The Role of Adaptive Cognitive Control in Voluntary Task Selection

by

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Abstract

Adaptive control processes underlie our ability to flexibly guide behavior in pursuit of our current goals. An important aspect of adaptive control is monitoring for signs of poor performance (e.g., interference or errors) which may indicate that increased control is needed. Current models of control posit that when poor performance is detected, control mechanisms enhance the representation of the current task in working memory. While these control mechanisms are largely understood in terms of their effects on task performance, it is unclear how they influence task selection in multitasking environments. Detecting poor performance in the current task may provide an important signal that more resources should be dedicated to the task at hand, rather than switching to a different task.

We predicted that 1) resolving interference during task selection would recruit control to improve subsequent performance; 2) detecting interference or errors during task performance would lead to an enhancement of the current task which would bias subsequent task choices; and 3) the amount of resources dedicated to processing a task would predict whether participants would repeat or switch tasks on the next trial. Findings from Chapters 2 and 3 supported the first prediction: when conflict during task selection was successfully resolved, subsequent task performance was improved relative to when there was no conflict or when the conflict was not resolved. The findings of Chapter 3 also demonstrate that there are robust bottom-up biases on task choice, and that overcoming these biases relies on the recruitment of control. The second prediction was

supported in Chapter 4, we found that while both response conflict interference and errors were associated with a bias to repeat tasks on the next trial, only response conflict appeared to be resolved by control. Finally, in Chapter 5, we found that the strength of a task's representation, as measured by the P3 component, predicted whether participants would repeat or switch on the next trial. In line with previous studies, repeating tasks (versus switching tasks) was associated with a stronger task representation on the previous trial. Together, these studies demonstrate the importance of adaptive control in mediating task selection.

Chapter 1
General Introduction

In multitasking environments we must rely on cognitive control to stay on the task at hand. When information in our environment affords multiple tasks, we must select only the information relevant for our current goals, while minimizing interference from information that might lead us astray (Kiesel, et al., 2010). The need for control can be readily seen in everyday multitasking situations such as driving. Only some traffic lights and signs are relevant for our current route, so it is important to have a mechanism for selecting the relevant information, while suppressing the influence of irrelevant information. Furthermore, we need to balance the task of driving with other, sometimes relevant tasks, such as changing the music, looking at the GPS for directions, or talking to a passenger. It is important to be able to know when the task of driving requires more or less of our attention, and adjust accordingly.

Cognitive or executive control refers to a set of processes that are thought to guide behavior in the pursuit of goals (Miller & Cohen, 2001; Norman & Shallice, 1986). Constituent processes include attention, inhibition, memory, and planning/ decision making. Cognitive control is thought to bias attention towards task relevant stimuli in the environment (Desimone & Duncan, 1995; Egner & Hirsch, 2005), and inhibit processing of task irrelevant stimuli and/ or responses (Aron, Robbins, & Poldrack, 2004). Task goals and rules are thought to be held in working memory and are updated when the task changes, or when behavior no longer meets the current goals (Cohen & Servan-Schreiber,

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1992). Furthermore, cognitive control is thought to guide the planning of future actions (Norman & Shallice, 1986).

While control is important for focusing on the current task, it is important that control be adaptive and flexible. The appropriateness of a given action may change or demands for control may fluctuate, so the allocation of control must be adapted accordingly. Control processes are resource intensive, drawing from a limited pool of shared resources (Kahneman, 1973); furthermore, control processes are not always required. The latter is clear in the task of driving; when we are travelling on a route that we are very familiar with, the task of driving can be accomplished quite easily, and somewhat automatically. However, if we are travelling on an unfamiliar, busy highway, we may need all the control that we can muster, and may turn off the radio and not converse with our passenger in order to avoid distraction.

In an attempt to explain how control is adjusted in response to current demands, the conflict monitoring model was developed (Botvinick, Braver, Barch, Carter, & Cohen, 2001). The conflict monitoring model posits that the current demands for control can be represented by the amount of conflict in information processing. When conflict is detected, a signal is sent to control processes so that additional resources can be recruited. Specifically, Botvinick and colleagues (2001) posited that a region of the brain known as the anterior cingulate cortex (ACC) detects the presence of response conflict, and then signals control regions of the brain, such as the dorsolateral prefrontal cortex (DLPFC), to enhance the representation of the current task in working memory.

This conflict-driven recruitment of control has been shown to carry-over to the next trial, in what is called the conflict adaptation (Mayr, Awh, & Laurey, 2003) or

Gratton (Gratton, Coles, & Donchin, 1992) effect. This effect describes a reduction of current trial conflict interference (i.e., incongruent RT – congruent RT) following an incongruent trial compared to following a congruent trial (Botvinick, et al., 2001). Further, the amount of ACC activity on one trial is positively associated with the size of the conflict adaption effect and the amount of DLPFC activity on the next trial (Kerns, 2006; Kerns, et al., 2004). There have been some claims that conflict monitoring does not reflect adjustments in control, but rather reflects bottom-up priming (Hommel, Proctor, & Vu, 2004; Mayr, et al., 2003). However, in studies that have accounted for priming, top-down control still—at least partially—explains the conflict adaptation effect (Notebaert & Verguts, 2007; Orr, Carp, & Weissman, 2011).

Thus far, relatively few studies have examined conflict-driven control in multitasking. One focus of these studies has been to examine whether conflict leads to recruitment of control in a general sense, improving control across all task contexts, or only in the same task context in which the conflict occurred. While some studies have shown evidence for global recruitments of control following conflict (Cho, Orr, Cohen, & Carter, 2009; Kunde & Wühr, 2006), it has been argued that the type of tasks used in these studies shared relevant information (Notebaert & Verguts, 2008). When using tasks that do not share relevant information, control is only recruited for the task in which the conflict occurred (Brown, Reynolds, & Braver, 2007; Cho, et al., 2009; Notebaert & Verguts, 2008). Thus, when switching away from the task in which conflict occurred, performance is not improved (and may be worsened) on the next trial compared to when the task repeats (Brown, et al., 2007; Notebaert & Verguts, 2008). As a matter of fact, this outcome is predicted by the conflict monitoring model (Botvinick, et al., 2001);

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conflict signals that control processes should enhance the representation of the current task (Botvinick, Cohen, & Carter, 2004). This suggests that conflict during multitasking situations may provide an important signal that one task may require more control resources than other tasks.

Task switching is often used to study how control is involved in quickly shifting from one task to another (Monsell, 2003). In typical task switching experiments, the participant is either explicitly cued which of several tasks to perform, or the tasks are performed in a predictable pattern. The typical finding is that participants take longer to switch tasks than to repeat tasks, and this is referred to as the switch cost. The origin of these switch costs have been a matter of much debate in the task switching literature, with the focus on whether they stem from top-down control processes or bottom-up stimulus driven processes. The argument for top-down processes accounting for switch costs assumes that the extra time to switch tasks stems from time-consuming processes that actively reconfigure cognitive system for the next task (Logan & Gordon, 2001; Meiran, 1996; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). On a switch trial, task goals and rules must be retrieved from long-term memory and brought in to working memory (Logan & Gordon, 2001; Rubinstein, et al., 2001). Switch costs are reduced with increased time between task cues and target presentation, suggesting that preparing for a switch takes time.

Alternatively, switch costs have been suggested to reflect passive interference from recently performed tasks (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000), as increasing the delay between trials reduces switch costs. This suggests that interference from recent tasks decays passively over time. Some accounts have proposed

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that top-down and bottom-up processes both affect switch costs; Mayr and Keele (2000) have suggested that when switching away from a task, active processes inhibit the task's representation. The strength of this inhibition passively fades over time, so that switch costs reduce with increasing numbers of trials before a task is returned to.

In an attempt to more clearly demonstrate a role of top-down control in task switching, Arrington and Logan (2004) developed the voluntary task switching paradigm. Instead of a cue instructing the task in each trial, participants voluntarily chose which task to perform. Participants are instructed to perform the tasks equally often, and in a random order. Arrington and Logan argued that "… unlike responding to an externally provided cue to switch tasks, which may not involve an act of control, voluntary task switching necessarily involves active processing" (Arrington & Logan, 2004, p. 611). This paradigm allows researchers to not only examine how control influences reaction times, but also how control influences task choices.

While participants may voluntarily choose the task in each trial, task choice in the voluntary task switching paradigm is thought to depend on a combination of a top-down representativeness heuristic and a bottom-up availability heuristic (Arrington & Logan, 2005). The representativeness heuristic is thought to select tasks by comparing a mental record of the recently performed tasks to a representation of a random sequence (Arrington & Logan, 2005) or by performing a mental coin-flip in each trial (Mayr & Bell, 2006). The availability heuristic selects the task whose representation is the most active in working memory. Cognitive control is required to overcome the more automatic availability heuristic. The availability heuristic may bias task choice when cognitive control resources are not available (Arrington & Logan, 2005; Demanet, Liefooghe,

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Verbruggen, & Vandierendonck, 2010), or simply because participants may not want to exert the effort to choose randomly (Botvinick, 2007; De Jong, 2000).

The following studies examined the role of control in guiding behavior in multitasking situations. The first two studies examined the role of control in resolving conflict during task selection. The second two studies examined how the amount of control allocated to processing a task in one trial predicted whether participants choose to repeat or switch tasks in the next trial. Together these studies provide novel tests of existing theories of cognitive control, while also demonstrating several novel findings regarding the role of control in multitasking.

The first study (Chapter 2) used functional MRI (fMRI) to demonstrate that different regions of the ACC were responsible for detecting the presence of response conflict and for resolving conflict. Participants performed a cross-modal attentional cuing paradigm where a cue instructed participants to identify an upcoming auditory or visual target. Irrelevant information presented along with the cue signaled participants to either the same task (auditory or visual) or the other task. The target was presented concurrently with an irrelevant distracter that was associated with same or the opposite response as the target. The results showed that a dorsal region of the ACC was involved in resolving conflict during task selection, while a more rostral region of the ACC was involved in detecting response conflict during the target. Increased activity in the dorsal region was associated with better task performance, and activity in this region resembled that in the DLPFC. These findings demonstrate that the ACC does not just detect conflict as the conflict monitoring model posits (Botvinick, et al., 2001), but is involved more directly in

cognitive control (Posner & DiGirolamo, 1998). This study was published by Cerebral Cortex in 2009 with Daniel Weissman.

The second study (Chapter 3) extended the findings of the first study by examining whether failing to resolve cue conflict biases task choice. In the first study, failing to resolve the cue conflict would possibly have led to errors. However, under conditions of voluntary task choice, failing to resolve interference from a distracter associated with a given task biased task choice. In this behavioral study, participants either voluntarily chose which one of two possible tasks to perform, or they were explicitly instructed which task to perform. Irrelevant distracters presented during the cue were associated with a particular task. We predicted that on voluntary choice trials, participants would be biased to choose the task associated with the distracters. In line with suggestions that bottom-up biases on task-choice reflect a reduction of top-down control (Arrington & Logan, 2005; Arrington & Yates, 2009; Demanet, et al., 2010; Mayr & Bell, 2006), we predicted that succumbing to such biases would be associated with poorer performance. The results demonstrated a robust bottom-up bias to choose the task associated with the distracters, and succumbing to such biases was associated with increased switch costs during subsequent task performance. This study was published by Frontiers in Cognition in 2011 with Daniel Weissman.

The third study (Chapter 4) aimed to provide a novel test of the conflict monitoring model (Botvinick, et al., 2001). Evidence that conflict is resolved by enhancing the representation of a given task may be explained by enhancements of lower-level task settings such as stimulus and response representations (Egner, 2008). If participants in voluntary task switching paradigms are biased to choose the task with the

strongest representation, then the conflict monitoring model predicts that participants should be biased to repeat a task following a high conflict trial than after a low conflict trial. To investigate this hypothesis, participants performed a voluntary task switching version of a numerical Stroop task. Critically, task choice cues and task targets were temporally separated in order to examine the effect of conflict on task choice independent of effects of conflict on target stimulus and response representations. In line with our predictions, participants chose to repeat tasks more often following trials high versus low in conflict. This finding provides novel support for the hypothesis that conflict is resolved by enhancing a task's representation. This study was published by Psychological Research in 2011 with Joshua Carp and Daniel Weissman.

The fourth study (Chapter 5) used Event-Related Potentials (ERPs) to examine if task choice could be predicted based on the strength of a task's representation on the previous trial. In the voluntary task switching paradigm, participants are biased to choose the task with the strongest representation (Arrington & Logan, 2005; Mayr & Bell, 2006). The P3 component has previously been associated with the amount of resources or attention allocated to processing task stimuli (Kok, 2001; Polich, 2007), and the strength of a task set (Barceló, Muñoz-Céspedes, Pozo, & Rubia, 2000; Kieffaber & Hetrick, 2005), therefore we used the P3 to track the strength of a task's representation. In line with this prediction, larger P3 amplitudes were associated with repeating on the next trial than with switching on the next trial. This study demonstrates that ERPs can used to track the efficiency of mental processes that guide behavior. The manuscript for this study is in preparation and will soon submitted to a peer-reviewed journal.

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Chapter 2
Anterior cingulate cortex makes two contributions to minimizing distraction

Abstract

When we detect conflicting irrelevant stimuli (e.g., nearby conversations), we often minimize distraction by increasing attention to relevant stimuli. However, dissociating the neural substrates of processes that detect conflict and processes that increase attention has proven exceptionally difficult. Using a novel cross-modal attentional cueing task in humans, we observed regional specialization for these processes in the cognitive division of the anterior cingulate cortex (ACC_{cd}). Activity in a dorsal subregion was associated with increasing attention to relevant stimuli, correlated with behavioral measures of orienting attention to those stimuli, and resembled activity in dorsolateral prefrontal regions that are also thought to bias attention toward relevant stimuli. In contrast, activity in a rostral subregion was associated only with detecting response conflict caused by irrelevant stimuli. These findings support a two-component model for minimizing distraction and speak to a longstanding debate over how the ACC_{cd} contributes to cognitive control.

