncorrected.

Region	Statistical effects / t-value (coordinates)			
	Word-oddball	Stroop-incongruency	Word-oddball > Stroop-incongruency	Stroop-incongruency > Word-oddball
a) activations unique to Word-oddballs				
R inferior frontal cortex (IFJA)	4.31 (42 6 24)	n.s.	3.34 (42 6 27)	n.s.
L inferior frontal cortex (IFJA)	7.20 (-36 12 27)	n.s.	7.58 (-33 9 27)	n.s.
R inferior frontal gyrus	3.90 (54 30 15)	n.s.	3.77 (54 30 12)	n.s.
R inferior frontal gyrus	3.59 (54 36 3)	n.s.	6.45 (54 33 -6)	n.s.
L medial frontal (posterior frontomedian cortex)	3.51 (-9 18 45)	n.s.	3.50 (-6 36 48)	n.s.
R inferior temporo-polar cortex	3.99 (39 3 -30)	n.s.	3.44 (42 0 -33)	n.s.
L inferior temporo-polar cortex	9.01 (-33 3 -39)	n.s.	7.78 (-30 3 -39)	n.s.
L fusiform gyrus	4.60 (-42 -66 -15)	n.s.	5.08 (-42 -66 -15)	n.s.
R intraparietal sulcus	4.22 (24 -60 51)	n.s.	5.17 (24 -60 51)	n.s.
L intraparietal sulcus	3.68 (-21 -57 42)	n.s.	4.23 (-30 -48 57)	n.s.
R lateral occipital sulcus	3.78 (33 -72 24)	n.s.	3.38 (33 -69 24)	n.s.
L lateral occipital sulcus	4.01 (-36 -75 18)	n.s.	3.88 (-27 -66 24)	n.s.
R extrastriate visual cortex	6.35 (36 -90 -6)	n.s.	4.59 (36 -93 -9)	n.s.
L extrastriate visual cortex	5.58 (-21 -93 -3)	n.s.	6.22 (-27 -87 -9)	n.s.
b) activations unique to Stroop-incongruency				
R posterior frontomedian cortex (pre-SMA)	n.s.	3.91 (15 9 42)	n.s.	2.34 (18 6 39)
R anterior cingulate cortex (subgenual)	n.s.	3.09 (3 27 -3)	n.s.	3.84 (3 21 3)
L insula (anterior)	n.s.	4.44 (-45 3 0)	n.s.	2.47 (-51 -9 -9)
L precentral gyrus / dorsal premotor cortex	n.s.	4.09 (-42 -18 66)	n.s.	5.33 (-45 -21 51)
R basal ganglia / thalamus	n.s.	4.97 (24 -21 12)	n.s.	3.79 (21 -18 18)
R cuneus	n.s.	3.82 (6 -87 39)	n.s.	3.11 (6 -87 42)
L cuneus	n.s.	2.38 (-6 -75 42)	n.s.	5.45 (-12 -87 39)
R inferior cerebellum	n.s.	6.39 (24 -42 -45)	n.s.	4.56 (18 -45 -42)
R superior cerebellum	n.s.	2.92 (18 -57 -27)	n.s.	4.25 (12 -45 -21)
R gyrus occipitalis lateralis	n.s.	3.54 (36 -63 18)	n.s.	2.10 (36 -63 18)
c) common activations of Word-oddballs and Stroop-incongruency				
R insula (anterior)	4.28 (42 12 9)	6.38 (42 6 3)	3.61 (42 15 9)	n.s.
L insula (posterior)	3.84 (-42 -18 9)	4.49 (-39 -15 6)	3.91 (-39 -3 27)	2.59 (-39 -18 9)
L precentral sulcus / ventral premotor cortex	4.74 (-54 9 33)	3.95 (-60 6 36)	3.42 (-51 9 33)	n.s.
L precentral gyrus / ventral premotor cortex	5.57 (-39 -3 27)	3.47 (-51 0 36)	7.58 (-33 9 27)	n.s.
L central sulcus	4.41 (-30 -15 45)	4.22 (-18 -24 57)	4.73 (-42 -9 45)	2.51 (-24 -27 48)
L postcentral gyrus	4.16 (-48 -24 36)	3.97 (-45 -21 42)	n.s.	5.33 (-45 -21 51)

Table 2: Comparative listing of regions sensitive to Color-oddball interference and Word-oddball interference. Common and differential activations associated with interference from Color-oddballs (Color-oddball vs. Oddball control condition / OC-SU) and Word-oddballs (Word-oddball vs. Oddball control condition / OW-SU). Differential activations were revealed by interaction contrasts. All activations were determined by random effects analyses on single subject contrast images and thresholded at $p < 0.005$, uncorrected.

Region	Statistical effects / t-value (coordinates)			
	Color-oddball	Word-oddball	Color-oddball > Word-oddball	Word-oddball > Color-oddball
a) activations unique to Color-oddballs				
R medial frontal cortex (SFG)	6.83 (9 30 60)	n.s.	4.73 (9 27 54)	n.s.
L medial frontal cortex (SFG)	5.21 (-9 39 48)	n.s.	1.86 (-3 39 48)	n.s.
L inferior frontal gyrus (IFG)	11.32 (-57 18 15)	n.s.	4.72 (-36 36 18)	n.s.
L inferior frontal gyrus (pars orbitalis)	5.22 (-42 33 -15)	n.s.	4.98 (-36 39 -24)	n.s.
L frontomedian cortex (cingulate sulcus)	6.70 (-12 36 21)	n.s.	5.46 (-15 42 9)	n.s.
L head of caudate nucleus	7.00 (-6 0 9)	n.s.	n.s.	n.s.
L temporo-polar cortex	8.86 (-39 12 -33),	n.s.	4.02 (-33 27 -27)	n.s.
R temporo-polar cortex	9.41 (42 12 -33)	n.s.	7.07 (54 -9 -30)	n.s.
R parahippocampal gyrus	5.21 (21 -6 -33)	n.s.	1.96 (18 -9 -36)	n.s.
L postcentral sulcus	5.02 (-66 -21 24)	n.s.	2.38 (-66 -24 24)	n.s.
L middle temporal gyrus	7.33 (-60 -48 0)	n.s.	4.42 (-54 -48 -9)	n.s.
R superior temporal sulcus (post. part)	7.53 (57 -45 0)	n.s.	4.51 (54 -45 -3)	n.s.
L thalamus	6.66 (-9 -18 3)	n.s.	1.95 (-9 -18 -9)	n.s.
R thalamus	3.69 (9 -12 9)	n.s.	3.20 (6 -15 18)	n.s.
R precuneus	3.81 (9 -72 48)	n.s.	5.48 (9 -63 48)	n.s.
L precuneus	6.85 (-18 -63 36)	n.s.	3.46 (-3 -63 48)	n.s.
L lingual gyrus	3.64 (-9 -51 -6)	n.s.	4.46 (-18 -51 -6)	n.s.
R cerebellum	8.53 (39 -57 -30)	n.s.	3.17 (24 -57 -42)	n.s.
b) activations unique to Word-oddballs				
R insula (anterior)	n.s.	4.28 (42 12 9)	n.s.	3.10 (39 12 9)
L temporo-polar cortex	n.s.	9.01 (-33 3 -39)	n.s.	4.47 (-33 3 -33)
R temporo-polar cortex	n.s.	3.99 (39 3 -30)	n.s.	3.71 (42 0 -33)
L central sulcus	n.s.	4.41 (-30 -15 45)	n.s.	3.77 (-30 -18 48)
L insula (posterior)	n.s.	3.84 (-42 -18 9)	n.s.	2.15 (-45 -18 15)
R inferior temporal gyrus	n.s.	4.23 (54 -42 -24)	n.s.	3.12 (48 -36 -27)
c) common activations of Color-oddballs and Word-oddballs				
R inferior frontal cortex (IFJA)	4.80 (42 6 24)	4.31 (42 6 24)	n.s.	n.s.
L inferior frontal cortex (IFJA)	12.25 (-39 6 21)	7.20 (-36 12 27)	n.s.	n.s.
R inferior frontal gyrus (pars triangularis)	5.75 (60 21 6)	3.90 (54 30 15)	n.s.	n.s.
L precentral gyrus / precentral sulcus	6.61 (-39 3 27)	5.57 (-39 -3 27)	n.s.	3.21 (-39 -3 24)
L/R medial frontal (posterior frontomedian cortex)	4.43 (0 18 48)	3.51 (-9 18 45)	n.s.	n.s.
L inferior temporal gyrus (post. part)	8.67 (-51 -54 -15)	4.60 (-42 -66 -15)	4.42 (-54 -48 -9)	n.s.
L fusiform gyrus	6.90 (-36 -75 -18)	4.60 (-42 -66 -15)	n.s.	n.s.
R intraparietal sulcus	6.20 (36 -54 45)	4.22 (24 -60 51)	n.s.	n.s.
L intraparietal sulcus	6.18 (-30 -69 45)	3.68 (-21 -57 42)	6.72 (-21 -81 39)	2.85 (-18 -57 45)
L lateral occipital sulcus	5.99 (-39 -69 27)	4.01 (-36 -75 18)	3.79 (-36 -60 30)	1.96 (-27 -63 21)
R extrastriate visual cortex	5.97 (48 -81 0)	6.35 (36 -90 -6)	n.s.	n.s.
L extrastriate visual cortex	5.27 (-30 -84 -9)	5.58 (-21 -93 -3)	n.s.	n.s.
R head of caudate nucleus	6.09 (12 -6 -3)	5.03 (15 6 6)	n.s.	n.s.



A-C: activations associated with different interference effects (i.e. contrasts).

- A: Stroop-interference (RI-CO)
- B: Word-oddball interference (OW-SU)
- C: Color-oddball (OC-SU)

D-E: composite renderings showing commonalities and differences between single interference effects (i.e. contrasts) as revealed by interaction contrasts.

- D: comparison between Stroop-interference and Word-oddball
- E: comparison between Color-oddball and Word-oddball

red: common activations

blue: activations significantly stronger for Word-oddball

green: activations significantly stronger for Stroop-incongruency (D) / Color-oddball (E)

Figure 8: Neuroimaging data. A-C: Renderings of group-averaged brain activations associated with different interference effects. Part A refers to Stroop-interference (contrast: RI-CO), part B refers to interference from Word-oddballs (contrast: OW-SU), and part C to interference from Color-oddballs (contrast: OC-SU). D-E: Renderings of brain activations (composed multi-color brain maps) to compare between the defined interference effects. Part D refers to the comparison between Stroop-interference and interference from Word-Oddballs (interaction contrast). Common activations are shown in red, activations unique to Word-oddballs in blue, and activations unique to Stroop-interference in green. Part E refers to the comparison between interference from Color-oddballs and interference from Word-Oddballs (interaction contrast). Common activations are shown in red, activations unique to Word-oddballs again in blue, and activations unique to Color-oddballs in green. All activations were rendered onto a surface reconstruction of the MNI template and thresholded at $p < 0.005$, uncorrected.