Introduction

Think about the last time you spoke with a friend at a crowded party. Occasionally, when you detected the volume of background conversations rising, you probably increased attention to your friend's voice in order to avoid becoming distracted. Consistent with this example, minimizing distraction is thought to depend on complementary brain systems that first detect the presence of distracting stimuli and then quickly increase attention to relevant stimuli (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter, et al., 1998; Kerns, 2006). Identifying these systems has attracted much interest recently because heightened levels of distraction are associated with adverse outcomes in numerous clinical syndromes, including drug addiction (Goldstein, et al., 2007), attention deficit and hyperactivity disorder (Dickstein, Bannon, Castellanos, & Milham, 2006), and schizophrenia (Kerns, et al., 2005). However, because these systems are thought to be active at nearly the same time, dissociating them has proven to be a difficult and controversial enterprise.

At the center of this controversy lies the precise contribution to cognitive control that is made by the so-called 'cognitive division' of the anterior cingulate cortex (ACC$_{cd}$; the subscript 'cd' refers to 'cognitive division' and is used throughout the paper to distinguish the dorsal and rostral subregions of ACCcd that we investigate from dorsal and rostral regions of the ACC as a whole). Some models posit that the ACC$_{cd}$ increases attention to task-relevant stimuli (Dreher & Berman, 2002; Michael I. Posner & DiGirolamo, 1998; Weissman, Gopalakrishnan, Hazlett, & Woldorff, 2005). Others posit that the ACC$_{cd}$ signals the coactivation of competing responses (i.e., response conflict, which can be highly distracting) to the dorsolateral prefrontal cortex (DLPFC) which, in

turn, resolves conflict by increasing attention to relevant stimuli (Botvinick, et al., 2001; Carter, et al., 1998; Kerns, 2006). Still others posit a role for the ACC_{cd} in response selection (Roelofs, van Turennout, & Coles, 2006), novelty detection (Matsumoto, Matsumoto, & Tanaka, 2007; Ranganath & Rainer, 2003), anticipation (Murtha, Chertkow, Beauregard, Dixon, & Evans, 1996), error monitoring (W. J. Gehring & Fencsik, 2001; William J. Gehring, Goss, Coles, & Meyer, 1993), reward assessment (Bush, et al., 2002), and computing error likelihood (Brown & Braver, 2005). Although numerous investigators have sought to determine which model best explains ACC_{cd} activity (Banich, et al., 2000; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns, et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000; Weissman, Warner, & Woldorff, 2004), the findings have been mixed and relatively little consensus has been reached.

Given the heterogeneity of findings in the literature, some authors have suggested the existence of regional specialization in the ACC_{cd} for distinct control processes (Bush, et al., 2002; Goldstein, et al., 2007; Milham & Banich, 2005). In line with the regional specialization hypothesis, we recently reported evidence implicating a dorsal subregion of the ACC_{cd} in increasing attention to relevant stimuli and a rostral subregion in detecting response conflict caused by irrelevant stimuli (Weissman, et al., 2004). In our prior study, however, demands on processes that increase attention to relevant stimuli were confounded with the expected difficulty of the upcoming task, which also influences ACC_{cd} activity (Brown & Braver, 2005).

In the present study we therefore used a novel cross-modal attentional cueing task to investigate regional specialization in the ACC_{cd} for processes that increase attention to

relevant stimuli and processes that detect response conflict (Figure 2.1). In each trial, participants received a visually-presented cue word ('Look' or 'Hear') that instructed them to attend to and identify either the visual letter or the auditory letter of a possibly upcoming, audiovisual target-distracter letter pair. The visually-presented cue word was accompanied by an irrelevant, binaurally-presented auditory word that was equally likely to signal the same task as the visual word (less demanding congruent cues) or a different task (more demanding incongruent cues). After a brief interval, an audiovisual target-distracter letter pair was presented. The distracter letter was equally likely to be mapped to the same response as the target letter (less demanding congruent target-distracter pairs) or to a different response (more demanding incongruent target-distracter pairs). To isolate cue-triggered activity associated with increasing attention to relevant stimuli from target-triggered activity associated with detecting response conflict, in cue-only trials (33%) the cue was not followed by a target-distracter letter pair.

Our hypothesis predicts that dorsal and rostral subregions of the ACC_{cd}, respectively, should be differentially sensitive to processes that increase attention to relevant stimuli and processes that detect response conflict. Processes (and brain regions) that increase attention to relevant stimuli should be more strongly recruited by incongruent than by congruent cue-only trials. Indeed, during the processing of incongruent cues, such processes should need to work especially hard to ensure that attention is oriented to the cued modality rather than to the irrelevant modality signaled by the distracter word. Our hypothesis therefore predicts relatively strong effects of cue congruency (i.e., peak activity that is greater for incongruent than for congruent cue-only trials) in the dorsal ACC_{cd}. On the other hand, processes (and brain regions) that detect

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response conflict should be more highly activated by incongruent than by congruent target-distracter pairs, since only incongruent target-distracter pairs engender response conflict. Thus, our hypothesis predicts relatively strong effects of target congruency (i.e., peak activity that is greater for incongruent than for congruent target-distracter pairs) in the rostral ACC_{cd}.

<div align="center">

Method

</div>

Participants

Seventeen healthy participants (7 males and 10 females, age range, 19–36 years) took part in the study. All had normal or corrected-to-normal vision and had no history of serious neurological trauma or disorders. All except one were right handed. Before the magnetic resonance (MR) session, each participant practiced the experimental task. Participants were paid $20 per hour for their participation, which lasted approximately 2 hours. Participants gave informed consent before the experiment in accordance with the University of Michigan Behavioral Sciences Institutional Review Board.

Experimental Task

An IBM-compatible PC was used to present stimuli and to record the participants' responses. Visual stimuli were projected onto a screen at the back of the bore of the magnet that participants viewed through a mirror. Auditory stimuli were voice recordings of a female speaker (duration, 350 ms) delivered binaurally through MR-compatible headphones. Headphone volume was adjusted for each participant so that the auditory stimuli could be heard clearly over the background MR scanner noise. All stimuli were presented using Presentation software (Neurobehavioral Systems, Albany, CA).

Responses were made using the index and middle fingers of the right hand and recorded with an MR-compatible response box.

In each 3.75-second trial, a visually-presented cue word ('Look' or 'Hear': 3.12° x 0.86°) instructed participants to attend to and identify either the visual letter ('X,' 1.10° x 1.36°; or 'O', 1.18° x 1.38°) or the auditory letter ('X' or 'O') of a possibly upcoming, audiovisual target-distracter letter pair. The visually-presented cue word (duration, 350 ms) was accompanied by an irrelevant, binaurally-presented auditory word (duration, 350 ms) that was equally likely to signal the same task as the visual cue (Figure 2.1, top left) or a different task (Figure 2.1, top right). After a brief interval (cue-target stimulus onset asynchrony, 1875 ms), an audiovisual target-distracter letter pair was presented (duration, 350 ms). The distracter letter in the uncued modality was equally likely to be mapped to the same response as the target letter (Figure 2.1, bottom left) or to a different response (Figure 2.1, bottom right). Participants were instructed to press one button if the cued target letter was an X and a different button if it was an O, as quickly as possible without making mistakes, using the index and middle fingers of their right hand (stimulus-response mappings were counterbalanced across participants). The next trial began after an inter-trial-interval that lasted between 0 and 6.25 seconds.

We used two main trial types to distinguish brain activity associated with cues from activity associated with targets. To isolate activity related to cues, we included 'cue-only' trials in which only the cue was presented (33% of all trials). To isolate activity related to targets, we included 'cue-plus-target' trials in which a cue was followed by a target (66% of all trials). Using a mixture of cue-only and cue-plus-target trials allows

one to distinguish neural activity for cues from activity for targets even in rapid event-related fMRI designs (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000).
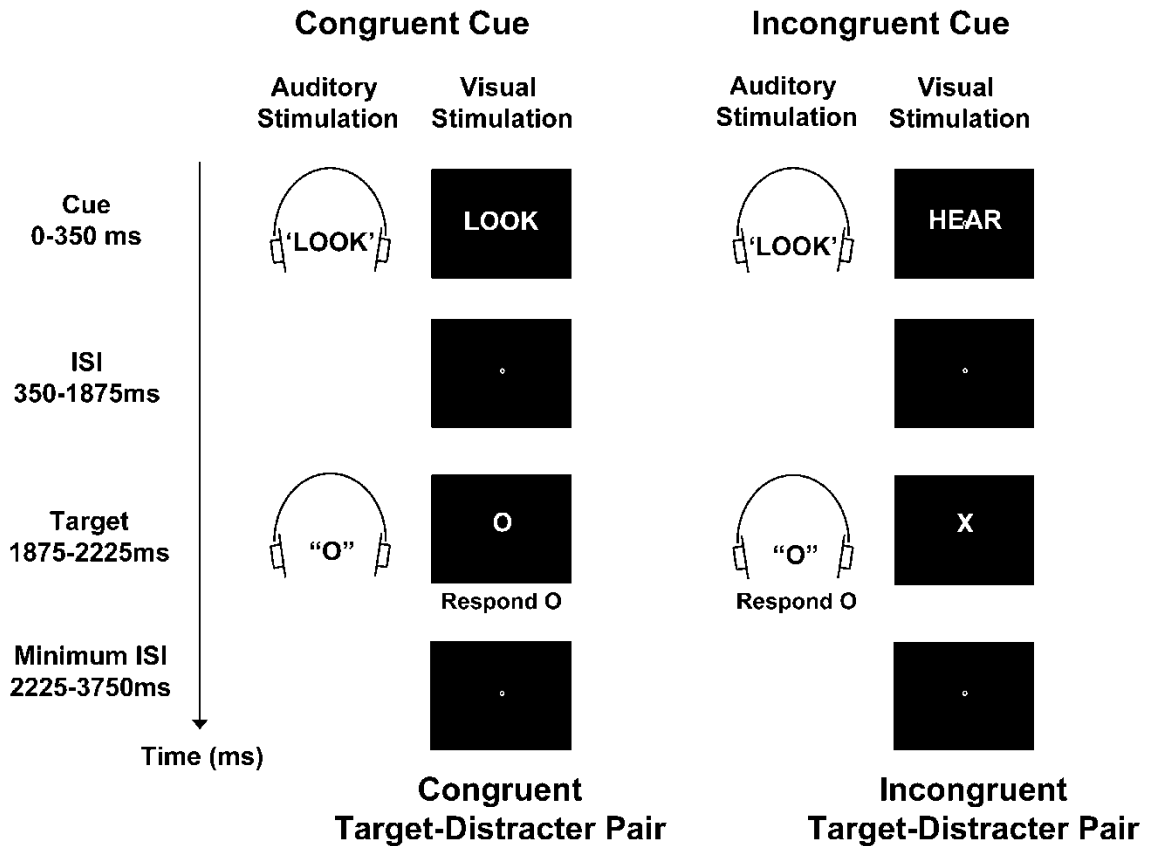
Figure 2.1. Experimental task.
In each trial, a visually-presented cue word ('Look' or 'Hear') instructed participants to attend to and identify either the visual letter ('X' or 'O') or the auditory letter ('X' or 'O') of a possibly upcoming target-distracter letter pair. To modulate demands on cue-triggered processes that increase attention to relevant stimuli, we varied whether an irrelevant auditory word signaled the same task as the visual word ('Congruent Cue') or a different task ('Incongruent Cue'). After a 1.875-second interval, an audiovisual target-distracter letter pair was presented. To modulate demands on target-triggered processes that detect response conflict, we varied whether the distracter letter was mapped to the same response as the target ('Congruent Target-Distracter Pair') or to a different response ('Incongruent Target-Distracter Pair'). In cue-only trials (33%, not shown), the cue was not followed by a target-distracter letter pair.

We were also able to identify differences in activity associated with incongruent and congruent target-distracter pairs in cue-plus-target trials. Indeed, exactly the same cues appeared in (1) cue-plus-target trials containing incongruent target-distracter pairs and (2) cue-plus-target trials containing congruent target-distracter pairs. Thus,

contrasting activity for these different trial types allowed us to subtract out the common

cue activations, thereby isolating differences in activity between incongruent and

congruent target-distracter pairs.

In all trials, the fixation dot (0.15° x 0.17°) changed color from white to red 1.875

sec after cue onset (coincident with target presentation in cue-plus-target trials and to

signal that no target would occur in cue-only trials). Participants were instructed to cease

attending if the fixation dot turned red and a target failed to appear (cue-only trials).

Event-related Design

In every run, there were 12 event-related trial types (four cue-only and eight cue-

plus-target), each of which was presented eight times in a completely randomized order.

The four cue-only trial types consisted of the four possible combinations of Cue Type

(look, hear) and Cue Congruency (congruent, incongruent). The eight cue-plus-target

trials consisted of the eight possible combinations of Cue Type (look, hear), Cue

Congruency (congruent, incongruent), and Target Congruency (congruent, incongruent).

To optimize regression estimates of the BOLD responses produced by each of the 12 trial

types, the inter-trial interval (ITI) was varied between zero and five TRs (0 and 6.25

seconds) using a nearly exponential distribution that favored short it is (Miezin,

Maccotta, Ollinger, Petersen, & Buckner, 2000).

Data Acquisition

All MRI images were collected on a 3-T GE Signa whole-body scanner with a

standard head coil. The blood oxygenation level-dependent (BOLD) signal was measured

with a reverse spiral imaging sequence (TR, 1250 ms; TE, 30 ms; FOV, 22cm; 27

contiguous 4.5-mm-thick slices; in-plane resolution, 3.44 x 3.44 mm). Anatomical

images were collected in-plane with the functional images using a T1-weighted gradient-echo (GRE) sequence (TR, 250 ms; TE, 5.4 ms; flip angle, 90°, in-plane resolution 0.86 X 0.86 mm). Every participant completed five runs, each consisting of 96 trials. During each run, 395 brain volumes were collected. The first six functional images of each run contained no trials and were discarded.