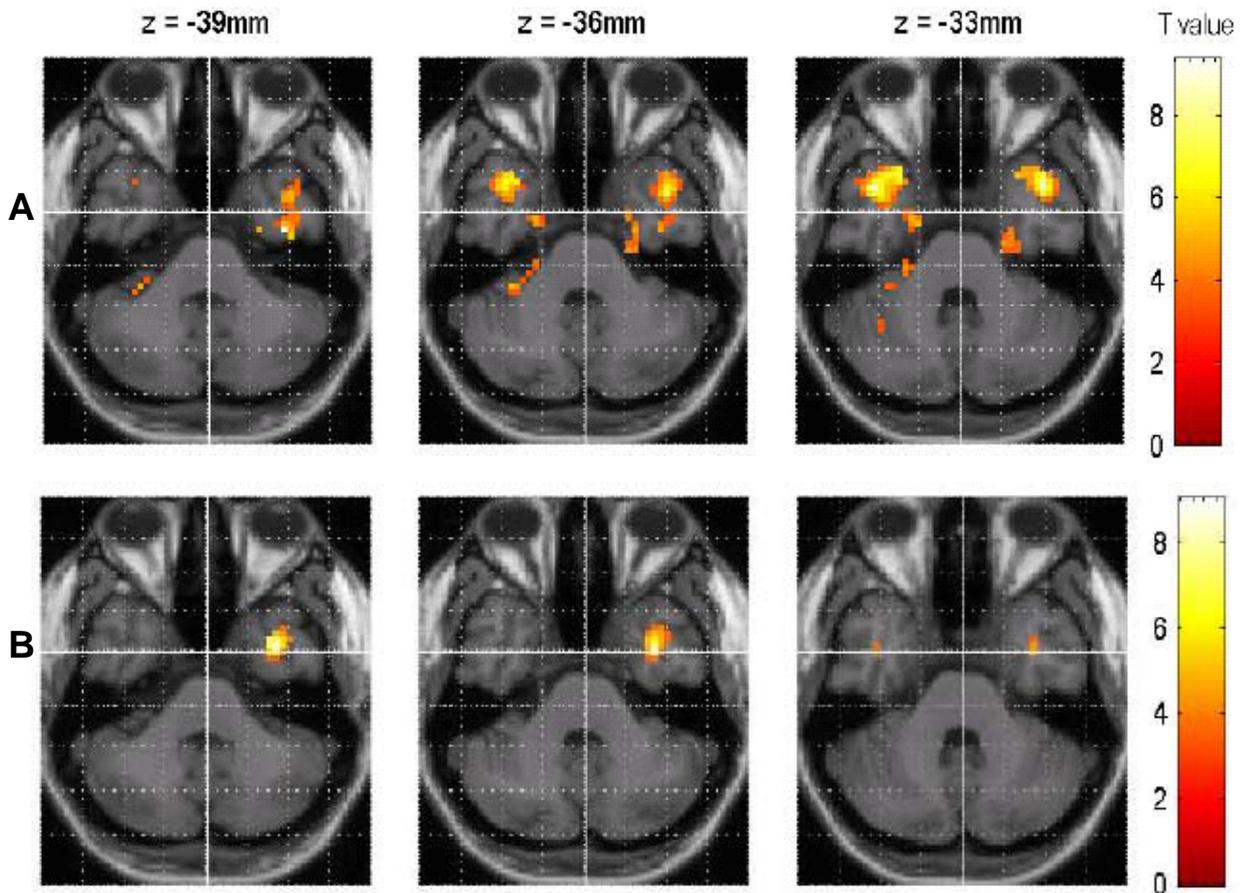


Figure 9: Neuroimaging data. Double dissociation of activations in temporo-polar cortex for Color-oddballs (A) and Word-oddballs (B). Color-oddballs exhibited more anterior and superior bilateral activation foci as compared to Word-oddballs (see also Table 2). The illustration is thresholded at $p < 0.005$, uncorrected, and the view is according to the radiological convention (left brain hemisphere on the right side of the illustration, and vice versa).

3.2.3 Neural activations related to different conflict factors of Stroop-interference

3.2.3.1 Response-incompatibility vs. semantic incongruency

Activations related to Stroop-interference as revealed by the contrast RI-CO should be separated into two subgroups that represent (the influence of) different conflict factors as two distinct and independent neurocognitive subcomponents of Stroop-interference: (a) activations related to response-incompatibility and (b) activations related to semantic incongruency (see [3.2.1.1](#)), construed to reflect response-conflict and semantic conflict, respectively (see [1.2.1](#)). For this purpose, the contrast RI-CO has been conjoined with the contrast RI-SI and with the contrast SI-CO, separately, in order to delineate activations related to response-incompatibility and semantic incongruency, respectively. Table 3 lists activations

of the mentioned contrast conjunctions as well as the corresponding activation foci that have been revealed in the single contrasts. There was only one activation focus specifically associated with response-incompatibility located in the left precentral gyrus (left ventral premotor cortex). This focus was significantly activated for both contrasts RI-SI and RI-CO, as well as in the corresponding conjunction. On the other hand, semantic incongruency was associated with activation in the posterior frontomedian cortex (pre-SMA), in the left postcentral gyrus (left ventral somatosensory cortex), bilateral anterior insula, right cerebellum, as well as in the right basal ganglia and thalamus. These brain regions were significantly activated for both single contrasts RI-CO and SI-CO, as well as in their conjunction. The reported activations are listed in Table 3 and depicted in Figure 10A/B.

Table 3: Activations associated with response-incompatibility (section A) and semantic incongruency (section B), both revealed by contrast conjunctions (i.e. conjunction analyses). Common activations of the contrasts RI-CO and RI-SI were attributed to response-incompatibility, whereas common activations of RI-CO and SI-CO were ascribed to semantic incongruency. All activations were determined by random effects analyses on single subject contrast images, thresholded at $p \leq 0.005$.

Region	Statistical effects / t-value (coordinates)				
	single contrasts			contrast conjunctions	
	RI-SI	RI-CO	SI-CO	RI-CO \cap RI-SI	RI-CO \cap SI-CO
(A) response-incompatibility					
L ventral premotor cortex	5.00 (-60 3 33)***	3.95 (-60 6 36)**	n.s.	3.70 (-60 6 36)***	n.s.
(B) semantic incongruency					
L / R posterior frontomedian cortex (pre-SMA)	n.s.	3.91 (15 9 42)**	6.52 (-15 -6 45)*** 5.27 (-12 6 42)***	n.s.	2.86 (12 6 42)** [2.82 (-12 12 42)*]
L postcentral gyrus	n.s.	3.97 (-45 -21 42)**	7.05 (-51 -21 45)***	n.s.	3.77 (-48 -21 45)***
L insula (anterior)	n.s.	4.44 (-45 3 0)**	4.85 (-39 15 6)***	n.s.	3.42 (-42 3 0)**
R insula (anterior)	n.s.	6.38 (42 6 3)***	3.88 (42 6 3)**	n.s.	3.33 (42 6 3)**
R basal ganglia / thalamus	n.s.	4.97 (24 -21 12)***	9.74 (21 -21 9)***	n.s.	5.13 (24 -21 12)***
R inferior cerebellum	n.s.	6.39 (24 -42 -45)***	4.46 (30 -66 -21)**	n.s.	3.42 (24 -42 -45)**

*** $p \leq 0.001$ ** $p \leq 0.005$ [* $p \leq 0.01$]; n.s.=not significant

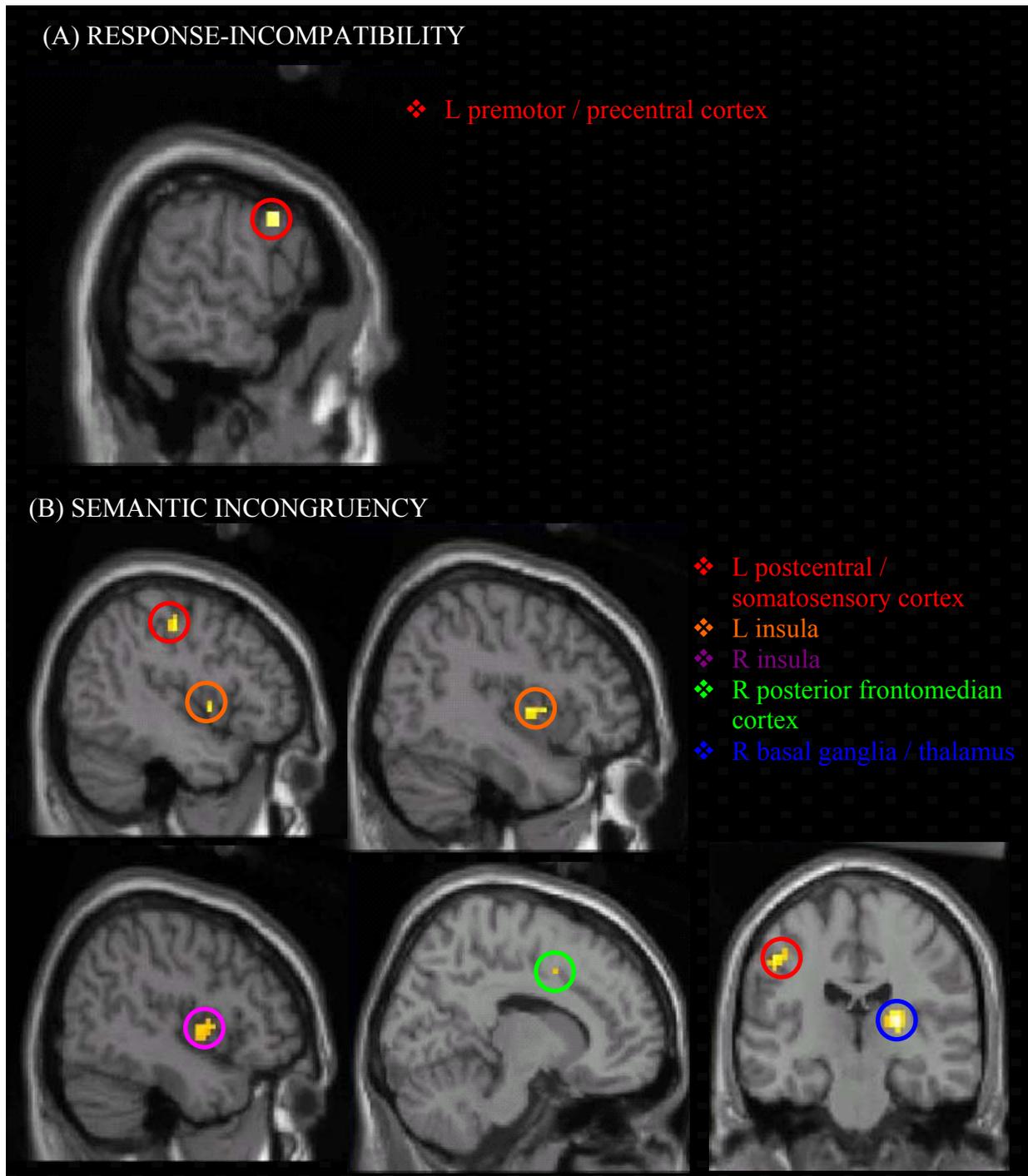


Figure 10: Activations related to response-incompatibility (revealed by the contrast conjunction $RI-CO \cap RI-SI$) and related to semantic incongruency (revealed by the contrast conjunction $RI-CO \cap SI-CO$). Depicted activations were rendered onto cross-sectional (sagittal, coronar, and axial) slices of the anatomic MNI template, thresholded at $p \leq 0.005$, uncorrected.

3.2.3.1 Task reference

The neural substrate of task-reference, the third conflict factor of interest, was determined by the single contrast CO-SU that includes no other incremental component. Significant activations related to task-reference comprised the left rostro-ventral or fronto-opercular cortex (BA 47) and adjacent orbitofrontal cortex (OFC, BA 11), the right medial SFG (BA 9), and the left TPC (BA 38). The reported activations are listed in Table 4 and depicted in Figure 11.

Table 4: Activations associated with task-reference revealed by contrast CO-SU. Activations were determined by random effects analyses on single subject contrast images, thresholded at $p \leq 0.005$; uncorrected.