Data Analysis

Using SPM2 (Friston, 1995), the functional images were corrected for asynchronous slice acquisition and head movement, normalized to MNI (Montreal Neurological Institute) space with dimensions 3.75 mm x 3.75 mm x 4.5 mm, and spatially smoothed with a three-dimensional Gaussian filter (8 mm at full-width half-max). Due to head movements greater than 3 mm, the final run was eliminated from two participants' data, and the final two runs were removed from one participant's data. Next, the time series for each run was analyzed using a version of the general linear model that makes no assumptions about the shape of the BOLD response. This model, sometimes called the finite impulse response (FIR) model, estimates the average stimulus-locked fMRI response for each trial type and has been used successfully in many prior studies (Ollinger, Corbetta, & Shulman, 2001; Ollinger, Shulman, & Corbetta, 2001; Shulman, et al., 1999). We estimated 14 TRs (17.5 s) of the average BOLD response for each of the 12 trial types. This resulted in 168 regressors (12 trial types X 14 timepoints) being entered into the design matrix. We also included six head movement regressors (i.e., SPM2 motion estimates) and two regressors for the linear trend and the *y*-intercept term. Parameter estimates for each run were converted to units of percent change from baseline and then averaged across runs for each participant.

Voxelwise Analyses

A voxelwise, repeated-measures analysis of variance (ANOVA) was conducted to test for a significant 3-way interaction between Cue Congruency, Target Congruency, and Time (0 -17.5 seconds) in prefrontal regions (thresholded at $F_{13, 208} = 2.8$, $P < 0.001$ and 5 contiguous voxels). This analysis identified a region of the left DLPFC (10 voxels; MNI center of mass: $x = -44$, $y = 10$, $z = 39$; BA 9).

Region of Interest (ROI) Analyses

Two regions of interest from our prior study of regional specialization in the ACC_{cd} (Weissman, et al., 2004) were chosen to test whether there is regional specialization in the ACC_{cd} for processes that increase attention to relevant stimuli and processes that detect response conflict from irrelevant stimuli: (1) a dorsal subregion of the ACC_{cd} that included parts of the caudal ACC and pre-supplementary motor area (20 voxels; Montreal Neurological Institute (MNI) center of mass: $x = -2$, $y = 6$, $z = 52$; Brodmann Area (BA) 32) and (2) a rostral subregion of the ACC_{cd} that included parts of the rostral cingulate zone (20 voxels; MNI center of mass: $x = 0$, $y = 25$, $z = 29$; BA 32). ROI analyses were also performed for a region of the left DLPFC that was identified in a voxelwise analysis of the present data (see *Voxelwise Analyses*).

In all ROI analyses, we averaged the responses to particular trial types across all voxels within each ROI. Statistical tests were then performed to contrast peak activity for the different trial types. In the rostral ACC_{cd}, inspection of the average BOLD responses revealed that peak activity in cue-only trials occurred 3.75 seconds after cue onset while peak activity in cue-plus-target trials occurred 6.25 seconds after cue onset (Figure 2.2d). The delay of peak activity in cue-plus-target trials is consistent with the target being

presented about two seconds after the cue. In both the dorsal ACC_{cd} and the left DLPFC (Figures 2.2c and 2.3d), inspection of the average BOLD responses revealed that peak activity in cue-only trials was distributed across two time points (3.75 and 5 seconds after cue onset) as was peak activity in cue-plus-target trials (5 and 6.25 seconds after cue onset). Thus, for both cue-only and cue-plus-target trials, peak activity in these regions was defined as the average amount of activity across two time points. We made a single exception to these definitions of peak activity when contrasting activity for incongruent hear cue-only and incongruent look cue-only trials in the dorsal ACC_{cd}. Inspection of the average BOLD responses for these trial types revealed substantial inter-participant variability in the timing of peak activity. Therefore, for each of these trial types, we defined peak activity separately in each participant as the maximum activation at either 3.75 or 5 seconds after cue onset and performed statistical tests on that single time point. Given the small number of ROIs (i.e., 3), we considered p-values less than 0.05 to be significant. Moreover, since all of our hypotheses were directional all t-tests were one-tailed.

The ROI analyses also involved correlating behavioral and neural (i.e., fMRI) measures of attention. Specifically, we correlated the behavioral cue congruency effect (i.e., the degree to which responses to targets were faster after incongruent than after congruent cues) with the neural cue congruency effect (i.e., the degree to which incongruent cue-only trials evoked greater activity than congruent cue-only trials in particular ROIs). The purpose of these correlations was to gain greater insight into the behavioral significance of the brain activations that we observed.

Results

Behavior

   The behavioral data indicated that our task manipulations were highly effective.

First, we observed an effect of cue congruency: participants were faster [870 ms versus

899 ms; $F(1, 16) = 14.5$, $p < 0.005$] and marginally more accurate [98% versus 97%; $F(1,$

$16) = 4.2$, $p < 0.06$] when responding to targets that followed incongruent (compared to

congruent) cues. Since increasing attention to relevant stimuli facilitates identifying those

stimuli (Posner, 1980; Stoffer, 1993), this result suggests that, in line with predictions,

participants recruited processes that increase attention to relevant stimuli more strongly

when they encountered incongruent cues than when they encountered congruent cues.

Second, in line with prior work (Weissman, et al., 2004), we observed an effect of target

congruency: participants were both slower [929 ms versus 840 ms; $F(1, 16) = 44.6$, $p <$

0.001] and less accurate [96% versus 99%; $F(1, 16) = 34.2$, $p < 0.001$] when responding

to incongruent (compared to congruent) target-distracter pairs. Third, the target

congruency effect was smaller, $F(1, 16) = 7.42$, $p < 0.02$, following incongruent cues [69

ms, $t(16) = 4.94$, $p < 0.001$] than following congruent cues [109 ms, $t(16) = 6.63$, $p <$

0.001]. Because increasing attention to relevant stimuli reduces interference from

irrelevant stimuli (Lavie, 1995; Weissman, et al., 2004), this result provides further

evidence that participants increased attention to relevant stimuli more strongly when they

encountered incongruent cues than when they encountered congruent cues. Fourth, the

target congruency effect was also smaller, $F(1, 16) = 4.70$, $p < 0.05$, when the cue in the

immediately preceding trial was incongruent [79 ms, $t(16) = 4.96$, $p < 0.001$] than when it

was congruent [116 ms, $t(16) = 5.59$, $p < 0.001$], indicating that the effect of more

strongly increasing attention to relevant stimuli following an incongruent (compared to congruent) cue persisted across trials.

In addition to the main findings above, which were averaged across the visual and auditory modalities, we observed two differences between the visual and auditory modalities that were not crucial for testing our hypotheses. First, the cue congruency effect was larger when participants responded to visual targets [54 ms; $t(16) = 5.27$, $p <$ 0.001] compared to auditory targets [2 ms; $t(16) = 0.17$, $p < 0.44$], $F(1, 16) = 17.59$, $p <$ .001. And, second, as in our prior study (Weissman, et al., 2004) participants were both slower [915 ms versus 854 ms; $F(1, 16) = 20.6$, $p < 0.001$] and less accurate [97% versus 98%; $F(1, 16) = 5.5$, $p < .05$] when they responded to auditory targets than when they responded to visual targets. No other behavioral effects were significant.

FMRI

Our hypothesis predicts that the dorsal ACC_{cd} should be especially sensitive to cue congruency while the rostral ACC_{cd} should be especially sensitive to target congruency. To test this prediction, we probed activity within two regions of interest (ROIs) that were identified in our prior study of regional specialization in the ACC_{cd} (Weissman, et al., 2004) (Figure 2.2a): (1) a dorsal subregion of the ACC_{cd} that included parts of the caudal ACC and pre-supplementary motor area (20 voxels; Montreal Neurological Institute (MNI) center of mass: $x = -2$, $y = 6$, $z = 52$; BA 32) and (2) a rostral subregion of the ACC_{cd} that included parts of the rostral cingulate zone (20 voxels; MNI center of mass: $x = 0$, $y = 25$, $z = 29$; BA 32).

In line with our hypothesis, ROI analyses on peak activity revealed a significant 3-way interaction between ACC_{cd} Subregion (rostral, dorsal), Cue Congruency

(congruent, incongruent), and Target Congruency (congruent, incongruent) [$F(1, 16) =$ 12.62, $p < 0.005$; see Figure 2.2b]. First, and consistent with a role in increasing attention to relevant stimuli, in the dorsal subregion the cue congruency effect was significantly larger than the target congruency effect [$t(16) = 1.94$, $p < 0.04$; see Figure 2.2b]. Additional tests revealed significant effects of both cue congruency [$t(16) = 4.34$, $p < 0.001$], and target congruency [$t(16) = 3.48$, $p < 0.001$; see Figure 2.2c], consistent with models in which resolving response conflict involves further increasing attention to relevant stimuli (Weissman, et al., 2004). Second, and consistent with a role in detecting response conflict, in the rostral subregion the target congruency effect was significantly larger than the cue congruency effect [$t(16) = 2.12$, $p < 0.025$; see Figure 2.2b]. Further tests revealed a significant target congruency effect [$t(16) = 2.816$, $p < 0.0005$], in the absence of a significant cue congruency effect [$t(16) = 0.48$, $p < 0.49$; see Figure 2.2d]. These findings support our hypothesis that a dorsal subregion of the ACC_{cd} is especially involved in increasing attention to relevant stimuli while a rostral subregion is differentially involved in detecting response conflict.

Three additional predictions stem from our hypothesis that the dorsal subregion of the ACC_{cd} increases attention to relevant stimuli. First, as in our prior study (Weissman, et al., 2004), the dorsal subregion should show greater activity in hear cue-only trials than in look cue-only trials, since only in hear cue-only trials is it necessary to switch attention from the visual cue to the auditory modality. Moreover, this effect should be most visible in incongruent cue-only trials in which attention to the visual aspect of the cue is absolutely necessary to correctly identify the upcoming task. In line with this prediction, peak activity in the dorsal subregion was significantly greater for incongruent hear cue-
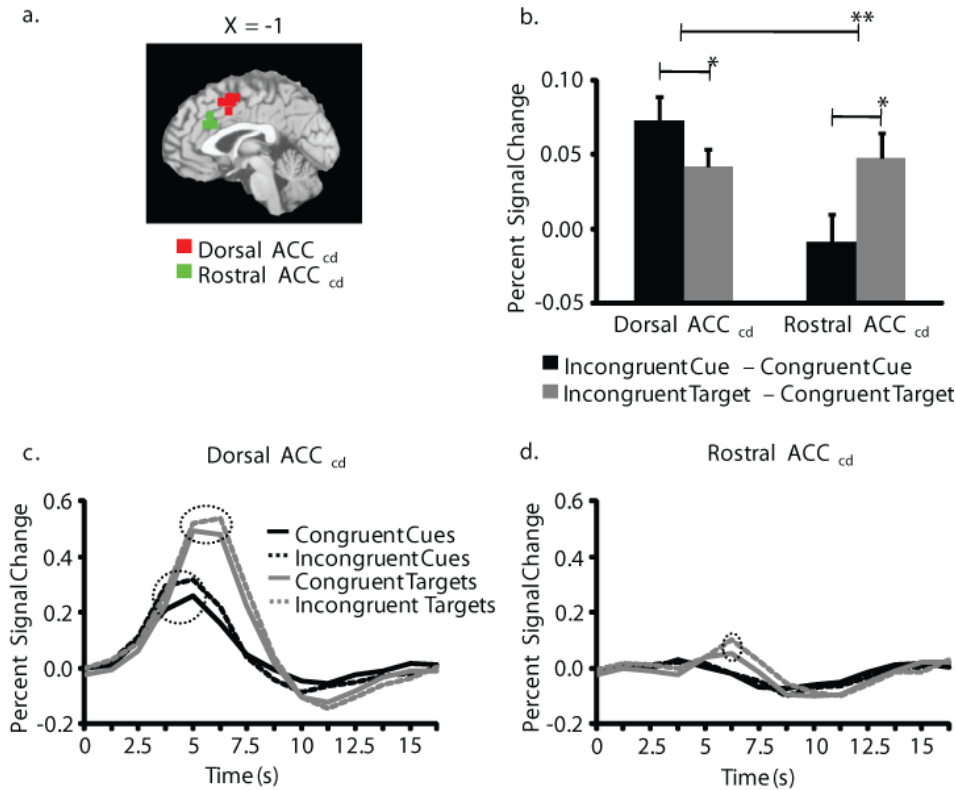
Figure 2.2. Regional specialization for cognitive control in the ACC_cd.
(a) Saggital slice indicating our rostral ACC_cd subregion (green) and our dorsal ACC_cd subregion (red) on the MNI-normalized brain. (b) Activity specific to cue congruency and target congruency in the dorsal ACC_cd and in the rostral ACC_cd. In the dorsal ACC_cd, we observed significantly greater activity specific to cue congruency than to target congruency, while in the rostral ACC_cd we observed exactly the opposite effect. (c) The average fMRI signal across time (in units of percent signal change from baseline) in the dorsal ACC_cd for the various cue and target stimuli. There were significant effects of both cue congruency (i.e., greater peak activity for incongruent cues than for congruent cues) and target congruency (i.e., greater peak activity for incongruent target-distracter pairs than for congruent target-distracter pairs). (d) The average fMRI signal across time for the various cue and target stimuli in the rostral ACC_cd. There was a significant effect of target congruency, but not of cue congruency. Dashed circles in b and c indicate significant differences in peak activity ($P < 0.05$). In d, a single asterisk denotes $P < 0.05$ while two asterisks denote $P < 0.005$. Error bars represent S.E.M.

only than for incongruent look cue-only trials [$t(16) = 2.26$, $p < 0.02$; see Figure 2.3a], but did not significantly differ for congruent hear cue-only and congruent look-cue only trials [$t(16) < 1$]. Note that semantic conflict between the relevant visual aspect of the cue and the irrelevant auditory aspect was present in both incongruent hear cue-only and incongruent look cue-only trials, making it highly unlikely that the difference in activity between these trial types indexed processes that monitor for semantic conflict. Also

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important, a significant difference in peak activity between incongruent and congruent cue-only trials was not observed in the rostral subregion [$t(16) = 1.33$, $p > 0.10$], suggesting that this subregion was not involved in increasing attention to relevant stimuli, and leading to a significant interaction between ACC_{cd} Subregion (rostral, dorsal) and Incongruent Cue Type (Look, Hear) [$F(1, 16) = 5.34$, $p < 0.04$; see Figure 2.3a].