Region	Statistical effects / t-value (coordinates)	
	CO-SU	
(C) task-reference		
L fronto-opercular / orbitofrontal cortex	4.59 (-36 33 -12)***	4.18 (-33 39 0)**
R medial superior frontal gyrus	7.24 (18 51 42)***	5.59 (24 39 42)***
L temporo-polar cortex	5.82 (-42 9 -33)***	3.96 (-27 21 -30)**

** $p < .005$ *** $p < .001$

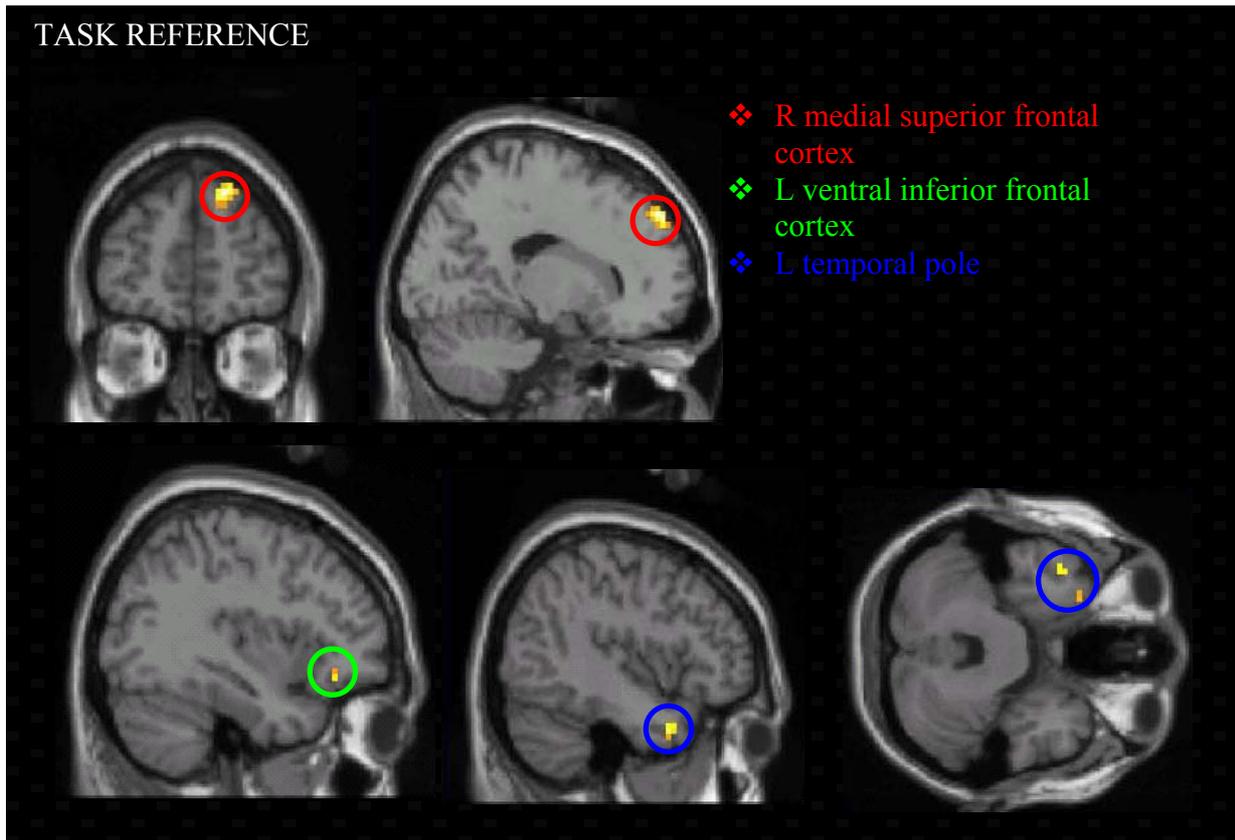


Figure 11: Activations related to task-reference revealed by the contrast CO-SU. Depicted activations were rendered onto cross-sectional (sagittal, coronar, and axial) slices of the anatomic MNI template, thresholded at $p < 0.005$, uncorrected.

4 Discussion

4.1 Dissociating motor and attentional components of cognitive interference

On the one hand, the current oddball activations (i.e. activations related to color oddballs and word oddballs) nicely match those that were found in the reported prior investigation of Gruber and collaborators (e.g. Gruber & Goschke, 2004; Melcher et al., 2004; see [1.3.4](#)). In essence, the current data exhibited oddball activation in the same frontoparietal network comprising the lateral prefrontal cortex including the IFJA, the posterior frontomedian cortex, intraparietal regions and extrastriate visual cortices. On the other hand, however, the current data's activations related to Stroop-interference did not match the findings of Zysset and colleagues (Zysset et al., 2000; see [1.3.4](#)), who observed a frontoparietal activation pattern related to Stroop-interference that broadly corresponded to the oddball pattern described above. Therefore, the current data does not corroborate the initial observation of a common activation pattern for Stroop-interference and oddball interference. Rather, Stroop-interference and Word-oddballs elicited quite distinct patterns of neural activation that exhibited only sparse overlap.

In conclusion, the comparison between Stroop-interference and oddball interference did not define one single or core neural mechanism of cognitive control as was initially expected, but rather dissociated two functionally distinct and complementary control mechanisms. In other words, the reported findings suggest that the two contrasts focusing on Stroop-interference and interference from Word-oddballs in the present study do not converge in a common or core neural mechanisms of cognitive control but rather map two different subcomponents (or levels) of cognitive interference, (A) *a motor component* and (B) *an attentional component*, that refer to distinct control functions (i.e. neural mechanisms). In the following two subsections, the delineated subcomponents will be presented and explained in more detail.

4.1.1 A motor component of interference

Stroop-incongruent (SI) trials and Stroop-congruent (CO) trials used exactly the same words (BIG and SMALL), that only differed in the particular color-size combination. Hence, word meaning (i.e. the lexical dimension) in both conditions is equally associated with the current task-set and can be expected to be equally able to distract attention from the currently relevant

size dimension. In accordance with this assertion, Milham and Banich (2005) found enhanced activity in a posterior division of the ACC in relation to both incongruent and congruent Stroop trials. Based on this and prior findings (Milham et al., 2002; Milham et al., 2003b; Milham & Banich, 2005; see [1.2.2](#)), they argued that attentional demands may be similarly increased on both incongruent and congruent trials due to competition between task-relevant and task-irrelevant information (for priority in processing), as task-irrelevant information in both conditions is semantically related to the current task-set, i.e. provides competing task-related information (see also below, [4.1.2](#) and [4.4.2](#)). On the other hand, words (i.e. word meanings) of RI trials introduce incompatible information at the response-level whereas words of CO trials do not. Taken together, the contrast RI-CO reasonably subtracts out – at least to some extent – the attentional component of interference (i.e. equates for interference at the attentional level) and focuses on interference occurring at the level of motor or response preparation (i.e. response conflict). This conclusion is strongly supported by the activations revealed by this contrast which comprised dorsal and ventral premotor cortices, the pre-SMA, the cerebellum, as well as the basal ganglia and thalamus, regions that are well known to be implicated in the preparation and control of motor responses (e.g. Ikeda, 1992; Wiese et al., 2004; Monchi et al., 2006). Generally, response conflict can be expected to recruit additional motor control in terms of strengthened response selection or inhibition. Specifically the dorsal premotor cortex, a prominent activation focus of the Stroop-interference contrast (RI-CO), has been described to play an important role in the mapping of sensory signals onto motor responses (Wise et al., 1996), and there is convincing evidence that this region is strongly involved in inhibitory motor control, i.e. controlled response selection (Praamstra et al., 1999). Similarly, an influential hypothesis – primarily derived from electrophysiological studies – assumes that the basal ganglia essentially contribute to motor control by inhibiting incompatible motor tendencies that (might) interfere with an actually intended motor action (Mink, 1996; Aron et al., 2003). Moreover, several studies implicated the thalamus conjointly with the basal ganglia in motor control, i.e. in the implementation or inhibition of motor responses, during conflict situations (e.g. Huettel, 2001; Monchi et al., 2001; Aron et al., 2003). Given the reported findings, it is persuasive – if not highly probable – that the activation pattern related to Stroop-interference primarily reflects strengthened motor control triggered by response conflict (i.e. the co-activation of two incompatible response tendencies) which should prevent false responding.

Moreover, there was significant activation in the left ventral somatosensory cortex related to Stroop-interference which appeared to be significantly stronger than in the Word-oddball

contrast. Activation in this region has been repeatedly related to the processing of tactile sensations of the contralateral fingertip (e.g. Burton et al., 1999; Pleger et al., 2006) and beyond that has been shown to be boosted by increased attention towards proprioception, even in absence of proper stimulation (Burton et al., 1999). Furthermore, as revealed by morphological investigations of the animal brain (Porter, 1991, Porter, 1997), the somatosensory cortex projects to primary motor areas and in this way may essentially contribute to motor preparation (see Pleger et al., 2006). In conclusion, the observed somatosensory activation assumably underlie enhanced proprioceptive/tactile attention to the responding fingers as further aspect of strengthened motor control efforts.

As already pointed out, the contrast RI-CO may intermingle interference at the semantic level and the motor level as the word's lexical meaning on RI trials is both semantic incongruent and response-incompatible (see [1.4.2.3](#)). In the current work, these properties of task-irrelevant word information were defined as conflict factors (see [1.2.1](#)), and one major purpose of the current work was to further split activations of the contrast RI-CO in two subgroups, (a) activations related to response-incompatibility (reflecting motor conflict) and (b) activations related to semantic incongruency (reflecting semantic conflict). The corresponding results are discussed in one of the following subsections (see [4.4.1](#)).

4.1.2 An attentional component of interference

According to the conceptualization of oddball interference in this work (see [1.2.3.3](#)), the task-irrelevant word dimension in the Word-oddball condition gains saliency through the relative rareness of occurrence of the presented words and consequently evokes an attentional orienting response (i.e. an involuntary attentional switch) which subjects have to override. Thereby, as words' lexical meaning on Word-oddball trials is response-ineligible, response preparation in this condition should be widely unaffected. Consequently, interference emanating from Word-oddballs – which is also true for Color-oddballs – assumably occurs at an earlier processing stage, solely at the attentional level and not at the response or motor level. In line with this notion, Word-oddballs – which is again also true for Color-oddballs – exhibited significant activation in a frontoparietal network which in the neuroimaging literature has been consistently related to conditions of enhanced attentional demands during cognitive tasks and, beyond this, has been interpreted as to reflect the exertion of top-down attentional control, particularly the implementation of selective attention (e.g. Corbetta & Shulman, 2002, Fan et al., 2003; see [1.3.2](#)). Regarding the current investigation, frontoparietal

activation arguably underlay the overriding of the orienting response to the oddball events (i.e. to the oddball dimension) which has disrupted the task-appropriate attentional set. Within the frontoparietal network, both oddball conditions exhibited the IFJA as one main site of activation which, in accordance with the prior expectations of this work (see [1.4.2](#)), suggests that this cortical region plays a pivotal role in attentional control during competition (see also below; [4.3](#)).

As mentioned above, the current data did not replicate the frontoparietal activation pattern associated with Stroop-interference as it was observed in the Zysset study (Zysset et al., 2000). Rather, Stroop-interference in the current work exhibited primarily activation in premotor and motor regions, that can be convincingly interpreted as reflecting the implementation of strengthened motor control (see above). There are obvious differences between the two studies that may account for the divergence of findings. First, Zysset and colleagues employed another variant of the Stroop paradigm, the “Color-Word Matching Stroop Task”. Here, on each trial subjects are presented with two words simultaneously while they have to match the color of the first (above-standing) to the meaning of the second (below-standing). In this task version, interference takes place at a pure conceptual level and is (chronologically) separated from response preparation which – beyond that – is kept balanced across the experimental conditions (see [1.3.4](#)). Second, to define Stroop-interference, Zysset contrasted incongruent trials against neutral trials, while the present study contrasted incongruent trials against congruent trials, a contrast that arguably equalizes for attentional components of competition processing (see above; [4.1.1](#)). On the other hand, the contrast incongruent against neutral trials in the Zysset study comprises substantial attentional components because the used baseline neutral trials (consisting of a row of colored Xs) include no word meaning to attentionally interfere with the attended color. In contrast, lexical word meanings of congruent trials are exactly the same as those of incongruent trials, which should therefore be equally able to draw attention (see above; [4.1.1](#)). Accordingly, Milham and Banich considered the employment of a broader definition of cognitive conflict that is not restricted to cases of incongruity (see Milham & Banich, 2005). Basically, conflict may be conceptualized as any situation in which there are two or more competing sources of response-eligible information or, alternatively, as situations in which task-irrelevant information is related to task-demands (i.e. to the task set). In this context, task reference and response mapping (i.e. response eligibility), as properties of word meaning in both incongruent and congruent Stroop trials, might be conceived as conflict factors through which

task-irrelevant information gains saliency and thus may induce attentional interference, i.e. competition (see [1.4.2.3](#)).

Zysset and colleagues reported strong activation in the posterior lateral PFC belonging to the IFJA related to Stroop-interference whereas the contrast RI-CO in the current work did not exhibit activation in this cortical structure. As activation in the IFJA was essentially expected to occur when top-down control is required for (re-)orienting attention to task-relevant information (see [1.4.2](#)), the lack of IFJA activation particularly corroborates the assumption that the contrast RI-CO equalizes – at least partly – for attentional processing. Furthermore, Stroop-interference as defined by the contrast RI-SU did exhibit IFJA activation which also fits in the outlined interpretation in so far as SU trials – as already evident from their label – are semantically unrelated to the task. Therefore, the contrast RI-SU conclusively involves substantial attentional processing. The functional role of the IFJA in the present work (in particular) and in cognitive control (in general) will be further discussed in a following subsection (see [4.3](#)).

4.2 Oddball activations and their sensitivity to processing domain

The two oddball conditions exhibited a broad overlap of neural activation, mainly in anterior regions comprising both frontolateral and frontomedian cortices, but also in parietal cortices and other posterior processing areas. Thereby, Color-oddballs exhibited the more extensive activation pattern relative to Word-oddballs and also additional unique activations, e.g. in the left inferior frontolateral cortex, the medial superior frontal gyrus, the precuneus, and the left lingual gyrus. Activation in the left lingual gyrus has been previously implicated in processing of color (e.g. Corbetta et al., 1991; Zeki & Marini, 1998) and therefore in the present context substantiates the statement that the oddball color did draw special attention (i.e. did evoke an orienting response). Other unique activations of Color-oddballs may alternatively reflect quantitative differences, i.e. differences related to the degree of evoked interference, rather than qualitative differences between the two oddball conditions. Interestingly enough, the data revealed a double dissociation within the left and right TPC between the two oddball conditions. The TPC has been repeatedly implicated in conscious perception as well as semantic encoding and decoding of objects or object features (Markowitsch, 1995; Mesulam, 1998; Sowards & Sowards, 2002; Damasio et al., 2004). The observed double dissociation putatively reflects the deviation detection in (i.e. orienting response to) different visual

attributes, i.e. the respective dimension – color or lexical word meaning – in which the oddball event has occurred.

The strong activation overlap that was found in prefrontal areas is in line with the assumption that an anterior prefrontal system dynamically modulates activation in posterior processing areas in order to select task-relevant over task-irrelevant information (e.g. Banich et al., 2000; LaBerge, 2005; see [1.3.1](#)). The posterior lateral PFC or IFJA – that represents a main activation focus in both oddball contrasts – is a candidate region to exert this attentional control function (see below). In this context, the interesting question arose as to whether attentional selection works through boosting the processing of task-relevant information and/or through inhibition the processing of task-irrelevant information (e.g. Banich et al., 2000; Egner & Hirsch, 2005). In the present study, the two oddball conditions showed – with few exceptions – a broad overlap of activation in posterior processing areas while they shared the same task-relevant information (size) and differed in the distracting task-irrelevant attribute dimension (word vs. color). This finding is compatible with the notion that boosting the processing of task-relevant information plays an especially important role in attentional selection and particularly in the processing (i.e. resolution) of cognitive interference (e.g. Wojciulik et al., 1998; Egner & Hirsch, 2005). Banich et al. (2000) also investigated the influence of the processing domain of task-irrelevant information during interference (i.e. conflict) processing by comparing two different versions of the Stroop task which differed in the task-irrelevant information of the presented stimuli but not in the dimension which had to be attended. While Banich and colleagues likewise found highly overlapping activations within the frontolateral cortex, in contrast to our data, they also reported a strong influence of task-irrelevant information on posterior processing regions, suggesting that attentional selection also involves modulating the processing of task-irrelevant information. However, task-irrelevant information in the Banich study was semantically related to the task-relevant information, which is not true for the oddball conditions in the present study and which may account for its strong influence on posterior activations. As pointed out by Banich and colleagues themselves, selection of task-relevant information by prefrontal regions may involve “alerting” all posterior brain regions that process information related to the current task set, even if this information is presented in the irrelevant dimension. Generally, when individuals direct their attention to one particular attribute of an item, increased activity is observed in the posterior brain region specialized for processing this visual attribute (e.g. human equivalent of MT or V5; O’Craven et al., 1997; Kastner et al., 1998; Martinez et al., 1999).

Color-oddballs compared to Word-oddballs elicited more extensive neural activations as well as a stronger effect in the RT data. Thus, both the behavioral and neuroimaging data indicated stronger interference emanating from Color-oddballs as compared to Word-oddballs which can be explained twofold: (a) Color also occurred as task-relevant attribute during the experimental course within the color-task, whereas word-meaning did not (see [2.1.2.2](#)). As color had been previously attended to as task-relevant information, it hence may have been better able to attract attentional resources even as task-irrelevant attribute. (b) Independent of the task context, color is inherently a quite salient and conspicuous attribute dimension that apparently can be cognitively represented in a rather direct manner. Word-meaning, in contrast, appears to be much less salient and requires mediating semantic decoding processes to be cognitively represented. Therefore, task-irrelevant deviances in color may be generally more outstanding and influential compared to task-irrelevant deviances in word meaning.

4.3 Neural activations to impose an attentional set

There was strong activation related to both Color- and Word-oddballs in posterior parts of the lateral PFC, belonging to the inferior frontal junction area (IFJA). As was emphasized in the introduction of the present work, there is a growing body of evidence suggesting an important role of this cortical region in task-set management as well as in the selection of task-relevant over task-irrelevant information (see [1.3.5](#)). For instance, the IFJA has been related to task-set preparation (Brass and von Cramon, 2004; Gruber et al., 2006), cognitive set shifting (e.g. Konishi et al., 1998; Konishi et al., 1999; Dove et al., 2000; Derrfuss et al., 2005), response inhibition (Konishi et al., 1999; Konishi et al., 2003), as well as to the processing of Stroop-incongruency (e.g. Leung et al., 2000; Zysset et al., 2000; Milham et al., 2003a, Derrfuss et al., 2005), and task-irrelevant oddball events (e.g. Milham et al., 2003a; Gruber & Goschke, 2004; Melcher et al., 2003). In a study similar to the present work, Milham and colleagues (Milham et al., 2003a; see also [1.3.5](#)) sought to investigate prefrontal involvement in top-down attentional control, and thereby they wanted to elucidate whether Stroop interference and word oddball interference produce similar or distinct neural activation. As one main result, word oddball trials and Stroop-incongruent trials produced marked activation overlap in a posterior region of the PFC which belongs to the IFJA. Based on this and prior findings, Milham and colleagues concluded that the posterior inferior PFC is substantially involved in manipulating posterior regions to ensure selection of task-relevant information. In contrast to Milham's results, the current data exhibited no IFJA activation in relation to Stroop-interference as represented by the contrast RI-CO. Rather, the current data exhibited IFJA

activation only in relation to Color- and Word-oddballs, that nevertheless can be assumed to underlie the same cognitive control function as the IFJA activation in the Milham study. The reported discrepancy of findings can be plausibly attributed to differences between the contrasts that have been computed to define effects of Stroop-interference in the current investigation and in the Milham study. While in the analyses of the current work response-eligible incongruent trials were contrasted against congruent trials (RI-CO) – a contrast which arguably equalizes at least partly for attentional processing (see [4.1.1](#)) – Milham and colleagues contrasted response-eligible incongruent trials against response-ineligible incongruent trials. Response-ineligible incongruent color words, in contrast to congruent color words, are not part of the task-set (i.e. response-set) and therefore might be expected to be less salient (i.e. attention-capturing) as compared to both incongruent-eligible and congruent trials. Hence, the contrast “incongruent-eligible vs. incongruent-ineligible” in the Milham study arguably not only includes motor but also substantial attentional components of interference processing.

Note: In a previous subsection of the discussion (see [4.1.1](#)), the discrepancy of neuroimaging findings, regarding the involvement of the IFJA in Stroop-interference, between the current work and a Stroop study of Zysset and collaborators (Zysset et al., 2000) was explained in a very similar and compatible way.

In the current work, the contrast RI-SU was additionally computed in order to derive effects of Stroop-interference from the same baseline as the oddball effects. In this contrast, Stroop-interference did exhibit a significant activation in the IFJA. This finding corroborates the above explanation for differences regarding the IFJA involvement in the present work and the Milham study. As word meaning on SU trials is not semantically related to the task at hand (i.e. is not part of the task-set), the contrast can be expected to map not only motor but also attentional components of interference.

Taken together, in accordance with findings of prior investigations (e.g. Banich et al., 2000; Zysset et al., 2000; Milham et al., 2003a; Brass & von Cramon, 2004), the current data emphasize a prominent role of the posterior inferior frontolateral cortex, i.e. the IFJA, in attentional control. Particularly, the IFJA may provide a top-down executive mechanism for imposing an attentional set for task-relevant information by modulating processing in posterior neuronal perceptual systems.

This putative role of the IFJA is also in line with the widespread general assumption of a basically twofold functional and neural organization of cognitive control comprising a monitoring or evaluative instance represented by frontomedian cortices and an executive or

regulative instance represented by frontolateral cortices. Specifically, the conflict monitoring theory (see [1.3.3](#)) postulates that the anterior cingulate cortex (AAC) monitors for and responds to the occurrence of conflict in information processing and thereby signals the frontolateral cortex to strengthen control efforts in a context-sensitive manner (e.g. Carter et al., 1998; MacDonald et al., 2000; Botvinick et al., 2001; Kerns et al., 2004). However, neuroimaging studies providing evidence for the conflict monitoring theory most consistently pointed to the more anteriorly located mid-dorsolateral prefrontal cortex (mid-DLPFC) rather than the IFJA as the crucial frontolateral area in cognitive control (Petrides, 2000; see [1.3.3](#)). In contrast, the current data – in line with a recent series of brain imaging studies – indicate that the IFJA represents the primary frontolateral region in the exertion of top-down attentional control (see [1.3.5](#); for a review see Brass et al., 2005). Taken together, findings may give rise to the speculation that the primary role attributed to mid-DLPFC in the context of cognitive control and frontolateral cortex function is owed to the fact that consistent activation in the IFJA has been neglected (see Brass et al., 2005).

4.4 Conflict factors during Stroop task performance

One major issue of the current work was to trace back Stroop-interference to the influence of circumscribed properties of task-irrelevant word information that can be conceived as conflict factors (see [1.2.1](#)), and thereby to determine the properties' (i.e. the conflict factors') neural effects. In particular, it was sought to delineate the neural substrates of three conflict factors: **(A) response-incompatibility** (i.e. word identity indicates an opposed response), **(B) semantic incongruency** (i.e. word identity is incongruent, independent of its response-eligibility), and **(C) task-reference** (i.e. word identity is semantically related to the task-set, independent of its semantic concordance with the relevant dimension) (see [1.4.2.3](#)).

Specifically, it was planned to split activations of the contrast RI-CO – that have been already presented and discussed in prior subsections (see [3.2.1.1](#) and [4.1](#)) – in two subgroups referring to response-incompatibility and semantic incongruency that reflect motor conflict and semantic conflict, respectively. For this purpose, conflict factors were assigned to common activations of contrast pairings (i.e. to contrast conjunctions) comprising the contrast RI-CO on the one hand and one further contrast – RI-SI for response-incompatibility and SI-CO for semantic incongruency – on the other hand (see [2.2.1.3.3](#)). Furthermore, it was planned to determine the influence of task-reference of task-irrelevant word meaning – i.e. being a

(response-eligible) size word – as third conflict factor that is inherent in both incongruent and congruent trials, and that might essentially contribute to the overall Stroop interference effect.

4.4.1 Splitting intermingled effects of response-incompatibility and semantic incongruency

4.4.1.1 Behavioral effects of response-incompatibility and semantic incongruency

The behavioral data showed that only response-incompatibility (as implemented in RI trials) but not semantic incongruency (as implemented in SI trials) led to significantly increased RTs, i.e. produced a behavioral effect. Although SI trials exhibited descriptively longer RTs compared to both CO and SU trials, the corresponding behavioral effects did not reach the level of statistical significance. In contrast, van Veen and Carter (van Veen & Carter, 2005) observed significantly prolonged RTs for both eligible-incongruent (widely corresponding to RI) and ineligible-incongruent (widely corresponding to SI) trials (compared to congruent trials), indicating a behavioral effect of both response-incompatibility (i.e. response conflict) and semantic incongruency (i.e. semantic conflict). However, the study of van Veen and Carter used another Stroop paradigm that was introduced by De Houwer (2003) which may account for the divergent findings. The outstanding feature of this paradigm is that it contains four response-eligible color values (and none response-ineligible value), two for each response side (i.e. response category). Therefore, in De Houwer's paradigm, on each trial type – RI, SI, and CO trials – the distracting word information is part of the response-set. This feature was explicitly implemented to create a Stroop paradigm that experimentally controls for response eligibility (response mapping). In contrast to De Houwer's paradigm, the word meaning of the SI condition in the current work is response-ineligible which might explain that the behavioral effect of this condition did not reach the statistical threshold. Moreover, and also in contrast to the current work, van Veen & Carter used color rather than size as relevant dimension, while a semantically incongruent color word might be more influential as the semantically incongruent size-related word 'BROAD'.