Second, if the dorsal subregion participates in increasing attention to relevant stimuli, then participants who show the largest cue congruency effect in the dorsal subregion should exhibit the fastest speedup in response time for targets that follow incongruent (compared to congruent) cues. In line with this prediction, an across-participants correlation indicated that the larger the effect of cue congruency on dorsal subregion peak activity in an individual participant, the faster that participant tended to respond to targets that followed incongruent (compared to congruent) cues [$r(15) = -0.59$, $p < 0.05$; see Figure 2.3b]. The correlation remained significant after controlling for possible outliers [$r(13) = -.52$, $p < 0.05$]. This correlation was not significant in the rostral subregion [$r(15) = -0.37$, $p = 0.14$], suggesting that this subregion was not involved in increasing attention to relevant stimuli.

Third, if the dorsal subregion helps to increase attention to relevant stimuli, then the pattern of activity in this region should mirror that in the left DLPFC, a region that is widely posited to focus attention on relevant stimuli (Banich, et al., 2000; MacDonald, et al., 2000; Miller and Cohen 2001; Weissman, et al., 2004). Moreover, this effect should be most pronounced at the time of peak activation. Consistent with this prediction, a voxelwise, repeated-measures analysis of variance (ANOVA) restricted to prefrontal regions (thresholded at $F(13, 208) = 2.8$, $p < 0.001$ and 5 contiguous voxels) revealed a
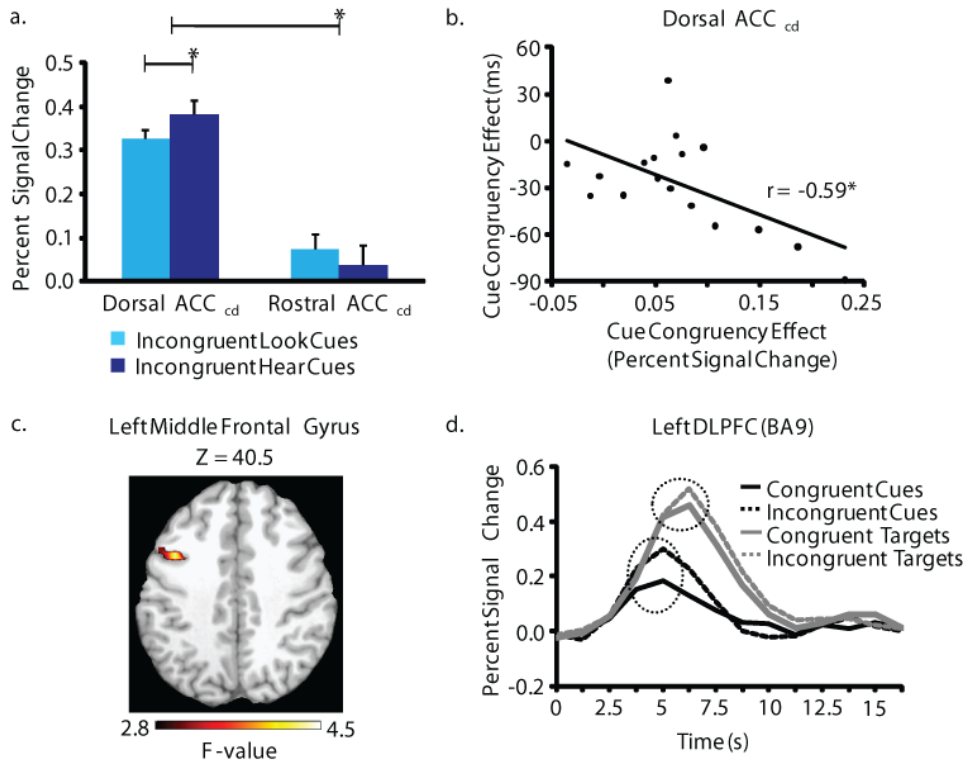
30

Figure 2.3. Effects of cue type, cue congruency, and target congruency in the ACC$_{cd}$ and in the left dorsolateral prefrontal cortex (DLPFC).
(a) Peak activity was significantly greater for incongruent hear cue-only trials than for incongruent look cue-only trials in the dorsal ACC$_{cd}$, but not in the rostral ACC$_{cd}$. (b) An across-participants correlation showing that participants with larger differences in peak activity between incongruent cue-only trials and congruent cue-only trials in the dorsal ACC$_{cd}$ tended to respond more quickly to targets following incongruent cues than to targets following congruent cues. (c) A region of the left prefrontal cortex (24 voxels; BAs 6, 8, and 9), centered in the left DLPFC, in which cue congruency modulated activity significantly more than target congruency displayed on the MNI-normalized brain. (d) The average fMRI signal across time in the left DLPFC (10 voxels; BA 9) for the various cue and target stimuli. Dashed circles represent significant differences in peak activity ($P < 0.05$). In a and b, a single asterisk represents $P < 0.05$. Error bars represent S.E.M.

significant 3-way interaction between Cue Congruency, Target Congruency, and Time (0-17.5 seconds) in the left middle frontal gyrus (24 voxels; MNI center of mass: $x = -42$, $y = 10$, $z = 39$; BAs 6, 8, and 9; Figure 2.3c), and part of this region was located within the left DLPFC (10 voxels; MNI center of mass: $x = -44$, $y = 10$, $z = 39$; BA 9).

Subsequent ROI analyses of the simple effects of this interaction focused on peak activity in the left DLPFC. These analyses confirmed that, as in the dorsal ACC$_{cd}$ subregion (but opposite to the rostral ACC$_{cd}$ subregion), the cue congruency effect was significantly

larger than the target congruency effect [$t(16) = 1.81$, $p < 0.05$]. Also as in the dorsal ACC$_{cd}$ subregion, there were significant effects of both cue congruency [$t(16) = 3.16$, $p < 0.005$], and target congruency [$t(16) = 2.22$, $p < 0.025$; see Figure 2.3d]. Further underscoring the similar patterns of activity that we observed in the left DLPFC and in dorsal subregions of the ACCcd, the three-way interaction between ROI (dorsal ACCcd, left DLPFC), Cue Congruency (congruent, incongruent) and Target Congruency (congruent, incongruent) was far from achieving significance [$F(1, 16) = 1.0$, $p > 0.33$]. These findings further implicate the dorsal ACC$_{cd}$ in increasing attention to relevant stimuli.

Discussion

Minimizing distraction is thought to involve distinct control processes that first detect conflict caused by irrelevant stimuli and then quickly resolve such conflict by increasing attention to stimuli of interest (Botvinick, et al., 2001; Carter, et al., 1998; Kerns, 2006). Consistent with this two-component model, we found that rostral and dorsal subregions of the ACC$_{cd}$, respectively, are differentially involved in implementing processes that detect response conflict and processes that increase attention to relevant stimuli. This finding sheds new light on the brain mechanisms that minimize distraction (Botvinick, et al., 2001; Carter, et al., 1998; Kerns, 2006) and speaks directly to a longstanding debate over how the ACC$_{cd}$ contributes to cognitive control.

Several of our findings provide compelling evidence that a dorsal subregion of the ACC$_{cd}$ participates in increasing attention to relevant stimuli. First, activity in the dorsal subregion was significantly greater when participants shifted their attention from the visual cue to the auditory modality than when they simply maintained attention in the

visual modality. This finding strongly implicates this subregion in increasing attention to relevant stimuli. Second, the cue congruency effect was significantly larger than the target congruency effect not only in the dorsal subregion of the ACC_{cd}, but also in the left DLPFC, a region that is widely posited to increase attention to relevant stimuli (Banich, et al., 2000; MacDonald, et al., 2000; Miller & Cohen, 2001; Weissman, et al., 2004). Moreover, a significant effect of target congruency was also observed in both regions, consistent with models in which resolving conflict involves further increasing attention to relevant stimuli (Botvinick, et al., 2001; Weissman, et al., 2005; Weissman, et al., 2004). Given that our findings implicate both dorsal subregions of the ACCcd and the left DLPFC in implementing processes that increase attention to relevant stimuli, future work should be aimed at determining whether these regions make identical or distinct contributions to such processes. Third, in line with prior findings that increasing attention to relevant stimuli speeds response times to identify those stimuli (M. I. Posner, 1980; Stoffer, 1993), the more a given participant exhibited greater activity in the dorsal subregion for incongruent cue-only than for congruent cue-only trials (i.e., a cue congruency effect), the more that participant tended to respond faster to targets that followed incongruent cues than to targets that followed congruent cues. Taken in isolation, one might interpret this correlation as indicating that greater conflict detection by the dorsal subregion leads to greater recruitment of other brain regions (e.g., the DLPFC) that resolve conflict during cue processing. However, given that several of our other findings implicate the dorsal subregion in implementing attentional processes, the most parsimonious interpretation of our findings is that the dorsal subregion of the ACC_{cd} implements attentional processes in multiple contexts, consistent with recent claims that

the dorsal ACCcd is a critical component of a "core task-set system" (Dosenbach, et al., 2007; Dosenbach, et al., 2006).

Of importance, our findings also weigh against the possibility that the cue congruency effect in the dorsal subregion of the ACC_{cd} reflects control processes other than those that increase attention to relevant stimuli. First, the cue congruency effect is unlikely to index processes that detect pre-response (e.g., semantic) conflict (van Veen & Carter, 2005; Weissman, Giesbrecht, Song, Mangun, & Woldorff, 2003). Indeed, even when semantic conflict was equated during the processing of incongruent cues, switching attention from the visual to the auditory modality was associated with greater activity in the dorsal subregion than was maintaining attention in the visual modality. Second, the cue congruency effect is unlikely to reflect processes that signal an increased likelihood of making an error in an upcoming task (Brown & Braver, 2005) or an increased probability of receiving a reduced reward when an error is relatively likely (Hewig, et al., 2007). Specifically, activity in the dorsal subregion was greater for incongruent than for congruent cues despite the fact that behavioral performance was both faster and more accurate for targets that followed incongruent cues than for targets that followed congruent cues. Third, the cue congruency effect is unlikely to index processes underlying response selection (Roelofs, et al., 2006) because no responses were made to the cue stimuli. Fourth, the cue congruency effect is unlikely to index the expectation of greater response conflict in an upcoming task (Sohn, Albert, Jung, Carter, & Anderson, 2007) because behavioral measures of response conflict were significantly smaller following incongruent cues than following congruent cues. And, fifth, the cue congruency effect is unlikely to index processes underlying anticipation (Murtha, et al.,

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1996) or novelty detection (Matsumoto, et al., 2007; Ranganath & Rainer, 2003) because we held constant the nature of the task that followed incongruent and congruent cues. For all of these reasons, our findings are most compatible with a role for the dorsal subregion of the ACC$_{cd}$ in increasing attention to relevant stimuli (Dreher & Berman, 2002; Michael I. Posner & DiGirolamo, 1998).

Although we have argued against an interpretation of the cue congruency effect in dorsal subregions of the ACCcd as reflecting processes that monitor for semantic conflict, one might wonder whether a visually-presented cue instructing participants to shift their attention to the auditory modality is inherently associated with greater semantic conflict than a visually-presented cue instructing subjects to maintain their attention in the visual modality. Such a view may appear plausible at first, but two pieces of data argue against it as an alternative account of our findings. First, we did not observe significantly greater activity in the dorsal ACCcd for congruent hear cue-only than for congruent look cue-only trials, even though, according to this view, congruent hear cue-only trials should be associated with greater semantic conflict than congruent look cue-only trials. Second, in a prior study (Weissman, et al., 2004) we observed significantly greater activity for hear cue-only than for look cue-only trials, even though each type of cue was presented in the visual modality in half the trials and in the auditory modality in the other half, a manipulation that should have equated for these trial types the specific form of semantic conflict that is under consideration. For these reasons (and others discussed in the preceding paragraph), we would argue that the cue congruency effect that we have observed in the dorsal ACCcd is much more consistent with a role for this

region in implementing attentional processes than with a role in monitoring for semantic conflict.

We have also argued that the cue congruency effect in dorsal subregions of the ACCcd is unlikely to index processes underlying response selection (Roelofs, et al., 2006) because no responses were made to the cue stimuli. Nonetheless, it is important to consider whether our findings might be accounted for by a more broadly-conceived response selection model (Milham & Banich, 2005). In this model, dorsal subregions of the ACCcd that are activated during cue processing might link information from the currently relevant sensory stream to mechanisms that plan future responses. Some investigators have argued that support for this type of response selection model comes from findings that dorsal ACCcd activity is greater for both congruent and incongruent trials than for neutral trials in the classic Stroop task (Milham & Banich, 2005). The central claim is that demands on processes that link a relevant channel of information (ink color) to response mechanisms are greater when an irrelevant channel of information (word identity) contains task-relevant information (a color-related word) than when it contains task-irrelevant information (a color-unrelated word). Clearly, this response selection model differs from the attention-based model that we favor, which posits that dorsal subregions of the ACCcd bias attention at perceptual stages of processing toward whichever stream of sensory information is currently relevant.

We now consider whether the response selection model can provide a better account of our findings than the attention-based model. According to the response selection model, cue-related activity in dorsal subregions of the ACCcd reflects processes that select the channel of information (auditory or visual) upon which a future response

will be based. In this view, basing a response on the auditory channel should impose

similar demands on response selection processes as basing a response on the visual

channel. In both cases, information from a single sensory modality needs to be linked to

response mechanisms, and there is no *a priori* reason to hypothesize that this link should

be more difficult to make for one sensory modality than for another. For example, the

number of irrelevant channels that contain task-relevant information during cue

processing (i.e., one auditory channel) is the same regardless of whether participants are

cued to direct their attention toward the auditory or toward the visual sensory modality.