4.4.1.1 Neural effects of response-incompatibility and semantic incongruency

The conjunction analyses revealed only one activation focus specific to response-incompatibility which was located in the left precentral gyrus. This region belongs to the ventral premotor cortex (BA 6). Generally, as already evident from its name, the premotor

cortex is well known to play a pivotal role in the planning or preparation of motor responses, i.e. limb movements (e.g. Ikeda, 1992; Wiese et al., 2004). Specifically, a number of neuroimaging studies related activation in the ventral premotor cortex (i.e. inferior precentral gyrus) to the imagination, selection, and execution of contralateral finger movements (e.g. Cunnington et al., 2006), suggesting that the activated area is part of (or corresponds to) the finger or hand representation of the premotor cortex. Therefore, in the current data, this activation focus conceivably reflects incremental or competing (button-press) response tendencies (in terms of response conflict) induced by response-incompatible word emanating. In line with this assertion, several other studies that used button-presses as response categories observed activation in the ventral premotor cortex under conditions of response competition, e.g. in the flanker task (Ullsperger & von Cramon, 2001) and in the Stroop task (Leung et al., 2000; Mead et al., 2002). The attribution of this activation focus specifically to response-incompatibility (rather than semantic incongruency) in the current work further corroborates this interpretation.

Other activations of the contrast RI-CO appeared as common activation with the contrast SI-CO and therefore were attributed (i.e. assigned) to semantic incongruency. These activations mainly comprised the posterior frontomedian cortex (pre-SMA), the left postcentral (i.e. somatosensory) cortex, the cerebellum, as well as the basal ganglia and thalamus. In a previous subsection, these activation foci have been already discussed as reflecting strengthened motor control efforts to prevent false responding, i.e. to ensure task-appropriate performance (see [4.1.1](#)). For instance, the observed somatosensory activation was discussed as conceivable neural substrate of enhanced “proprioceptive attention” to the responding fingers as one aspect of strengthened motor control. Semantic incongruency further appeared related to activation in the bilateral anterior insula. For a long time, the insula has been primarily or even exclusively related to non-cognitive functions (e.g. visceral, sensational functions) as well as to language comprehension and production (Augustine, 1985/1996). However, recent studies seem to implicate the insula in top-down attentional processing. For instance, insular activity has been reported related to cognitive interference (Egner & Hirsch, 2005; Leung et al., 2000), inhibitory filtering of invalid information (Thomsen et al., 2005), and selective stimulus processing (Hopfinger et al., 2000). The reported findings may lead one to conjecture that activity in the insula generally contributes to cognitive control to minimize or resolve interference. Alternatively, insular activation during cognitive interference may underlie an altered body sensation – e.g. enhanced tenseness – related to the agent’s efforts to meet the increased situational requirements.

Taken together, the activation pattern related to semantic incongruency conceivably underlies strengthened control efforts, particularly selective motor processing in terms of reinforcing or shielding the correct and/or inhibiting the incorrect response (see above; [4.1.1](#)). Hence, the current findings suggest that the neural executive system recruits strengthened motor control already in case of semantic conflict without the occurrence of proper response competition. As semantic conflict generally does not implicate an enhanced error probability (e.g. van Veen & Carter, 2005), strengthened motor control in response to pure semantic incongruency on SI trials may appear somewhat unnecessary. However, as the cognitive system also encountered response conflict and perhaps detected erroneous responses on previous RI trials that also included semantically incongruent word meaning (i.e. also included semantic incongruency as conflict factor), it may recruit control mechanisms in a preventive (rather than remedial) manner on both RI and SI trials. Hence, the current data provide no evidence for the existence of different control mechanisms for the processing (i.e. the resolution) of response conflict and semantic conflict which has been proposed by van Veen and Carter in the above-mentioned fMRI Stroop study (see van Veen & Carter, 2005). Essentially, this study showed a double dissociation of activation in ACC and DLPFC for the comparison between response conflict and semantic conflict. Based on this finding, the authors proposed that the neural control system possesses two distinct and parallel attentional networks in conflict processing that are specific to the level of cognitive processing – either the semantic or the motor level – at which conflict occurs. In contrast to this notion, the present investigation's findings suggest that conflict processing recruit the same attentional mechanisms regardless of whether conflict occurs solely at the semantic level or additionally at the motor level.

4.4.2 Competition and residual semantic processing due to task-reference

All three conditions RI, SI, and CO trials included lexical word meaning that was semantically related to the task-set, i.e. provided competing size-information. It has been proposed that task-related irrelevant information may generally cause competition in information processing (see Milham et al., 2002; Milham & Banich, 2005). Accordingly, several authors have suggested that congruent Stroop-trials may have increased attentional requirements relative to neutral (i.e. semantically unrelated) Stroop-trials (Carter et al., 1995; Posner & Girolamo, 1998; Milham et al., 2002; Milham & Banich, 2005; see [4.1.1](#)). In the current work, to define the neural substrate of task relatedness or task-reference – the third conflict factor of interest – the contrast CO-SU was computed. This contrast revealed

circumscribed activation in rostro-ventral regions of the left inferior frontal cortex (BA 47 / BA 11), the right medial superior frontal cortex (BA 9), and in the left temporal pole (BA 38). There is a body of empirical evidence for each of these cortical areas to implicate them in semantic processing of linguistic tokens. Therefore, the current data's activations in these areas may be conclusively interpreted as reflecting residual semantic processing of task-irrelevant lexical word meaning when this is related to the task-set. In particular, results of imaging studies using both PET and fMRI strongly suggest that activation in the left inferior prefrontal cortex is directly related to stimulus-driven semantic processing. Specifically, anterior inferior frontal regions in the left hemisphere have been repeatedly shown to exhibit stronger activity in semantic than in non-semantic word-level processing and thus may substantially contribute to semantic elaboration (Petersen et al., 1988; Poldrack et al., 1999; Noppeney & Price, 2002). Likewise, neuroimaging studies converge to suggest that the left TPC plays a particularly important role in meaning or concept identification of lexical information. For instance, the left-hemispherical temporal pole has been implicated in word recollection and word comparison (e.g. Damasio et al., 1996, Vandenberghe et al., 1996), semantic priming (e.g. Kutas & Hillyard, 1984, Mummery et al., 1999), as well as meaning composition during sentence reading (e.g. Stowe et al., 1998), and focal lesions in this region have been associated with semantic deficits (for review, see Saffran & Sholl, 1999). Finally, there are studies that reported activation in dorsal frontomedian cortex which included linguistic tasks that require meaning-based inductive reasoning (Goel et al., 1997), semantic coherence judgments (Ferstl & von Cramon, 2001) and semantic categorizations (Binder et al., 1997).

Against an interpretation of the superior frontal activation as reflecting semantico-linguistic processing, one may object that this activation focus is localized in the right hemisphere. Generally, there is a strong dominance of the left hemisphere for the majority of language functions, and the right hemisphere normally does not appear to have much responsibility for basic cognitive-linguistic processes (Capozzoli, 1999; Gernsbacher & Kaschak, 2003). However, higher-order linguistic processes like meta-semantic interpretations or inferences (e.g. understanding metaphors, indirect requests, and humor) have been related to bilateral activations equally involving the right hemisphere, including prefrontal regions (e.g. Bottini et al., 1994; Mitchell & Crow, 2005). Furthermore, it has been proposed that the right hemisphere gets specifically involved in lexical processing when subordinate associations rather than basic semantic connotations of a given word form become relevant (Coney & Evans, 2000). Hence, the right-hemispherical location of the superior frontal activation does

not contradict the interpretation of semantic-linguistic processing but rather converges with prior studies findings.

Taken together, incremental (i.e. increased) semantic processing of task-irrelevant information may provide a meaningful and plausible concretization of ‘competition’ between task-relevant and task-irrelevant information during Stroop-performance which has been expected to occur during both incongruent and congruent trials (see Milham et al., 2002; Milham & Banich, 2005).

4.5 Outlook – Future Directions

The present data revealed definitive and meaningful results regarding the current work’s questions and purposes. Hence, findings may significantly contribute to refine and broaden the understanding of neural mechanisms that underlie cognitive control during cognitive interference. Beyond the current work’s objectives, results raise interesting new questions and thus may provide a fruitful basis or starting point for related successional investigations. In this last subsection, different issues for potential future projects to build up on the present work’s findings will be stated.

4.5.1 Replicating current findings within the ‘traditional’ color word Stroop task

It would be a particularly interesting issue to replicate findings of the present study with a more “traditional” version of the Stroop task that uses ink color instead of font size as relevant target attribute. In the current work, font size was chosen as target dimension because this allowed to implement a color oddball condition that consisted of a task-irrelevant rarely occurring and response-ineligible color value. To create a suchlike color oddball condition – which was one main issue of the present work – would not have been feasible within a traditional color Stroop task where color already serves as target dimension (see [2.1.3.2](#)). Specifically, a related study that uses a color Stroop paradigm could elucidate whether the two distinct components of cognitive interference that have been delineated in the present work – a motor component and an attentional component (see [4.1](#)) – can be replicated across different paradigm versions. Similarly, one may repeat the factorial decomposition analyses – conducted in the present work to define the neural substrates of the defined conflict factors (response-incompatibility, semantic incongruency, and task-reference; see [4.4](#)) – on neuroimaging data that have been acquired during subject’s performance of a color Stroop

task version. The underlying question here would be whether the defined conflict factors exhibit comparable neural substrates across different task versions of the Stroop paradigm. In both outlined cases, replications of findings would confirm the present conclusions and interpretations concerning the existence of different neurocognitive (sub-)components of interference resolution and their respective characters. On the other hand, functional neuroanatomical dissociations could also be instructive as these might give relevant insights in the task- or context-dependency of the delineated neurocognitive mechanisms.

4.5.2 Investigation of the influence of transient emotional states on cognitive control processes

The existence of a close interaction between cognitive processes and emotional states is intuitively evident, as it is commonly manifest in everyday human experience and behavior. Thereby, emotional states can attenuate cognitive activity, and vice versa, in terms of a reciprocal suppression (e.g. Drevets & Raichle, 1998). Prior neuroimaging studies support the view that an interplay between emotion and cognition is reflected in discernable changes in the brain's functional anatomy (e.g. Lane et al., 1998; Pessoa & Ungerleider, 2004). However, further tests to substantiate this hypothesis are needed. Thereby, the behavioral and neural instantiation of the influence of experimentally induced – either negative or positive – emotional states on Stroop-task performance would be an especially relevant issue, as the Stroop paradigm is among the most widely used and cited experimental tasks to investigate cognitive control mechanisms. In particular, future studies may be set out to examine the susceptibility of the neurocognitive mechanisms of interference processing – particularly those that were defined in the current work – to the agent's current emotional state. As a concrete procedure, one may apply standardized picture materials – for instance, the IAPS (International Affective Picture System; Lang, et al., 1988/1995/2005) – to look at the influence of emotion on cognition on a trial-by-trial basis. Such a study design would allow to systematically expand the analyses of the current work by additionally including “emotional state” (in terms of a pre-induced transient emotional arousal state) as factor or moderator variable in the statistical model and thereby to elucidate its influence on the created condition contrasts and contrast conjunctions, i.e. on the respective neurocognitive mechanisms and components.

4.5.3 Functional specialization and functional integration of circumscribed brain areas

The present findings provide interesting insights into the ‘*functional specialization*’ of circumscribed brain areas in the context of cognitive or attentional control. For instance, the present findings support the assumption that the inferior frontal junction area (IFJA) essentially contributes to top-down attentional control during competition by biasing activation in posterior sensory systems (see 4.3). Moreover, activation in the left temporo-polar cortex was conclusively interpreted as reflecting residual semantic processing of distracting, task-irrelevant information when this is related to the current task-set (see 4.4.2), and the ventral somatosensory (i.e. postcentral) cortex was convincingly implicated in motor control or motor attention in the case of cognitive conflict (see 4.4.1). The present findings and their interpretations may motivate future studies that seek to further elucidate the functional specialization of certain of the highlighted cortical areas in cognitive control. Generally, the term ‘functional specialization’ denotes regionally specific effects – i.e. physiological variations in a circumscribed neuroanatomical area – that can be attributed to changes in stimuli or task-conditions and thus can be (indirectly) related to cognitive factors or processes (Friston, 1998). However, this approach might not be sufficient for an adequate description of the neural implementation of neurocognitive mechanisms or functions, as it completely neglects interactions among the actually focused and other distant brain areas. In other words, cognitive control may not be meaningfully conceptualized as activity of single, isolated neuroanatomical units but rather as emanating from multiple interacting cortical and subcortical areas that together constitute functionally specialized neural networks. Accordingly, it would be an important and highly relevant issue to investigate the functional connectivity of areas that exhibited prominent activation in the current data. There exists a number of statistical approaches that allow to address functional integration or interactions between different brain areas by looking for correlations among activity in different brain areas, i.e. by trying to explain activity in one brain area in relation to others (e.g. Friston et al., 1993; McIntosh et al., 1994). These analyses are usually conceptually framed in terms of ‘*effective connectivity*’, which means that statistical relations are construed as (direct) influence that one area exerts over another. The term ‘*functional connectivity*’, on the other hand, denotes a mere co-occurrence of activation in different brain regions without inferring directional or causal interpretations. The concept of ‘*psychophysiological interactions*’ (PPIs) (Friston et al., 1997) provides a very interesting and valuable statistical approach for the investigation of functional integration, according to the authors who developed this approach,

in terms of effective connectivity. The basic idea behind PPI analyses is to explain responses in one cortical area in terms of an interaction between the influence of another area and some experimental (e.g. cognitive or sensational) parameter. In other words, a PPI means that the contribution of one area to another area changes significantly with the experimental context, i.e. with the required cognitive performance. Future studies may purposefully look for PPIs of certain areas that exhibited prominent activation in the current study and thereby may further elucidate their functional role or contribution to cognitive control, especially during Stroop task performance. For instance, it would be of special relevance to look for connectivity patterns of the IFJA during oddball conditions or of the primary somatosensory cortex during conditions of motor conflict so as to further elucidate the areas' contribution to cognitive control at the attentional and motor level, respectively.