Contrary to the response selection view, however, we observed greater activity in dorsal

subregions of the ACCcd for hear cue-only than for look cue-only trials. As we discussed

earlier, this finding is highly consistent with our view that the dorsal ACCcd implements

attentional processes. Indeed, demands on attentional processes should have been greater

when participants were cued to shift attention away from the visual modality and toward

the auditory modality (hear cue-only trials) than when they were cued to maintain

attention in the visual modality (look cue-only trials). The response selection model is not

about increasing attention to relevant stimuli at perceptual stages of processing, but rather

about pre-setting or biasing response-related aspects of selection. Therefore, our finding

that the dorsal ACCcd is more highly activated for hear cue-only than for look cue-only

trials appears to be better explained by the attention model than by the response selection

model.

Our conclusion that the dorsal subregion of the ACC_{cd} increases attention to

relevant stimuli raises an important question about how we should interpret previous

findings implicating these regions in various aspects of performance monitoring, such as

conflict monitoring, error monitoring, and reward assessment (Ridderinkhof, Ullsperger,

Crone, & Nieuwenhuiss, 2004). In our view, the present data suggest that dorsal ACC_{cd}

activity attributed to performance monitoring in some prior studies may actually have

reflected attentional processes. Specifically, as in the present study, dorsal ACC_{cd} activity

that varied with demands on performance monitoring processes might also have varied

with demands on cue-triggered attentional processes, even when demands on

performance monitoring processes were minimal. Such a result would be highly

consistent with a role for the dorsal ACC_{cd} in implementing attentional processes that are

recruited not only during cue processing to orient attention, but also during target

processing to resolve response conflict by further increasing attention to relevant stimuli

(Weissman, et al., 2004). Unfortunately, only a handful of previous investigators have

used experimental designs in which attentional and performance monitoring processes

can be distinguished from one another as in the present study (MacDonald, et al., 2000;

Weissman, et al., 2005; Weissman, et al., 2004). Thus, additional studies are needed to

determine whether, and to what degree, dorsal ACC_{cd} activity that is frequently

associated with various performance monitoring processes (e.g., error monitoring, reward

assessment, etc.) may actually reflect attentional processes.

     The present findings also weigh against the possibility that the target congruency

effect in the rostral subregion of the ACC_{cd} reflects control processes other than those

that detect response conflict. First, if these regions detected pre-response (e.g., semantic)

conflict (van Veen & Carter, 2005; Weissman, et al., 2003), then we should have

observed greater activity for incongruent than for congruent cue-only trials. Incongruent

cue-only trials were high in semantic conflict because the two words ('Look' and 'Hear')

had different meanings, whereas congruent cue-only trials were low in semantic conflict because the same word (e.g., 'Look') was presented twice. However, we observed no such effect. Second, if these regions signaled either when an error was relatively likely in an upcoming task (Brown & Braver, 2005) or when an upcoming task was more likely to be less rewarding because an error was relatively likely (Hewig, et al., 2007), then we should have observed greater activity for congruent than for incongruent cue-only trials. Indeed, as we mentioned earlier, behavioral performance was worse for targets that followed congruent cues than for targets that followed incongruent cues. However, once again we observed no such effect. Thus, our findings are most compatible with a role for the rostral subregion of the ACC_{cd} in detecting response conflict.

More broadly, the present results add to a growing body of work indicating regional specialization of function in the ACC (Bush, et al., 2002; Goldstein, et al., 2007; Somerville, Heatherton, & Kelley, 2006). A major finding of this work has been that relatively dorsal and caudal ACC regions (i.e., the so-called 'cognitive' division of the ACC) participate in implementing cognitive processes while relatively ventral and rostral ACC regions (i.e., the so-called 'emotional' division of the ACC) contribute to emotional processes. The present findings of regional specialization completely within the cognitive division of the ACC indicate regional specialization on a much finer spatial scale than have many prior studies, consistent with recent data indicating that rostral and dorsal subregions of the ACC_{cd} exhibit different patterns of functional connectivity with other brain regions when participants are not actively performing a cognitive task (Margulies, et al., 2007). As such, our findings suggest that brain imaging techniques offering relatively high degrees of spatial resolution may be useful for mapping the complete

spatial topography of cognitive and emotional processes in the ACC. Such techniques have already been applied successfully to study regional specialization within the visual system. For example, recent findings from 'high-resolution' fMRI suggest that regions of the visual cortex that are specialized for processing faces can, in fact, be subdivided into smaller regions that are specialized for processing different types of objects (Grill-Spector, Sayres, & Ress, 2006). Future high-resolution studies may therefore be helpful for obtaining a more fine-grained characterization of regional specialization in the ACC for various cognitive control processes.

Although the present findings of regional specialization in the ACC_{cd} provide novel support for two-component models of minimizing distraction, they also have some limitations. Most important, they do not reveal the relative timing with which different brain regions become activated during the process of minimizing distraction. For instance, brain regions that detect response conflict should become activated *before* brain regions that increase attention to relevant stimuli. Given the sluggishness of the hemodynamic signal that is measured with fMRI, brain imaging techniques offering higher temporal resolution will likely be necessary to test such important predictions.

In conclusion, our findings support a two-component model of minimizing distraction from irrelevant stimuli (Botvinick, et al., 2001; Carter, et al., 1998; Kerns, 2006). Moreover, they speak to a longstanding controversy over the role of the ACC_{cd} in cognitive control by showing that, rather than performing a single cognitive control process as some models posit (Botvinick, et al., 2001; Carter, et al., 1998; Kerns, 2006), the ACC_{cd} implements multiple control processes. Future studies characterizing the spatial topography and relative timing of control processes in the ACC may enhance our

understanding of behavior in neurologically-intact populations and in numerous clinical

syndromes that are characterized by disruptions of cognitive control, including drug

addiction (Goldstein, et al., 2007), attention deficit and hyperactivity disorder (Dickstein,

et al., 2006), and schizophrenia (Kerns, et al., 2005).

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Chapter 3

Succumbing to bottom-up biases on task choice predicts increased switch costs in the voluntary task switching paradigm

Abstract

Bottom-up biases are widely thought to influence task choice in the voluntary task switching paradigm. Definitive support for this hypothesis is lacking, however, because task choice and task performance are usually confounded. We therefore revisited this hypothesis using a paradigm in which task choice and task performance are temporally separated. As predicted, participants tended to choose the task that was primed by bottom-up biases. Moreover, such choices were linked to increased switch costs during subsequent task performance. These findings provide compelling evidence that bottom-up biases influence voluntary task choice. They also suggest that succumbing to such biases reflects a reduction of top-down control that persists to influence upcoming task performance.

Introduction

Much of human behavior is thought to reflect a mixture of top-down and bottom-up processes. For example, driving from Brooklyn to Los Angeles involves a combination of top-down processes that strategically plan a route and bottom-up processes that enable habitual responses to familiar stimuli (e.g., traffic lights) along the way. A mixture of such processes is also present in most laboratory tasks of selective attention. For instance, performance in the Stroop task is thought to be determined by a combination of top-down processes that bias attention toward ink color and bottom-up processes that underlie word reading (MacLeod, 1991). Similarly, the locus of spatial attention in the Posner cueing paradigm is thought to depend on top-down processes that underlie voluntary orienting of attention and bottom-up processes that orient attention to salient events (Corbetta, Patel, & Shulman, 2008; Posner, Snyder, & Davidson, 1980). Further developing our understanding of how top-down and bottom-up processes influence performance has therefore become a mainstay of modern attention research.

Recently, there has been growing interest in understanding how top-down and bottom-up processes influence task choice in the voluntary task switching paradigm. In each trial, participants are instructed to randomly choose one of two possible tasks to perform on an imperative stimulus (Arrington & Logan, 2004). As instructed, participants usually perform each task about half the time. However, they often exhibit a task-repetition bias, meaning that they switch tasks less than fifty percent of the time. To account for this effect, it has been suggested that voluntary task choice is influenced by two main processes (Arrington & Logan, 2005; Mayr & Bell, 2006). First, a top-down random sequence heuristic is thought to choose a task by (a) comparing the recent history

of task choices to a representative random sequence (Arrington & Logan, 2004, 2005) or

(b) treating each trial as a discrete event in which a task is chosen using, essentially, a

mental coin flip (Mayr & Bell, 2006). Second, a bottom-up availability heuristic is

thought to choose the task that is currently most active, or available, in working memory,

which is typically the task performed in the previous trial (Arrington & Logan, 2005;

Lien & Ruthruff, 2008; Mayr & Bell, 2006). Thus, the task-repetition bias is thought to

stem from the availability heuristic.

　　　　More direct evidence to suggest an influence of the availability heuristic on

voluntary task choice comes from studies of stimulus repetition. The logic is that a

stimulus-task association is strengthened each time a task is performed on an imperative

stimulus (Arrington, Weaver, & Pauker, 2010; Demanet, Liefooghe, Verbruggen, &

Vandierendonck, 2010; Verbruggen & Logan, 2008). Thus, presenting a stimulus that

appeared in a previous trial should increase the activation of the previous-trial task

representation in working memory, thereby amplifying the task-repetition bias. Several

findings are consistent with this view. First, the task-repetition bias is larger when an

imperative stimulus matches the stimulus from the previous trial than when it does not

(Mayr & Bell, 2006). Second, the task repetition bias is larger when an irrelevant

stimulus from the previous trial (e.g., a random shape) is repeated than when it is not,

suggesting that stimulus-task associations are formed even for irrelevant stimuli

(Demanet, et al., 2010). Third, participants are biased to perform the same task on a

repeated imperative stimulus that they initially performed, regardless of whether they

chose the initial task or the experimenter did (Arrington, et al., 2010; Demanet, et al.,

2010). And fourth, stimulus repetition amplifies the task-repetition bias more when a

concurrent working memory load is present than when it is absent (Demanet, et al., 2010), consistent with prior work indicating that working memory resources are important for inhibiting bottom-up biases (Lavie, 2004). These findings fit nicely with the view that a bottom-up availability heuristic influences voluntary task choice.

Additional evidence to suggest that a stimulus can influence voluntary task choice in a bottom-up fashion comes from recent findings concerning *stimulus availability* (Arrington, 2008). When two stimuli are presented in rapid succession (e.g., a letter and a digit), participants are biased to perform the task associated with the first stimulus (e.g., the letter). This finding suggests that the first stimulus activates its task representation in working memory before the second stimulus can activate its task representation, thereby increasing the chances that the first task will be chosen via the availability heuristic. In sum, studies of stimulus availability also suggest that a stimulus can influence voluntary task choice in a bottom-up fashion.

Definitive support for this view is lacking, however, because task choice and task performance are usually registered with a single button press to an imperative stimulus. Putative bottom-up biases on task choice may therefore reflect bottom-up biases on task performance. First, consider the finding that stimulus repetition amplifies the task-repetition bias (Mayr & Bell, 2006). Although repeating a stimulus may prime the task with which it was most recently associated (Arrington, et al., 2010; Demanet, et al., 2010; Verbruggen & Logan, 2008), it may also prime the task-relevant response with which it was most recently linked (Hommel, 1998). Participants may therefore execute this response without actually making a task choice (Arrington, et al., 2010; Demanet, et al., 2010). Second, consider the finding that stimulus availability biases participants to

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perform the task associated with the first of two rapidly presented stimuli (Arrington, 2008). This effect may occur because the first stimulus (e.g., a letter) activates its task representation in working memory more quickly than the second stimulus (e.g., a digit) (Arrington, 2008). However, the two stimuli are unambiguously mapped not only to different tasks, but also to different responses. The first stimulus may therefore also prime a task-relevant response more quickly than the second stimulus, and participants may simply execute this response without making a task choice. For these reasons, data to support the view that a stimulus can influence voluntary task choice in a bottom-up fashion are often ambiguous.

Given this ambiguity, it is also unclear whether any potential influence of the availability heuristic on voluntary task choice is related to subsequent task performance. If such an influence stems from a reduction of top-down control (Arrington & Yates, 2009; Demanet, et al., 2010) and if this reduction persists for a few seconds (e.g., due to fatigue, diminished motivation, etc.), then subsequent task performance might also exhibit signs of reduced control. For instance, switch costs might be higher when participants select the task primed by the availability heuristic (congruent task choice trials) as compared to the opposite task (incongruent task choice trials). Relatively little data speak to this issue, however, because the congruency of a task choice with respect to the availability heuristic is usually confounded with repeating versus switching tasks. For example, choosing the task that is primed by a stimulus repetition (i.e., a congruent task choice) usually involves repeating the task from the previous trial. Conversely, choosing the task that is not primed by a stimulus repetition (i.e., an incongruent task choice) typically involves switching to a new task. Given these typical confounds, it is unclear

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whether any potential influence of bottom-up biases on voluntary task choice predicts subsequent task performance.

In sum, ambiguity regarding whether bottom-up biases influence voluntary task choice through the availability heuristic has arisen because task choice and task performance are usually registered with a single response. We therefore investigated the influence of bottom-up biases on voluntary task choice using a paradigm in which voluntary task choice and subsequent task performance are registered with different responses (Arrington & Logan, 2005, Experiment 6). First, we investigated whether bottom-up biases influence voluntary task choice as indexed by a tendency to make congruent task choices. Second, we investigated whether congruent voluntary task choices reflect a reduction of top-down control that persists to influence subsequent task performance. Specifically, we investigated whether switch costs are larger after congruent as compared to incongruent voluntary task choices. Our findings supported both of these hypotheses.

Method

Participants

Fifty-seven healthy, right-handed participants with no history of neurological disorders were recruited from the University of Michigan community in accordance with the Institutional Review Board (mean age: 20.2 years, range: 18 – 30 years; 33 females). Data from three participants were excluded: two participants who repeated tasks on more than 80% of the trials, and one participant whose accuracy during task performance fell below 85%. Thus, only the data from the remaining 54 participants (30 females) were further analyzed in group analyses.

Apparatus and Stimuli

The stimuli were generated and displayed using Presentation software (Neurobehavioral Systems Inc., Albany, CA). Participants viewed the task stimuli on a 17" CRT monitor at a viewing distance of 60 cm. A chin rest was used for head stabilization.

Participants performed a voluntary task switching version of the numerical Stroop task, which involved comparing two digits in terms of their numerical size or in terms of their physical size (Henik & Tzelgov, 1982). In each trial, participants voluntarily chose to perform one of these tasks (Figure 3.1a) or were explicitly instructed to perform one of these tasks (Figure 3.1b). Voluntary and explicit task choice trials were presented in a random order throughout the experiment.

Each trial began with the presentation of a cue at the center of the screen. In voluntary task choice trials, the cue was a question mark that prompted participants to voluntarily choose a task. In explicit task choice trials, the cue was an 'N' or a 'P' which, respectively, instructed participants to perform either the numerical or the physical size comparison task. In each trial, the cue remained on the screen until participants pressed the D key (left middle finger) or the F key (left index finger) to indicate which task they would perform on the upcoming digit pair. The task-key mapping was counterbalanced across participants.

To manipulate which task was most salient to the availability heuristic, the central cue in each trial was flanked by two identical distracter letters: one appeared 1.37° to the left of the central cue and the other appeared 1.37° to the right (Figure 3.1). The distracter letters were often strongly associated with either the numerical or the physical size

comparison task because they served as explicit cues to perform these tasks in explicit

task choice trials. Specifically, in equal numbers of trials, the distracter letters were

associated with the numerical size comparison task (i.e., two 'Ns'), the physical size

comparison task (i.e. two 'Ps'), or with no task (i.e., two 'Os'). We reasoned that, while

serving as a distracter letter, an 'N' or a 'P' would activate (a) a representation of a

specific task and/or (b) a representation of the response involved in choosing that task.

Either or both of these representations might then influence voluntary task choice through

the availability heuristic (Arrington, et al., 2010).

To determine whether voluntary task choice was influenced by the distracter

letters, we distinguished among three types of voluntary task choice trials. In congruent

voluntary task choice trials, participants chose the task signaled by the distracter letters.

In incongruent voluntary task choice trials, participants chose the task that was not

signaled by the distracter letters. In neutral voluntary task choice trials, participants chose

a task in the presence of two distracter letters that were not associated with either of the

two possible tasks.

Five hundred milliseconds after participants indicated which task they would

perform in response to the central cue, two digits appeared (1.7° above and 1.7° below

fixation). One digit was numerically larger (7, 8, or 9) and the other was numerically

smaller (1, 2, or 3). Further, one digit was physically larger (0.7° by 1.1°) while the other

was physically smaller (0.4° by 0.6°). In congruent trials (50%), the numerically larger

digit was also physically larger. In incongruent trials (50%), the numerically larger digit

was physically smaller. The digits remained on the screen until the participant indicated

the spatial position (top or bottom) of the digit that was larger at the relevant dimension

(i.e., numerical size or physical size) by pressing the J key (the digit on top; right middle

finger) or the N key (the digit on the bottom; right index finger) on a computer keyboard.
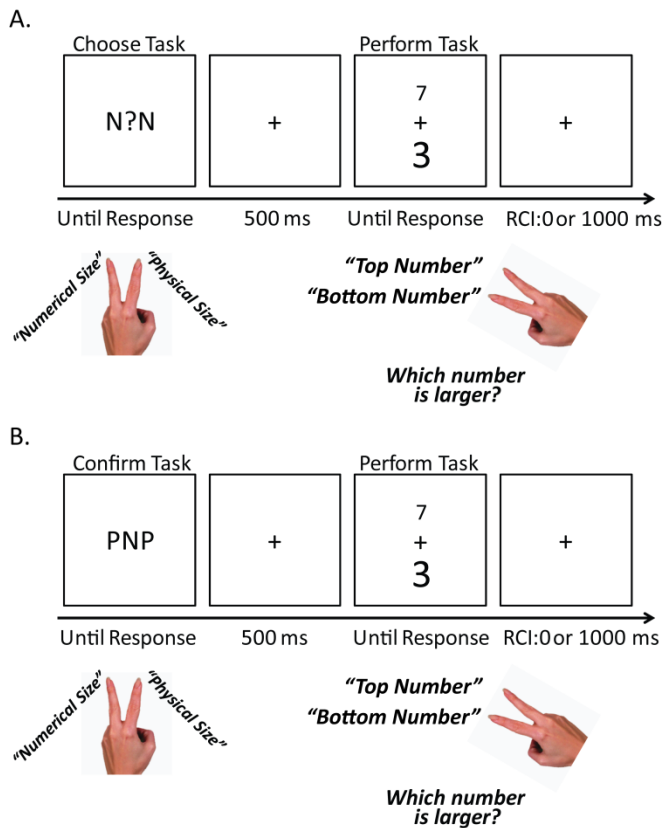

Figure 3.1. Experimental design.
Examples of voluntary and explicit task choice trials used in the experiment. Participants performed a task switching version of the numerical Stroop task, which involved comparing two digits with respect to their numerical size or with respect to their physical size. **(A)** Each voluntary task choice trial began with the presentation of a central question mark ('?'), which indicated that participants should voluntarily choose which task to perform in the current trial. Participants were instructed to indicate their task choice by pressing a button with the middle or index finger of their left hand. **(B)** Each explicit task choice trial began with the presentation of a central cue letter, which indicated that participants should choose to perform either the numerical or the physical size comparison task. Participants were instructed to confirm their task choice by pressing a button with the middle or index finger of their left hand. In both voluntary and explicit task choice trials, the central cue was flanked by two identical distracter letters that were associated with the numerical size comparison task (i.e. two 'Ns'), the physical size comparison task (i.e. two 'Ps'), or neither task (i.e. two 'Os'). The cue and flanking distracter letters remained on the screen until participants indicated their task choice. Five hundred ms after making a task choice, the imperative task stimuli (i.e., two digits) appeared. One was numerically larger (e.g. '7') while the other was numerically smaller (e.g. '3'). Further, one was presented in a larger font (e.g. '3') while the other was presented in a smaller font (e.g. '7'). In congruent trials, the numerically larger digit was also physically larger. In incongruent trials, the numerically larger digit was physically smaller. Depending on the task, participants indicated which of the two digits (top or bottom) was numerically larger or physically larger. They were instructed to indicate their decision as quickly and as accurately as possible by making a key press with either their right index finger or their right middle finger. The next trial began after a 100 ms or a 1000 ms response-to-cue interval (RCI), which varied across participants.

The next trial was presented after a response-cue interval (RCI) of either 0 ms or 1000 ms. Switch costs are typically larger after short as compared to long RCIs, suggesting a passive dissipation of the task-set from the previous trial (Allport, Styles, & Hsieh, 1994; Arrington & Logan, 2005). Recent findings, however, suggest that this effect occurs only when the RCI varies from one trial to the next and not when the RCI remains constant throughout a block of trials (Horoufchin, Philipp, & Koch, 2010). It has therefore been suggested that mechanisms other than a passive decay of the previous trial's task set, such as the temporal distinctiveness of the current task cue, may explain the effect of RCI on switch costs (Horoufchin, et al., 2010). Nonetheless, at least one prior study has revealed that switch costs are larger after short compared to long RCIs when the RCI remains constant throughout a block of trials, but varies across participants (Koch, 2001). Although this result appears more consistent with task-set decay than with temporal distinctiveness, it has been suggested that it may somehow have resulted from the fact that participants switched among three possible tasks, rather than just two (Horoufchin, et al., 2010). We therefore investigated whether we could replicate this result by varying the RCI across (but not within) participants in our paradigm, which involved switching between just two tasks. The RCI lasted 0 ms for 28 participants and 1000 ms for 26 participants.

Procedure

The procedure consisted of four parts. First, participants practiced the numerical and physical size comparison tasks separately. Each practice block (one for each task) consisted of 20 trials, and the order in which the tasks were practiced was counterbalanced across participants. Second, participants practiced voluntarily choosing

to perform either the numerical or the physical size comparison task when prompted by a question mark. In particular, they performed a single block of 36 voluntary task choice trials in the absence of distracter letters. Third, to prepare for the actual experiment, participants practiced randomly alternating between voluntary and explicit task choice trials. That is, they performed a single block of 32 trials in which voluntary and explicit task choice trials appeared in a random order. As in the actual experiment, each cue was flanked by two identical distracter letters. At the end of each voluntary task choice and mixed voluntary-explicit task choice practice block above, participants were told the proportion of trials in which they (a) performed each task and (b) switched tasks. If either proportion was less than 40% or greater than 60%, they performed that particular practice block again. Each type of practice block (i.e., voluntary and mixed voluntary-explicit) was practiced an average of 1.2 times. Fourth, participants' performance was measured in 15 blocks of the main experiment, each of which contained 72 trials. The instructions stressed that in voluntary task choice trials a task should be chosen randomly. Moreover, participants were told that they could take their time choosing which task to perform, but that they needed to subsequently perform the task as quickly as possible while remaining accurate.

Data Analysis

Prior to the main analyses, we discarded (a) outlier trials in which reaction time (RT) during task performance was either faster than 200 ms or slower than three standard deviations from the participant's mean RT and (b) trials that were preceded by outlier trials. In this manner, 2.9% of trials were discarded. We also discarded trials in which an error occurred and trials with a correct response that immediately followed errors. In this

manner, 11.5% of trials were discarded. In total, 13.4% of trials were discarded prior to the main analyses.

On the remaining data, omnibus tests were conducted using mixed analysis of variance (ANOVA). When necessary, Greenhouse-Geisser corrections for non-sphericity were applied to adjust the degrees of freedom. Post-hoc pairwise comparisons were performed using the Newman-Keuls test.

Results

Task Choice Proportions

The voluntary task choice data were largely consistent with prior studies of voluntary task switching. First, participants performed each task about half the time. The mean probabilities for voluntarily choosing (a) the numerical size comparison task (49.7%; 95% CI: 48.3% - 50.5%) and (b) the physical size comparison task (50.3%; 95% CI: 49.5% - 51.7%) both had 95% confidence intervals that included 50%. Second, participants exhibited a task-repetition bias: the mean voluntary switch rate (43.2%) had a confidence interval that fell below 50% (95% CI: 39.4% - 47.1%). Thus, we replicated two standard effects in the voluntary task switching paradigm.

Our first main hypothesis was that participants would exhibit a tendency to make congruent task choices. To test this hypothesis, we determined how often participants

Table 3.1
Task choice as a function of distracter identity.

Distracter Identity	Numerical Size Comparison	Physical Size Comparison
N	56% (1%)	44% (1%)
O	49% (0.7%)	51% (0.7%)
P	43% (1%)	57% (1%)

voluntarily chose each task as a function of the distracter letter pair (two 'Ns', two 'Ps', or two 'Os') that appeared in each trial. Next, for each of these three conditions, we created a task choice index: the proportion of trials in which participants voluntarily chose the numerical size comparison task minus the proportion of trials in which they voluntarily chose the physical size comparison task. We reasoned that if participants were biased to make congruent task choices, then the task choice index would be positive when the distracter letters were 'Ns' and negative when the distracter letters were 'Ps'. Further, we predicted that the task choice index would not differ from zero when the distracter letters were 'Os', which were associated with neither of the two possible tasks.

We evaluated these predictions by submitting the mean task choice index in voluntary task choice trials to a mixed ANOVA with one between-participants factor, RCI (0 ms, 1000 ms), and three within-participants factors: previous agency (voluntary, explicit), current task transition (repeat, switch), and current distracter identity ('N', 'P', 'O'). Table 3.1 indicates the proportion of trials in which participants chose each task as a function of current distracter identity. As predicted, there was a main effect of current distracter identity [$F(1.4, 75.3) = 45.1$, $p < 0.001$]. The task choice index was positive when the distracter letters were 'Ns' (14.3%; *95% CI*: 9.8% to 18.8%), negative when the distracter letters were 'Ps' (-16.0%; *95% CI*: -11.0% to -20.9%), and did not differ from zero when the distracter letters were 'Os' (-2.2%; *95% CI*: -5.3% to 1.0%). Also as expected, post-hoc tests revealed that the task choice index was (a) more positive when the distracter letters were 'Ns' than when they were 'Os' ($p < 0.001$) and (b) more negative when the distracters were 'Ps' than when they were 'Os' ($p < 0.001$). These

findings support the view that a stimulus can influence voluntary task choice in a bottom-up fashion through the availability heuristic.

There was also an interaction between previous agency and current distracter identity [$F(1.9, 100.7) = 12.1, p < 0.001$; Figure 3.2]. Post-hoc tests indicated that participants were more likely to choose the task associated with the distracter letters when the task choice in the previous trial was explicit than when it was voluntary (both $p < 0.001$). A potential explanation addressed below is that the association between a distracter letter and a task choice was stronger when that distracter letter had (versus had not) appeared as an explicit cue in the preceding trial. No other effects were significant.