References

- Allport, D.A., 1989. Visual attention. In: M.I. Posner (Ed.), *Foundations of cognitive science* (pp. 631–682). The MIT Press, Cambridge, MA.
- Amunts, K., Palomero-Gallagher, N., Brass, M., Derrfuss, J., Zilles, K., von Cramon, D. Y., 2004. A receptor- and cytoarchitectonic correlate of the functionally defined inferior-frontal junction area. *Neuroimage*, 22 (Suppl.), 50.
- Aron, A.R., Schlaghecken, F., Fletcher, P.C., Bullmore, E.T., Eimer, M., Barker, R., Sahakian, B.J., Robbins, T.W., 2003. Inhibition of subliminally primed responses is mediated by the caudate and thalamus: evidence from functional MRI and Huntington's disease. *Brain*, 126, 713-723.
- Augustine, J.R., 1985. The insular lobe in primates including humans. *Neurological Research*, 7, 2-10.
- Augustine, J.R., 1996. Circuitry and functional aspects of the insular lobe in primates including humans. *Brain Research Reviews*, 22, 229-244.
- Baddeley, A.D. (1986). *Working memory*. Oxford: Clarendon Press.
- Baddeley, A.D. (1990). *Human memory: Theory and practice*. Oxford, Oxford University Press.
- Bandettini, P.A., Kwong, K.K., Davis, T.L., Tootel, R.B., Wong, E.C., Fox, P.T., Belliveau, J.W., Weisskopf, R.M., Rosen, B.R., 1997. Characterization of cerebral blood oxygenation and flow changes during prolonged brain activation. *Human Brain Mapping*, 5, 93-109.
- Barbas, H., Mesulam, M.M., 1981. Organization of afferent inputs to subdivisions of area 8 in rhesus monkey. *Journal of Comparative Neurology*, 200, 407-431.

- Barkley, R.A., 1996. Linkages between attention and executive functions. In G.R. Lyon & N.A. Krasnegor (Eds.). *Attention memory, and executive function* (pp. 307-325). Baltimore, MD: Paul Brookes.
- Barkeley, R.A., 1997. Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, 121, 65-94.
- Berti, S., Schroger, E., 2001. A comparison of auditory and visual distractor effects: behavioral and event-related indices. *Cognitive Brain Research*, 10, 265-273.
- Binder, J. R., Frost, J. A., Hammeke, T. A., Cox, R. W., Rao, S. M., Prieto, T., 1997. Human brain language areas identified by functional magnetic resonance imaging. *Journal of Neuroscience*, 17, 353-362.
- Bledowski, C., Prvulovic, D., Goebel, R., Zanella F.E., Linden D.E.J., 2004. Attentional systems in target and distractor processing: a combined ERP and fMRI study. *Neuroimage*, 22, 530-540.
- Bottini, G, Corcoran, R., Sterzi, R., Paulesu, E., Schenone, P., Scarpa, P., Frackowiak, R.S.J., Frith, D., 1994. The role of the right hemisphere in the interpretation of figurative aspects of language. A positron emission tomography activation study. *Brain*, 117, 1241-1253.
- Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S. & Cohen, J. D., 1999. Conflict monitoring versus selection-for-action in the anterior cingulate cortex. *Nature*, 402, 179–181.
- Botvinick, M.B., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D., 2001. Conflict monitoring and cognitive control. *Psychological Review*, 108, 624-652.
- Botvinick, M.M., Cohen, J.D., Carter, C.S., 2004. Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Science*, 8, 539-546.
- Brass, M., von Cramon, D.Y., 2004. Decomposing components of task preparation with functional magnet resonance imaging. *Journal of Cognitive Neuroscience*, 16, 609-620.

Brass, M., Derrfuss, J., Forstmann, B., & von Cramon, D. Y., 2005. The role of the inferior frontal junction area in cognitive control. *Trends in Cognitive Sciences*, 9, 314-316.

Brown, J.W., Braver, T.S., 2005. Learned predictions of error likelihood in the anterior cingulate cortex. *Science*, 307, 1118-1121.

Buxton, R.B., Frank, L.R., 1997. A model for the coupling between cerebral blood flow and oxygen metabolism during neural stimulation. *Journal of Cerebral Blood Flow and Metabolism*, 17, 64-72.

Capazzoli, N. J., 1999. Why do we speak with the left hemisphere. *Medical Hypotheses* 52, 497-503.

Carter, S.C. Mintun, M., Cohen, J.D., 1995. Interference and facilitation effects during selective attention: An H215O PET study of Stroop task performance. *Neuroimage*, 2, 264-272.

Cohen, J. D., Braver, T. S., O'Reilly, R. C., 1996. A computational approach to prefrontal cortex, cognitive control and schizophrenia: Recent developments and current challenges. *Philosophical Transactions of the Royal Society, Series B* 351, 1515-1527.

Cohen, J. D., Dunbar, K., McClelland, J. L., 1990. On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, 97, 332-361.

Coney, J., Evans, K. D., 2000. Hemispheric asymmetries in the resolution of lexical ambiguity. *Neuropsychology*, 38, 272-282.

Courchesne, E., Hillyard, S.A. and Galambos, R., 1975. Stimulus novelty, task relevance and the visual evoked potential in man. *Electroencephalography Clinical Neurophysiology*, 39, 131-143.

- Corbetta, M., Miezin, F.M., Dobmeyer, S., Shulman, G.L., Petersen, S.E., 1991. Selective and divided attention during visual discrimination of shape, color, and speed: Functional anatomy by positron emission tomography. *Journal of Neuroscience*, 11, 2382-2402.
- Corbetta, M., Miezin, F.M., Shulman, G.L., Petersen, S.E., 1993. A PET study of visuospatial attention. *Journal of Neuroscience*, 13, 1202-1226.
- Corbetta, M., Kincade, J.M., Shulman, G.L., 2002. Neural systems for visual orienting and their relationships to spatial working memory. *Journal of Cognitive Neuroscience*, 14, 508-523.
- Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3, 201-215.
- Cunnington, R., Windischberger, C., Robinson, S., Moser, E., 2006. The selection of intended actions and the observation of others' actions: A time-resolved fMRI study. *Neuroimage*, 29, 1294-1302.
- Dalrymple-Alford, E.C., Budayr B., 1966. Examination of some aspects of the Stroop Color-Word Test. *Perceptual and Motor Skills*, 23, 1211-1214.
- Dalrymple-Alford, E.C., 1972. Associative facilitation and interference in the Stroop Color-Word Test. *Perception and Psychophysics*, 11, 274-276.
- Damasio, H., Grabowski, T.J., Tranel, D., Hichwa, R.D., Damasco, A.R., 1996. A neural basis for lexical retrieval. *Nature*, 380, 499-505.
- Damasio, H., Tranel, D., Grabowski, T., Adolphs, R., Damasco, A., 2004. Neural systems behind word and concept retrieval. *Cognition*, 92, 179-229.
- De Houwer, J., 2003. On the role of stimulus-stimulus and stimulus-response compatibility in the Stroop effect. *Memory and Cognition*, 31, 353-359.

Derrfuss, J., Brass, M., Neumann, J., & von Cramon, D. Y., 2005. Involvement of the inferior frontal junction in cognitive control: meta-analyses of switching and Stroop studies. *Human Brain Mapping*, 25, 22-34.

Derrfuss, J., Brass, M., von Cramon, D. Y., 2004. Cognitive control in the posterior frontolateral cortex: evidence from common activations in task coordination, interference control, and working memory. *Neuroimage*, 23, 604-612.

Desimone, R., Duncan, J., 1995. Neural mechanisms of selective visual attention. *Annual Review of Neuroscience* 18, 193-222.

D'Esposito, M., Detre, J.A., Alsop, D.C., Shin, R.K., Atlas, S., Grossman, M., 1995. The neural basis of the central executive system of working memory. *Nature*, 378, 279 – 281.

Dove, A., Pollmann, S., Schubert, T., Wiggins, C., von Cramon, D. Y., 2000. Prefrontal cortex activation in task switching: an event-related fMRI study. *Cognitive Brain Research*, 9, 103-109.

Downar, J., Crawley, A.P., Mikulis, D.J., Davis, K.D., 2000. A multimodal cortical network for the detection of changes in the sensory environment. *Nature Neuroscience*, 3, 277-283.

Downar, J., Crawley, A.P., Mikulis, D.J., and Davis, K.D., 2001. The effect of task-relevance on the cortical response to changes in visual and auditory stimuli: an event-related fMRI study. *Neuroimage*, 14, 1256-1276

Drevets, W.C., Raichle, M.E., 1998. Reciprocal suppression of regional cerebral blood flow during emotional versus higher order cognitive processes: implications for interactions between emotion and cognition. *Cognition and Emotion*, 12, 353-385.

Dunbar, K.N., MacLeod, C.M., 1984. A horse race of a different color: Stroop interference patterns with transformed words. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 622-639.

Egner, T., Hirsch, J., 2005. The neural correlates and functional integration of cognitive control in the Stroop task. *Neuroimage*, 24, 539-547.

Ernst, T., Hennig, J., 1994. Observation of a fast response in functional MR. *Magnetic Resonance in Medicine*, 32, 146-149.

Escera, C., Alho, K., Winkler, I., Näätänen, R., 1998. Neural mechanisms of involuntary attention to acoustic novelty and change. *Journal of Cognitive Neuroscience*, 10, 590-604.

Fan, J., Flombaum, J.I., McCandliss, B.D., Thomas, K.M., Posner, M.I., 2003. Cognitive and brain consequences of conflict. *Neuroimage*, 18, 42-57.

Falkenstein M., Hoormann J., Christ S., Hohnsbein J., 2000. ERP components on reaction errors and their functional significance. A tutorial. *Biological Psychology*, 51, 87-107.

Ferstl, E.C., von Cramon, D.Y., 2001. The role of coherence and cohesion in text comprehension: an event-related fMRI study. *Cognitive Brain Research*, 11, 325-340.

Fisher, R.A. (1935). *The design of experiments*. Edinburgh: Oliver & Boyd.

Friston, K.J., 1998. Imaging neuroscience: Principles or maps? *Proceedings of the National Academy of Sciences*, 95, 796-802.

Friston, K.J., Frith, C.D., Frackowiak, R.S.J., 1993. Time-dependent changes in effective connectivity measured with PET. *Human Brain Mapping*, 1, 69-80.

Friston, K.J., Buechel, C., Fink G. R.; Morris, J. Rolls, E., Dolan, R.J, 1997. Psychophysiological and Modulatory Interactions in Neuroimaging. *Neuroimage*, 6, 218-229.

Frith, C. 2001. A framework for studying the neural basis of attention. *Neuropsychologia*, 39, 1367-1371.

Gati, J.S., Menon, R.S., Ugurbil, K., Rutt, B.K., 1997. Experimental determination of the BOLD field strength dependence in vessels and tissue. *Magnetic Resonance in Medicine*, 38, 296-302.

Gerardi-Caulton, G. (2000). Sensitivity to spatial conflict and the development of self-regulation in children 24–36 months of age. *Developmental Science*, 3, 397–404.

Gernsbacher, M. A., Kaschak, M. P., 2003. Neuroimaging studies of language production and comprehension. *Annual Review of Psychology*, 54, 91-114.