As described above, participants were biased to make congruent task choices in voluntary task choice trials. We therefore reasoned that voluntary switch rates should be lower when the identity of the current distracter letters matched the previous-trial task (thus priming a task repeat) than when it mismatched and signaled the opposite task (thus priming a task switch). To test this prediction, we conducted a mixed ANOVA on switch rates with one between-participants factor, RCI (0 ms, 1000 ms), and two within-participants factors: current distracter identity – previous task relationship (match, mismatch, neutral) and previous agency (voluntary, explicit). As expected, there was a main effect of current distracter identity - previous task relationship [$F(1.4, 73.3) = 44.3$, $p < 0.001$]. Switch rates were lowest when the current distracter identity matched the previous task (36.3%), intermediate when the current distracter identity was neutral (44.3%), and highest when the current distracter identity mismatched the previous task and therefore signaled the opposite task (49.7%). Post-hoc pairwise comparisons revealed that each of these three values differed from the other two (all p's < 0.01). These findings

support previous claims that task availability influences voluntary switch rates (Arrington & Logan, 2005; Arrington, et al., 2010; Demanet, et al., 2010; Mayr & Bell, 2006).
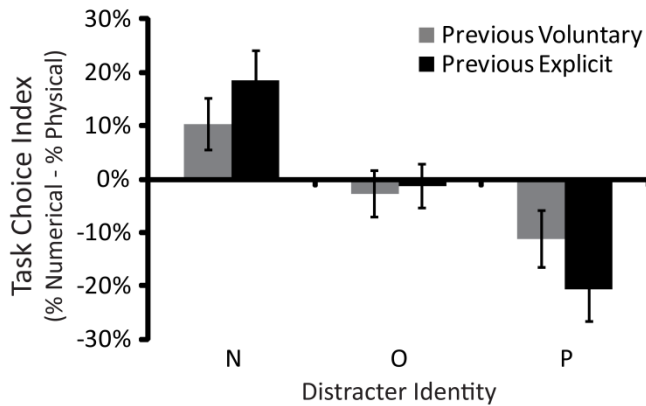

Figure 3.2. Task choice index.
The task choice index (i.e., the proportion of trials in which participants voluntarily chose the numerical size comparison task minus the proportion of trials in which they voluntarily chose the physical size comparison task) as a function of distracter identity (N, P, or O) and previous agency (voluntary, explicit). Positive values indicate a bias to choose the numerical size comparison task more often than the physical size comparison task. Negative values indicate the opposite bias. Participants tended to choose the task associated with the distracter letters (i.e., a positive task choice index for N distracters and a negative task choice index for P distracters) and this bias was stronger after explicit than after voluntary task choice trials. Error bars represent 95% confidence intervals.

There was also an interaction between current distracter identity - previous task relationship and previous agency [$F(1.9, 98.2) = 14.3$, $p < 0.001$; Figure 3.3]. When the current distracter identity matched the previous task, switch rates were lower if the previous trial contained an explicit cue as compared to a voluntary cue (post-hoc comparison: $p < 0.001$). Conversely, when the current distracter identity mismatched the previous task (i.e., signaled the opposite task), switch rates were higher if the previous trial contained an explicit cue as compared to a voluntary cue (post-hoc comparison: $p < 0.05$). Finally, when the current distracter identity was neutral with respect to the previous task (i.e., two 'Os'), switch rates did not vary with whether the previous trial contained an explicit cue as compared to a voluntary cue (post-hoc comparison: $p > 0.09$). These findings are consistent with our earlier suggestion that the strength of the

association between a distracter letter and a task choice was greater when the distracter

letter had served as an explicit cue in the previous trial. No other effects were significant.
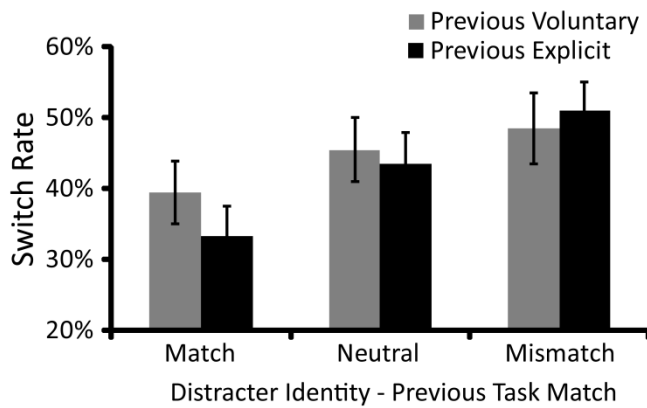

Figure 3.3. Switch rate.
Mean switch rate varied with an interaction between current distracter identity - previous task relationship and previous agency. When the current distracter identity (e.g., N) matched the previous task (e.g., the numerical size comparison task), switch rates were higher if the previous trial involved a voluntary task choice as compared to an explicit task choice. In contrast, when the current distracter identity (e.g., N) mismatched the previous task (e.g., the physical size comparison task), switch rates were higher if the previous trial involved an explicit task choice as compared to a voluntary task choice. Error bars represent 95% confidence intervals.

Task Performance – Mean RT

Our second main hypothesis was that congruent voluntary task choices would be

followed by larger switch costs during subsequent task performance than either

incongruent or neutral voluntary task choices. To investigate this hypothesis, we analyzed

mean RT during task performance using a mixed ANOVA with RCI (0 ms, 1000 ms) as a

between-participants factor and four within-participants factors: agency (voluntary,

explicit), cue congruency (congruent, incongruent, neutral), target congruency

(congruent, incongruent), and task transition (repeat, switch)[1]. Table 3.2 provides the

mean RT for each cell of this ANOVA. Critically, there was an interaction between cue

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[1] Unlike the task choice data, there were no main effects or interactions involving previous agency in the task performance data. Therefore, we did not include previous agency as a factor in the final analyses of these data.

congruency and task transition [$F(1.9, 100.2) = 5.5$, $p < 0.01$]. In line with predictions, switch costs in congruent task choice trials (70 ms) were larger than those in both incongruent [47 ms; $F(1, 52) = 7.9$, $p < 0.01$] and neutral [50 ms; $F(1, 52) = 7.6$, $p < 0.01$] task choice trials.

Table 3.2
Mean Reaction Time (ms) in the Main Conditions of the Study.

Task Transition	Congruent Task Choice		Incongruent Task Choice		Neutral Task Choice	
	Congruent Target	Incongruent Target	Congruent Target	Incongruent Target	Congruent Target	Incongruent Target
	0 ms RCI					
	Voluntary Trials					
Repeat	695 (22)	814 (24)	703 (23)	845 (25)	707 (24)	824 (26)
Switch	782 (26)	907 (25)	755 (27)	888 (26)	770 (22)	866 (24)
	Explicit Trials					
Repeat	672 (24)	798 (26)	679 (22)	824 (25)	687 (26)	798 (25)
Switch	768 (25)	885 (25)	769 (25)	900 (28)	780 (25)	893 (27)
	1000 ms RCI					
	Voluntary Trials					
Repeat	650 (23)	810 (25)	655 (24)	800 (26)	632 (25)	793 (27)
Switch	696 (27)	850 (26)	679 (28)	813 (27)	669 (23)	813 (25)
	Explicit Trials					
Repeat	628 (25)	763 (27)	637 (23)	793 (26)	648 (27)	799 (26)
Switch	660 (26)	842 (26)	671 (26)	835 (29)	670 (26)	830 (28)

We were particularly interested in whether these effects were present in voluntary task choice trials. We therefore conducted planned comparisons to determine the effect of cue congruency on switch costs separately in voluntary and explicit task choice trials. As predicted, switch costs were larger in congruent (67 ms) than in either incongruent [33 ms; $F(1, 52) = 8.0$, $p < 0.01$] or neutral [40 ms; $F(1, 52) = 6.4$, $p = 0.01$] voluntary task choice trials (see Figure 3.4). In contrast, switch costs in congruent explicit task choice trials (74 ms) did not differ from those in either incongruent [61 ms; $F(1, 52) = 1.6$, *n.s.*] or neutral [60 ms; $F(1, 52) = 2.2$, *n.s.*] explicit task choice trials. Nonetheless, in line with our second main hypothesis, our findings in voluntary task choice trials suggest that less

top-down control was recruited during task performance in congruent as compared to either incongruent or neutral task choice trials.
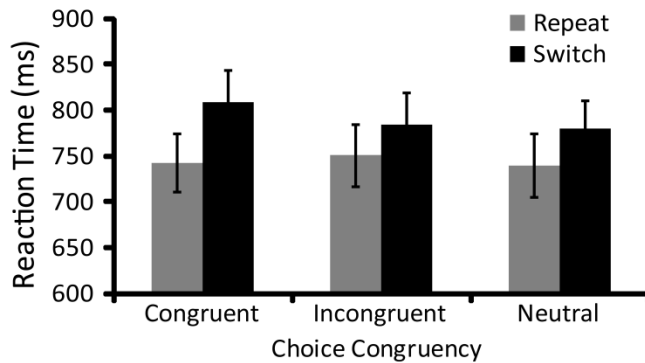

Figure 3.4. Switch costs.
Switch costs (i.e., incongruent RT – congruent RT) were larger in congruent task choice trials than in either incongruent or neutral task choice trials. Error bars represent 95% confidence intervals.

Two effects involving agency were also significant. First, there was an interaction between agency and task transition [$F(1, 52) = 6.4$, $p = 0.01$]. Replicating prior findings (Arrington & Logan, 2005), switch costs were larger in explicit [65 ms; $F(1, 52) = 110.1$, $p < 0.001$] than in voluntary [47 ms; $F(1, 52) = 40.4$, $p < 0.001$] task choice trials. Second, there was interaction between agency and cue congruency [$F(1, 52) = 6.3$, $p < 0.005$]. Recent work indicates that presenting an irrelevant task cue during task preparation slows responses when it signals a task that should not (versus should) be performed in the current trial (Braverman & Meiran, 2010). Thus, we performed planned comparisons to determine whether this cue congruency effect was significant in both explicit and voluntary task choice trials. The effect was significant in explicit [12 ms; $F(1, 52) = 5.5$, $p < 0.05$], but not in voluntary [-8 ms; $F(1, 52) = 1.3$, $n.s.$] task choice trials. Moreover, it was significantly larger in explicit than in voluntary task choice trials [$F(1, 52) = 5.9$, $p < 0.05$]. These results indicate that agency modulated both switch costs and the effect of cue congruency on task performance.

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Several expected effects that were less important for testing our hypothesis were also significant. First, there was a main effect of target congruency [$F(1, 52) = 492.3$, $p < 0.001$]: participants responded more slowly in incongruent (832 ms) than in congruent (694 ms) trials. Second, there was a main effect of task transition [$F(1, 52) = 93.4$, $p < 0.001$] because participants responded more slowly in task switch (791 ms) than in task repeat (735 ms) trials. Third, and also expected (Arrington & Logan, 2005), there was an interaction between task transition and RCI [$F(1, 52) = 13.0$, $p < 0.001$]: switch costs were greater after the short RCI [77 ms; $F(1, 52) = 91.4$, $p < 0.001$] than after the long RCI [35 ms; $F(1, 52) = 17.7$, $p < 0.01$]. This result appears more consistent with the task-set decay hypothesis of RCI effects on switch costs (Allport, et al., 1994; Arrington & Logan, 2005) than with the temporal distinctiveness hypothesis (Horoufchin, et al., 2010). Fourth, there was an interaction between target congruency and RCI [$F(1, 52) = 6.2$, $p < 0.05$]: the effect of target congruency was larger after the long RCI [153 ms; $F(1, 52) = 293.4$, $p < 0.001$] than after the short RCI [122 ms; $F(1, 52) = 201.6$, $p < 0.001$]. No other effects were significant[2].

Task Performance – Mean Error Rate

Mean error rates were relatively low (5.1%). As an analysis of error rates was not crucial for testing our hypotheses, we simply note two important findings. First, no

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[2] We performed supplementary analyses of the task performance RT data to investigate whether asymmetric switch costs were present in our paradigm, even though the presence or absence of such effects was not central to our hypotheses. These analyses involved a mixed ANOVA with four factors: RCI (0 ms, 1000 ms), agency (voluntary, explicit), task (numerical size comparison, physical size comparison), and task transition (repeat, switch). As expected, there was a main effect of task [$F(1, 52) = 14.0$, $p < 0.001$] as mean RT was faster for the relatively simple physical size comparison task (748 ms) than for the more complex numerical size comparison task (772 ms). Moreover, consistent with previous findings (Yeung, 2010), there was a significant interaction between task and task transition [$F(1, 52) = 6.9$, $p = 0.01$] indicating the presence of asymmetric switch costs in our paradigm. As expected based on these prior findings, switch costs were larger for the easier physical size comparison task (61 ms) than for the harder numerical size comparison task (43 ms).

speed-accuracy tradeoffs were observed. Second, mean error rates in voluntary task choice trials were low (4.5%) and did not differ among congruent (4.6%), incongruent (4.7%), and neutral (4.3%) task choice trials [$F(2, 104) = 0.05$, $n.s.$]. Indeed, even restricting our analyses to voluntary task choice trials in which an incongruent target was presented (in these trials, activating the correct task representation was absolutely necessary for achieving better than 50% performance) revealed no differences among congruent (8.3%), incongruent (8.3%), and neutral (7.9%) task choice trials [$F(2, 104) = 0.05$, $n.s.$]. Our finding that error rates were as low in congruent as in incongruent and neutral voluntary task choice trials suggests that the distracter letters in congruent voluntary task choice trials primed a decision about which task to perform, regardless of whether they also primed the task-selection response associated with choosing that task.

Task Choice – Mean RT

Consistent with our second hypothesis, switch costs were larger when participants selected the task primed by the availability heuristic (congruent task choice trials) than when they did not (i.e., incongruent and neutral task choice trials). This result suggests that congruent task choices reflect a reduction of top-down control that can persist to adversely influence subsequent task performance. An alternative explanation, however, is that congruent task choices were made more quickly than either incongruent or neutral task choices, thereby shortening the amount of time between successive trials. Given that slowly-dissipating proactive interference from the previous trial contributes to switch costs (Allport, et al., 1994), such a difference in timing could also have led to elevated switch costs in congruent task choice trials, relative to incongruent and neutral task choice trials.

To test this alternative account, we analyzed the mean choice RT data from voluntary task choice trials using a mixed ANOVA with one between-participants factor, RCI (0 ms, 1000 ms), and three within-participants factors: previous agency (voluntary, explicit), current task transition (repeat, switch), and cue congruency (congruent, incongruent, neutral). As expected (Arrington & Logan, 2005), there was a main effect of current task transition [$F(1, 52) = 9.2$, $p < 0.005$]: participants were slower when they chose to switch tasks (877 ms) than when they chose to repeat tasks (747 ms). Participants were also slower to voluntarily choose a task after an explicit (875 ms) as compared to a voluntary (712 ms) task choice trial [$F(1, 52) = 5.4$, $p < 0.05$]. However, no other effects were significant, including all main effects and interactions involving cue congruency. Thus, it is unlikely that the elevated switch costs in congruent as compared to incongruent and neutral voluntary task choice trials, reflected greater proactive interference from the previous trial.