Gitelman, D.R., Nobre, A.C., Parrish, T.B., LaBar, K.S., Kim, Y.H., Meyer, J.R., Mesulam, M.M., 1999. A large-scale distributed network for covert spatial attention: Further anatomical delineation based on stringent behavioural and cognitive controls. *Brain*, 122, 1093-1106.

Glaser, M.O. & Glaser, W.R. (1982). Time course analysis of the Stroop phenomenon. *Journal of Experimental Psychology: Human Perception and Performance*, 8, 875-894.

Goel, V., Gold, B., Kapur, S., Houle, S., 1997. The seats of reason? An imaging study of deductive and inductive reasoning. *Neuroreport*, 8, 1305-1310.

Goschke, T., 2003. Voluntary action and cognitive control from a cognitive neuroscience perspective. In: Maasen, S., Prinz, W., Roth, G. (Eds.), *Voluntary action. An issue at the interface of nature and culture* (pp. 49-85). Oxford University Press, Oxford.

Gruber, O., Goschke, T., 2004. Executive control emerging from dynamic interactions between brain systems mediating language, working memory and attentional processes. *Acta Psychologica*, 115, 115-122.

Gruber, O., 2005. Direkte Darstellbarkeit kognitiver Defizite fraglich. Diskussionsbeitrag (letter) zu T. Kircher et al.: Funktionelle Bildgebung am Beispiel der Schizophrenie. *Deutsches Ärzteblatt*, 102, 177.

Gruber, O., Karch, S., Schlueter, E., Falkai, P., Goschke, T., 2006. Neural mechanisms of advance preparation in task switching. *Neuroimage*, 31, 887-895.

- Huettel, S.A., Güzeldere, G., McCarthy, G., 2001. Dissociating the neural mechanisms of visual attention in change detection using functional MRI. *Journal of Cognitive Neuroscience*, 13, 1006-1018.
- Hopfinger, J.B., Buonocore, M.H., Mangun, G.R., 2000. The neural mechanisms of top-down attentional control. *Nature Neuroscience*, 3, 284-291.
- Kanwisher N., McDermott J., Chun, M.M., 1997. The fusiform face area: a module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience*, 17, 4302-4311.
- Kastner, S., de Weerd, P., Desimone, R., Ungerleider, L., 1998. Mechanisms of directed attention in the human extrastriate cortex as revealed by functional MRI. *Science*, 282, 108-111.
- Kastner, S., Pinsk, M.A., De Weerd, P., Desimone, R., Ungerleider, L.G., 1999: Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron*, 22, 751-761.
- Kastner, S., Ungerleider, L.G., 2000. Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience*, 23, 315-341.
- Kawashima, R., Roland, P.E., O'Sullivan, B., 1995. Functional anatomy of reaching and visuomotor learning: a positron emission tomography study. *Cerebral Cortex*, 5, 111-122.
- Kerns J.G., Cohen J.D., MacDonald A.W. 3rd, Cho R.Y., Stenger V.A., Carter C.S., 2004. Anterior cingulate conflict monitoring and adjustments in control. *Science*, 303, 1023-1026.
- Kiehl, K.A., Liddle, P.F., Hopfinger, J.B., 2000. Error processing and the rostral anterior cingulate: An event-related fMRI study. *Psychophysiology*, 37, 216-223.
- Klein, G.S., 1964. Semantic power measured through the interference of words with color-naming. *American Journal of Psychology*, 77, 576-588.

Knight, R., 1996. Contribution of human hippocampal region to novelty detection. *Nature*, 383, 256-259.

Konishi, S., Nakajima, K., Uccida, I., Kameyama, M., Nakahara, K., Sekihara, K., Miyshita, Y., 1998. Transient activation of inferior prefrontal cortex during cognitive set shifting. *Nature Neuroscience*, 1, 80-84.

Konishi, S., Nakajima, K., Uccida, I., Kameyama, M., Miyshita, Y., 1999. Common inhibitory mechanisms in human inferior prefrontal cortex revealed by event-related functional MRI. *Brain*, 122, 981-991.

Konishi, S., Jimura, K., Asari, T., Miyshita, Y., 2003. Transient activation of superior prefrontal cortex during inhibition of cognitive set. *Journal of Neuroscience*, 23, 7776-7782.

Kuhl, J., 1985. Volitional mediators of cognitive-behavior consistency: Self-regulatory processes and actions versus state orientation. In: J. Kuhl & J. Beckmann (Eds.). *Action control: From cognition to behavior* (pp. 101–128). Springer, Berlin.

Kutas, M., Hillyard, S. A., 1984. Brain potentials during reading reflect word expectancy and semantic association. *Nature*, 307, 161-163.

LaBerge, D., 1997. Attention, awareness, and the triangular circuit. *Cons. Cogn.* 6, 149-181.

LaBerge, D., 2005. Sustained attention and apical dendrite activity in recurrent circuits. *Brain Research Reviews*, 50, 86-99.

Lang, P.J., Öhmann, A., Vaitl, D., 1988. *The international affective picture system*. University of Florida, Gainesville, FL.

Lang, P.J., Bradley, M.M., Cuthbert, B.N., 1997. *International affective picture system (IAPS): Technical manual and affective ratings*. Gainesville, FL: NIH Center for the Study of Emotion and Attention.

- Lang, P.J., Bradley, M.M., Cuthbert, B.N., 2005. International affective picture system (IAPS): Digitized photographs, instruction manual and affective ratings. Technical Report A-6. University of Florida, Gainesville, FL.
- Lane, R.D., Reiman, E.M., Axelrod, B., Yun, L.S., Holmes, A., Schwartz, G.E., 1997. Neural correlates of levels of emotional awareness: evidence of an interaction between emotion and attention in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, 10, 525-535.
- Logothetis, N. K., Pauls, J., Augath, M., Trinath, T., & Oeltermann, A., 2001. Neurophysiological investigation of the basis of the fMRI signal. *Nature*, 412, 150-157.
- MacDonald, A. W., Cohen, J. D., Stenger, V.A., Carter, C.S., 2000. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, 288, 1835-1838.
- MacLeod, C.M., 1991a. Half a century of research on Stroop effect: an integrative review. *Psychological Bulletin*, 109, 163-203.
- MacLeod, C.M., 1991b. John Ridley Stroop: Creator of a landmark cognitive task. *Canadian Psychology*, 32, 521-524.
- MacLeod, C.M., 1998. Training on integrated versus separated Stroop tasks: the progression of interference and facilitation. *Memory & Cognition*, 26, 201-211.
- MacLeod, C. M., 2005. The Stroop task in cognitive research. In Wenzel, A., Rubin, D. C. (Eds.), *Cognitive methods and their application to clinical research* (pp. 17-40). Washington, DC: American Psychological Association.
- McIntosh, A.R., Grady, C.L. Ungerleider, L.G., Haxby, J.V., Rapoport, SI, Horwitz, B., 1994. Network analysis of cortical visual pathways mapped with PET. *Journal of Neuroscience*, 14, 655-666.
- Mansfield, P. (1977). Multi-planar image formation using NMR spin echoes. *Journal of Physics C: Solid State Physics*, 10, L55-L58.

Markowitsch, H.J., 1995. Which brain regions are critically involved in the retrieval of old episodic memory? *Brain Research Reviews*, 21, 117-127.

Martinez, A., Anllo-Vento, L., Sereno, M.I., Frank, L.R., Buxton, R.B., Dubowitz, D.J., Wong, E.C., Hinrichs, H., Heinze, H.J., Hillyard, S.A., 1999. Involvement of striate and extrastriate visual cortical areas in spatial attention. *Nature Neuroscience*, 2, 364-369.

Mead, L.A., Mayer, A.R., Bobholz, J.A., Woodley, S.J., Cunningham, J.M., Hammeke, T.A., Rao, S.M., 2002. Neural basis of the Stroop interference task: response competition or selective attention? *Journal of the International Neuropsychological Society*, 8, 735-42.

Melcher, T., Karch, S., Goschke, T., & Gruber, O., 2004. Brain mechanisms involved in background monitoring for potential behavioral conflicts. Presented at the 10th Annual Meeting of the Organization for Human Brain Mapping, June 2004, Budapest, Hungary. Available on CD-Rom in *Neuroimage*, 22 (S1).

Menon V., Adleman N.E., White C.D., Glover G.H., Reiss A.L., 2001. Error-related brain activation during a Go/NoGo response inhibition task. *Human Brain Mapping*, 12, 131-143.

Mesulam, M.-M., 1984. From sensation to cognition. *Brain* 121, 1013-1052.

Milham, M.P., Erickson, K.I., Banich, M.T., Kramer, A.F., Webb, A., Wszalek, T., Cohen, N.J., 2002. Attentional Control in the aging brain: insights from an fMRI study of the Stroop task. *Brain & Cognition*, 49, 277-296.

Milham, M.P., Banich, M.T., Barad, V., 2003a. Competition for priority in processing increases prefrontal cortex's involvement in top-down control: an event-related fMRI study of the Stroop task. *Cognitive Brain Research*, 17, 212-222.

Milham, M.P., Banich, M.T., Claus, E.D., Cohen, N.J., 2003b. Practice-related effects demonstrate complementary roles of anterior cingulate and prefrontal cortices in attentional control. *Neuroimage*, 18, 483-493.

Milham, M.P., Banich, M.T., 2005. Anterior Cingulate Cortex: An fMRI Analysis of Conflict Specificity and Functional Differentiation. *Human Brain Mapping*, 25, 328-335.

Mitchell, R.L.C., 2005. The BOLD response during Stroop task-like inhibition paradigms: Effects of task difficulty and task-relevant modality. *Brain and Cognition*, 59, 23-37.

Mitchell, R.L.C., Crow, T.J., 2005. Right hemisphere language functions and schizophrenia: the forgotten hemisphere? *Brain*, 128, 963-978.

Mink, J. W., 1996. The basal ganglia: focused selection and inhibition of competing motor programs. *Progress In Neurobiology* 50, 381-425.

Monchi, O., Petrides, M., Petre, V., Worsley, K., Dagher, A., 2001. Wisconsin Card Sorting Revisited: Distinct Neural Circuits Participating in Different Stages of the Task Identified by Event-Related Functional Magnetic Resonance Imaging. *The Journal of Neuroscience*, 21, 7733-7741.

Monsell, S., 1996. Control of mental processes. In V. Bruce (Ed.), *Mysteries of the mind: Tutorial essays on cognition* (pp. 93–148). Hove, UK: Erlbaum.

Monsell, S., 2003. Task swiching. *Trends in Cognitive Sciences* 7, 134-140.

Monsell, S., Sumner, P., & Waters, H., 2003. Task-set reconfiguration after a predictable or unpredictable task switch: Is one trial enough? *Memory and Cognition*, 31, 327-342.

Mummery, C.J., Shallice, T., Price, C. J., 1999. Dual-process model in semantic priming: A Functional Imaging Perspective. *Neuroimage*, 9, 516-525.

Näätänen, R., 1990. The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive functions. *Behavioral Brain Sciences*, 13, 291-308.

Näätänen, R., 1992. *Attention and brain function*. Hillsdale, NJ: Erlbaum.

- Näätänen, R., Gaillard, S. Mäntysalo, S., 1978. Early selective attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42, 313-329.
- Neumann et al., 2005. The meta-analysis of functional imaging data using replicator dynamics. *Human Brain Mapping*, 25, 165-173.
- Noppeney, M., Price, C.J., 2002. A PET study of stimulus- and task-induced semantic processing. *Neuroimage*, 15, 927-935.
- Norman, D.A., Shallice, T., 1980. Attention to action. Willed and automatic control of behavior. University of California San Diego CHIP Report 99.
- O'Craven, K.M., Rosen, B.R., Kwong, K.K., Treisman, A., Savoy, R.L., 1997. Voluntary attention modulates fMRI activity in human MT-MST. *Neuron*, 18, 591-598.
- Ogawa, S., Menon, R.S., Tank, D.W., Kim, S.G., Merkle, H., Ellermann, J.M., Ugurbil, K., 1993. Functional brain mapping by blood oxygenation level-dependent contrast magnetic resonance imaging. A comparison of signal characteristics with a biophysical model. *Biophysical Journal*, 64, 803-812.
- Pardo J.V., Pardo, P.J., Janer, K.W., Raichle, M.E., 1990. The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proceedings of the National Academy of Sciences*, 87, 256-259.
- Pauling, L., Coryell, C., 1936. The magnetic properties and structure of hemoglobin, oxyhemoglobin, and carbon monoxyhemoglobin. *Proceedings of the National Academy of Sciences*, 22, 210-216.
- Paus, T., Koski, L., Caramanos, Z., Westbury, C., 1998. Regional differences in the effects of task difficulty and motor output on blood flow response in the human anterior cingulate cortex: a review of 107 PET activation studies. *Neuroreport*, 9, R37-R47.
- Pazo-Alvarez, P., Cadaveira, F., Amenedo, E., 2003. MMN in the visual modality: a review. *Biological Psychology*, 63, 199-236.

- Pennington, B.F., Bennetto, L., McAller, O., Roberts, R.J., 1996. Executive functions and working memory: Theoretical and measurement issues. In G.R. Lyon & N.A. Krasnegor (Eds.), *Attention memory, and executive function* (pp. 327-348). Baltimore, MD: Paul Brookes.
- Pessoa, L., Ungerleider, L.G., 2004. Neuroimaging studies of attention and the processing of emotion-laden stimuli. *Progress in Brain Research*, 144, 171-182.
- Petersen, S.E., Fox, P.T., Posner, M.I., Mintun, M., Raichle, M.E., 1988. Positron emission tomographic studies of the cortical anatomy of single-word processing. *Nature*, 331, 585-589
- Peterson, B.S., Skudlarski, P., Gatenby, J. C., Zhang, H. H., Anderson, H., Gore, J. C. 1999. An fMRI study of Stroop word-color interference: evidence for cingulate subregions subserving multiple distributed attentional systems. *Biological Psychiatry*, 45, 1237-1258.
- Petrides, M., 2000, Mapping prefrontal cortex systems for the control of cognition. In Toga, A. W., Mazziotta, J. C. (Eds.), *Brain mapping: The systems* (pp. 159-176). Academic Press.
- Petrides, M., Pandya, D.N., 1984. Projections of the frontal cortex from the posterior parietal region in the rhesus monkey. *Journal of Comparative Neurology*, 228, 105-116.
- Petrides, M., Pandya, D.N., 1999. Dorsolateral prefrontal cortex: comparative cytoarchitectonic analysis in the human and the macaque brain and corticocortical connection patterns. *European Journal Neuroscience*, 11, 1011-1036.
- Picton, T.W., 1992. The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology*, 9, 379-391.
- Poldrack, R.A., Wagner, A.D., Prull, M.W., Desmond, J.E., Glover, G.H., Gabrieli, J.D., 1999. Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *Neuroimage*, 10, 15-35.

- Pollmann, S. Dove, A. von Cramon, D.Y., Wiggins, C.J., 2000. Event-related fMRI: Comparison of conditions with varying BOLD overlap. *Human Brain Mapping*, 9, 26-37.
- Posner M.I., Petersen S.E., 1990. The attention system of the human brain. *Annual Review of Neurosciences*, 13, 25-42.
- Posner, M.I., DiGirolamo, G.J., 1998. Executive attention: Conflict, target detection, and cognitive control. In R. Parasuraman (Ed.), *The Attentive Brain* (pp. 401-423). MIT Press, Cambridge, Massachusetts.
- Praamstra, P., Kleine, B.U., Schnitzler, A., 1999. Magnetic stimulation of the dorsal premotor cortex modulates the Simon effect. *Neuroreport*, 10, 3671-3674.
- Proctor, R.W., 1978. Sources of color-word interference in the Stroop color-word task. *Perception and Psychophysics*, 23, 413-419.
- Roelofs, A., 2003. Goal-Referenced Selection of Verbal Action: Modeling Attentional Control in the Stroop Task. *Psychological Review*, 110, 88-125.
- Roelofs, A., Hagoort, P., 2002. Control of language use: cognitive modeling of the hemodynamics of Stroop task performance. *Cognitive Brain Research*, 15, 85-97.
- Rogers R.D., Monsell S., 1995. Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, 124, 207-231
- Rowe, J.B., Toni, I., Frackowiak, R.S., Passingham, R.E., 2000. The prefrontal cortex: response selection or maintenance within working memory? *Science*, 288, 1656-1660.
- Rylander, G., 1939. Personality changes after operations on the frontal lobes. *Acta Psychiatrica Neurologica*, Supplement No. 30.
- Saffran, E. M., Scholl, A. (1999). Clues to the functional and neural architecture of word meaning. In C. Brown & P. Hagoort (Eds.), *The neurocognition of language* (pp. 241-272). New York: Oxford University Press.

Schiller, P.H., 1966. Developmental study of color-word interference. *Journal of Experimental Psychology*, 72, 105-108.

Schneider, D. W., Logan, G. D., 2005. Modeling task switching without switching tasks: A short-term priming account of explicitly cued performance. *Journal of Experimental Psychology: General*, 134, 343-367.

Schröger, E., 1996. A neural mechanism for involuntary attention shifts to changes in auditory stimulation. *Journal of Cognitive Neuroscience*, 8, 527-539.

Schröger, E., Wolff, C., 1998. Behavioral and electrophysiological effects of task-irrelevant sound change: a new distraction paradigm. *Cognitive Brain Research*, 7, 71-81.

Sewards, T.V., Sewards, M. M., 2002. On the neural correlates of object recognition awareness: relationship to computational activities and activities mediating perceptual awareness. *Consciousness and cognition* 11, 51-77.

Simon, J. R., Berbaum, K. (1990). Effect of conflicting cues on information processing: The "Stroop effect" vs. the "Simon effect". *Acta Psychologica*, 73, 159-170.

Shulman, G. L. et al., 1999. Areas involved in encoding and applying directional expectations to moving objects. *Journal of Neuroscience*, 19, 9480-9496.

Shulman, G. L., d'Avossa, G., Tansy, A. P., Corbetta, M., 2001. Two attentional processes in the parietal lobe. *Society for Neuroscience Abstracts*, 27, 722.20.

Smith, D. B. D., Donchin, E., Cohen, L., Starr, A., 1970. Auditory averaged evoked potentials in man during selective binaural listening. *Electroencephalography and Clinical Neurophysiology*, 28, 146-152.

Snyder, L.H., Bastia, A.P., Andersen, R.A., 1997. Coding of intention in posterior parietal cortex. *Nature*, 386, 167-170.

Sokolov, E. N., 1963. *Perception and the conditional reflex*. New York: Macmillan.

- Stowe, L., Broere, C., Paans, A., Wijers, A., Mulder, G., Vaalburg, W., Zwarts, F., 1998. Localizing components of a complex task: Sentence processing and working memory. *NeuroReport*, 9, 2995-2999.
- Stroop, J.R., 1992. Studies of interference in serial verbal reactions. *Journal Experimental Psychology*, 121, 15-23. (Original work published 1935)
- Sutton, S., Braren, M., Zubin, J., John, E. R., 1965. Evoked potential correlates of stimulus uncertainty. *Science*, 150, 1187-1188.
- Thomsen, T. Specht, K. Ersland, L. Hugdahl, K., 2005. Processing of conflicting cues in an attention-shift paradigm studied with fMRI. *Neuroscience Letters*, 380, 138-142.
- Treisman, A., Fearnley, S., 1969. The Stroop Test: Selective attention to colors and words. *Nature*, 222, 437-439.
- Ullsperger, M., von Cramon, D.Y., 2001. Subprocesses of performance monitoring: A dissociation of error processing and response competition revealed by event-related fMRI and ERPs. *Neuroimage*, 14, 1387-1401.
- Vandenberghe, R., Price, C., Wise, R., Josephs, O., Frackowiak, R. S., 1996. Functional anatomy of a common semantic system for words and pictures. *Nature*, 383, 254-256.
- van Veen, V., Carter, S.C., 2005. Separating semantic conflict and response conflict in the Stroop task: A functional MRI study. *Neuroimage*, 27, 497-504.
- Weissman, D.H., Giesbrecht, B., Song, A.W., Mangun, G.R., Woldorff, M.G., 2003. Conflict monitoring in the anterior cingulate cortex during selective attention to global and local object features. *Neuroimage*, 19, 1361-1368.
- Weissman, D.H., Warner, L.M., Woldorff, M.G., 2004. The neural mechanisms for minimizing cross-modal distraction. *The Journal of Neuroscience*, 24, 10941-10949.

Weissman, D.H., Gopalakrishnan, A., Hazlett, C.J., Woldorff, M.G., 2005. Dorsal anterior cingulate cortex resolves conflict from distracting stimuli by boosting attention toward relevant events. *Cerebral Cortex*, 15, 229-237.

Wiese, H., Stude, P., Nebel, K., de Greiff, A., Forsting, M., Diener, H.C., Keidel, M., 2004. Movement preparation in self-initiated versus externally triggered movements: an event-related fMRI-study. *Neuroscience Letters*, 371, 220-225.

Wise, S.P., Murray, E.A., Gerven, C.R., 1996. The frontal cortex-basal ganglia system in primates. *Critical Reviews in Neurobiology*, 10, 317-356.

Wojciulik, E., Kanwisher, N., Driver, J., 1998. Covert visual attention modulates face-specific activity in the human fusiform gyrus: fMRI study. *Journal of Neurophysiology*, 79, 1574-1578.

Wylie, G., Allport, A., 2000. Task switching and the measurement of switch costs. *Psychological Research*, 63, 212-233.

Zeki, S., Marini, L., 1998. Three cortical stages of colour processing in the human brain. *Brain*, 121, 1669-1685.

Zhang, H., Kornblum, S., 1998. The effect of stimulus-response mapping and irrelevant stimulus-response and stimulus-stimulus overlap in four-choice Stroop tasks with single-carrier stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 3-19.

Zysset, S., Müller, K., Lohmann, G., von Cramon, D.Y., 2001. Color-Word Matching Stroop Task: Separating Interference and Response Conflict. *Neuroimage*, 13, 29-36.

List of abbreviations

abbr. – abbreviation	OC – Color-oddball
AC – anterior commissure	OFC – orbitofrontal cortex
ACC – anterior cingulate cortex	OR – orienting reflex
ANOVA – analysis of variance	OW – Word-oddball
BA – Brodmann area	PC – posterior commissure
BOLD – blood oxygenation level dependent	PET – positron emission tomography
CO – congruent	PFC – prefrontal cortex
CSF – cerebrospinal fluid	PPI – psychophysiological interaction
CTI – cue-target interval	pre-SMA – pre-supplementary motor area
DES – dysexecutive syndrome	RI – response-incongruent
DLPFC – dorsolateral prefrontal cortex	RT – reaction time
Ed. – editor	SFG – superior frontal gyrus
Eds. – editors	SI – semantically incongruent
EPI – echo planar imaging	SOA – stimulus-onset asynchrony
ER – error rate	SPECT – single photon emission computed tomography
ERTS – Experimental Run Time System	SPM – statistical parametric mapping
FEF – frontal eye fields	SU – semantically unrelated
FFA – fusiform face area	TE – echo time
FG – fusiform gyrus	TPC – temporo-polar cortex
FID – free induced decay	TPJ – temporo-parietal junction
fMRI – functional magnetic resonance imaging	TR – repetition time / time of repetition
fMRT – funktionelle Kernspintomographie	
IFG – inferior frontal gyrus	
IFJ – inferior frontal junction	
IFJA – inferior frontal junction area	
IFS – inferior frontal sulcus	
IPS – intraparietal sulcus	
ITG – inferior temporal gyrus	
MMN – mismatch negativity	
MNI – Montreal Neurological Institute	
MRI – magnetic resonance imaging	
MRT – magnetic resonance tomography	

Publications

Melcher, T. & Gruber, O. (in press). Oddball and incongruity effects during Stroop task performance: a comparative fMRI study on selective attention. *Brain Research* (2006).

Melcher, T. & Gruber, O. (under review). Decomposing interference during Stroop performance into different conflict factors: an fMRI study. Submitted to *Neuroscience Letters*.

Melcher, T. & Gruber, O. (2005). Dissociating neural correlates of different kinds of cognitive conflict. Presented at the 11th Annual Meeting of the Organization for Human Brain Mapping, June 2005, Toronto, Canada. Available on CD-ROM in *Neuroimage*, 26 (S1).

Melcher, T. & Gruber, O. (2006). Decomposing interference during Stroop performance into different conflict factors: an event-related fMRI study. Presented at the 12th Annual Meeting of the Organization for Human Brain Mapping, June 2006, Florence, Italy. Available on CD-ROM in *Neuroimage*, 31 (S1).

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