Discussion

The present results make two important contributions to the literature on voluntary task switching. First, they unambiguously indicate that bottom-up biases influence voluntary task choice. Second, they show that succumbing to such biases predicts reduced top-down control (i.e., increased switch costs) during task performance. We now discuss our findings in relation to the existing literature along with several new questions that they raise.

Our finding that participants were biased to make congruent task choices (i.e., that they exhibited a *congruent task choice bias*) fits nicely with the literature on selective attention. Specifically, irrelevant distracters in selective attention tasks (e.g., Stroop,

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flanker, etc.) often prime the goals and/or responses with which they are associated, thereby interfering with task performance (e.g., Kane & Engle, 2003; MacLeod, 1991). The congruent task choice bias extends these previous results by showing that irrelevant distracters also interfere with voluntary task choice. Future studies might therefore further investigate the nature of this interference. For example, motivated by studies in the selective attention literature (Dehaene, et al., 1998; Lavie, 2004), such studies could investigate whether interference during voluntary task choice (a) requires conscious perception of the distracter letters, (b) depends on whether a concurrent working memory load is present, or (c) occurs in ecologically valid settings (e.g., deciding whether to check e-mail or send a text message).

Further analyses revealed that the congruent task choice bias was larger after explicit than after voluntary task choice trials. Moreover, following explicit task choice trials, this bias was greater when the distracter letters in the current trial matched the explicit cue in the previous trial than when they mismatched. The latter result suggests that the strength of the association between a distracter letter and a task choice was strongest (and exerted the largest influence on voluntary task choice) when the distracter letter had served as an explicit cue in the previous trial. Thus, by mixing voluntary and explicit task choice trials in the same blocks, we were able to obtain additional evidence that bottom-up factors influence task choice in the voluntary task switching paradigm.

The congruent task choice bias raises an interesting question about the locus of bottom-up influences on voluntary task choice in our paradigm. Specifically, do the distracter letters influence voluntary task choice by activating (a) the decision to perform a particular task, (b) the response used to indicate that task choice, or (c) both? The

critical distracter letters in voluntary task choice trials (i.e., 'N' and 'P') served as task cues in explicit task choice trials. Thus, they probably activated the decision to perform a specific task, regardless of whether they also activated the response used to indicate that choice. Consistent with this view, mean error rates in congruent, incongruent, and neutral voluntary task choice trials were uniformly low. Moreover, this was the case even when the upcoming imperative stimulus was incongruent, such that better-than-chance performance required activating the correct task goal. Thus, it would appear that the distracter letters in voluntary task choice trials activated the decision to perform a particular task.

There are two ways in which the critical distracter letters in congruent voluntary task choice trials could activate the decision to perform a particular task, and both are consistent with a bottom-up influence of the distracters on voluntary task choice. First, the distracter letters could directly prime the decision, or goal, to perform a particular task. Second, the distracter letters could prime a particular task-selection response which, in turn, leads to the decision to perform a particular task (i.e., via response-decision priming or because participants strategically activate the appropriate task goal after noticing that they make a particular task-selection response). In both of these scenarios, the distracter letters influence voluntary task choice in a bottom-up fashion (Arrington, et al., 2010). However, these scenarios differ with regard to whether this influence is direct or indirect. Future studies might therefore be conducted to distinguish between these interesting possibilities. For example, suppose that the distracter letters influence task choice only indirectly through response-decision priming. In that case, the congruent task

choice bias should vanish when the distracter letters are associated with the decision to perform a task, but not with the response used to indicate that decision.

Given that participants did not always make congruent task choices, one might wonder why the congruent task choice bias was present in some trials but not others. An intriguing possibility is that top-down control varied over the course of the experiment due to such factors as fatigue (De Jong, 2000), diminished motivation (Gray, 2001), or a bias to avoid expending cognitive effort (Botvinick, 2007; Kool, McGuire, Rosen, & Botvinick, 2010). Such temporary reductions of control may have reduced the efficiency of the top-down random task sequence heuristic, thereby allowing the bottom-up availability heuristic to more strongly influence task choice (Demanet, et al., 2010). Future studies could test this hypothesis by manipulating various factors (e.g., fatigue) that are thought to affect the recruitment of top-down control.

We have argued that the congruent task choice bias reflects a bottom-up influence on voluntary task choice. A typical signature of such influences, however, is that they dissipate with time. For example, the task-repetition bias is usually weaker when the interval between trials is relatively long than when it is relatively short (Arrington & Logan, 2004, 2005; Demanet, et al., 2010), likely because top-down processes have more time to select a task (and override the availability heuristic) before the next voluntary cue appears (Arrington, 2008; Arrington & Logan, 2005). Given such considerations, one might have expected weaker task-repetition and congruent task choice biases at the long RCI than at the short RCI. However, neither of these biases varied with the duration of the RCI. Our claim that the congruent task choice bias reflects a bottom-up influence on

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voluntary task choice may therefore seem at odds with the rest of the voluntary task switching literature.

However, this discrepancy is likely accounted for by an important difference between our paradigm and those typically used in voluntary task switching studies. In our paradigm, participants cannot predict whether a voluntary or an explicit task choice cue will appear in the next trial. In most other paradigms, however, participants always know when a voluntary task choice will be required. Given the uncertainty in our paradigm, top-down processes may not be recruited to choose a task during the RCI because such recruitment would often constitute a waste of effort. For example, voluntarily choosing to perform the numerical size comparison task during the RCI would be a waste of effort if an explicit cue to perform the physical size comparison task appeared in the next trial. Critically, if top-down processes were not recruited to choose a task during the RCI, then the task primed by the distracter letters would influence task choice just as much when the RCI was long as when it was short, exactly as we observed. Thus, our finding that the congruent task choice bias was not reduced over time likely reflects the inclusion of a high percentage of explicit task choice trials in our paradigm, which was necessary to associate the distracter letters in voluntary task choice trials with the representations they were meant to activate.

Our second finding was that switch costs in voluntary task choice trials were higher after congruent task choices than after incongruent task choices. This result suggests that congruent task choices reflected reductions of top-down control that persisted to influence subsequent task performance. However, this interpretation raises the question of why congruency effects during task performance were not also increased

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following congruent task choice trials. Numerous findings indicate that top-down control is required to limit interference from irrelevant stimuli (Egner & Hirsch, 2005; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Lavie, 2004). Thus, if congruent task choices were associated with a reduction of control that led to higher switch costs, then why were congruency effects not similarly elevated?

The answer to this question is far from obvious. However, factors influencing switch costs often fail to influence congruency effects. Several studies, for example, have reported that reducing the time between an explicit task cue and an imperative stimulus increases switch costs, but not congruency effects (Fagot, 1994; Hübner, Kluwe, Luna-Rodriguez, & Peters, 2004; Monsell, Sumner, & Waters, 2003; Rogers & Monsell, 1995; see Kiesel, et al., 2010 for a review). Shortening the duration of the cue-target interval is thought to reduce the time allowed by control process to prepare for an upcoming task switch (Meiran, 1996). Thus, these prior results also show that a reduction of top-down control can lead to increased switch costs in the absence of a change in the size of congruency effects.

One possible account of this dissociation is motivated by models that distinguish between two aspects of a task's representation in working memory: (1) the task-level representation and (2) the parameter-level representation (Logan & Gordon, 2001; Rubinstein, Meyer, & Evans, 2001). The task-level representation is roughly equal to the goal or intention of performing a task. The parameter-level representation specifies the relevant stimuli, responses, and rules (e.g., S-R mappings) that underlie task performance. In one model (Rubinstein, et al., 2001), the task-level representation is activated during cue-triggered task preparation while the parameter-level representation

is activated only after the imperative stimulus is presented. Thus, a reduction of top-down control during voluntary task choice might delay the formation of a task-level representation (i.e., the goal of performing a particular task), thereby biasing participants toward a congruent task choice and increased switch costs. However, it might not influence the parameter-level representation, which is activated only after an imperative stimulus appears. Therefore, congruency effects, which often index the activation of a currently-irrelevant S-R mapping (MacLeod, 1991), might be unchanged. Future studies will clearly be needed to fully understand the dissociation between switch costs and congruency effects that we and others have observed. At present, we simply note that this dissociation is consistent with the existing literature.

Finally, we ruled out an alternative account of our finding that switch costs were higher after congruent task choices than after incongruent and neutral task choices. Specifically, we ruled out the possibility that the elevated switch costs in congruent task choice trials reflected greater proactive interference from the previous trial. Proactive interference is more pronounced when the interval between successive imperative stimuli is relatively short than when it is relatively long (Allport, et al., 1994). Thus, relatively high levels of such interference could have contributed to the relatively high switch costs in congruent task choice trials if congruent task choices were made more quickly than incongruent task choices (thereby shortening the interval between successive imperative stimuli). Weighing against this possibility, mean task choice RT did not differ for congruent, incongruent, and neutral task choices. Thus, there is no evidence to suggest that heightened proactive interference contributed to the relatively high switch costs in congruent task choice trials.

In sum, the present results provide critical support for the view that bottom-up biases influence task choice in the voluntary task switching paradigm (Demanet, et al., 2010; Mayr & Bell, 2006). Moreover, they show that succumbing to such biases predicts reduced top-down control during subsequent task performance. Given that our paradigm provides a relatively unambiguous measure of bottom-up biases on voluntary task choice, future studies might use it to more fully characterize (a) which representations contribute to such biases and (b) why such biases exert a stronger influence on task choice in some trials than in others.

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Chapter 4
The influence of response conflict on voluntary task switching:
A novel test of the conflict monitoring model

Abstract

The conflict monitoring model of cognitive control posits that response conflict triggers a top-down enhancement of a task's representation in working memory. In the present study, we conducted a novel test of the conflict monitoring model using a voluntary task switching paradigm. We predicted that a task's representation would be enhanced following events associated with high response conflict (i.e., incongruent trials and incorrect responses), leading participants to voluntarily choose to repeat that task more often after these events than after events associated with low response conflict (i.e., congruent trials and correct responses). In two experiments, performance following incongruent trials was consistent with the conflict monitoring model. However, performance following incorrect trials did not fit with the model's predictions. These findings provide novel support for the conflict monitoring model while revealing new effects of incorrect trials that the model cannot explain.

Introduction

How do top-down control processes optimize future performance after a distracting stimulus activates a conflicting response? According to the influential conflict monitoring model, they enhance a task's representation in working memory, which leads to an increase of attention toward task-relevant stimuli (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004). Consistent with this view, distracter interference is lower after high-conflict trials than after low-conflict trials, a phenomenon known as conflict adaptation (Gratton, Coles, & Donchin, 1992).

However, the nature—and even existence—of conflict adaptation remains controversial. Indeed, some investigators have claimed that conflict adaptation vanishes when bottom-up processes like stimulus and response priming are properly controlled (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; but see also Ullsperger, Bylsma, & Botvinick, 2005). Efforts to distinguish conflict adaptation from these confounds typically involve discarding large numbers of trials (e.g., Kerns, et al., 2004) or simultaneously modeling the effects of top-down and bottom-up variables on task performance (e.g., Notebaert & Verguts, 2007). However, each of these approaches has its limitations: the first requires a relatively large number of trials, and the second requires an accurate and complete model of the variables that influence task performance.

By using the voluntary task switching (VTS) paradigm (Arrington & Logan, 2004, 2005), the present study avoids these pitfalls and provides a novel test of the conflict monitoring model. In each trial of this paradigm, participants are instructed to randomly choose one of two possible tasks to perform, after which an imperative stimulus is presented (Arrington & Logan, 2005, Experiment 6). Critically, the stimuli

and responses associated with task performance are distinct from those associated with task choice. Thus, effects of response conflict on subsequent task choice are not contaminated by stimulus or response priming.

Voluntary task choice is thought to reflect a combination of top-down and bottom-up processes (Arrington & Logan, 2004; Mayr & Bell, 2006). First, a top-down representativeness heuristic is thought to choose a task by comparing the recent trial history to a representative random sequence (Arrington & Logan, 2005) or by performing a mental coin flip (Mayr & Bell, 2006). Second, a bottom-up availability heuristic is thought to choose a task by selecting the task representation that is currently most active in working memory (Arrington & Logan, 2005). We reasoned that if response conflict in trial *n* is resolved by increasing the activation of a task's representation in working memory, then bottom-up processes should be more likely to select the same task in trial *n+1* than to select a different task. The conflict monitoring model therefore predicts that participants will repeat their task choices more often after high-conflict than after low-conflict trials.

Both correctly performed incongruent trials and errors are associated with high amounts of response conflict in the conflict monitoring model (Botvinick, et al., 2001; Yeung, Botvinick, & Cohen, 2004). The model also posits that the same mechanism detects conflict in these trial types. Thus, each of these trial types should be linked to an increase in the activation of the current task's representation in working memory[1]. Consistent with this view, incongruent trials and errors activate overlapping regions of

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[1] In the conflict monitoring model (Botvinick, et al., 2001), errors are linked to a shift along the speed-accuracy tradeoff function that leads participants to respond more slowly and more accurately after making an error than after making a correct response. However, there is no reason why such a shift could not co-occur with an increase in the activation of the current task's representation in working memory.

the anterior cingulate cortex, which is thought to detect response conflict (Kerns, et al., 2004; for a review, see Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). Moreover, interference is reduced not only after incongruent trials (Gratton, et al., 1992), but also after errors (Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002; Ridderinkhof, 2002).

Given these considerations, we predicted that participants would repeat their task choices more often after correctly performed incongruent (versus congruent) trials and more often after incorrect (versus correct) responses. Our findings supported the model's claims with regard to incongruent trials, but not with regard to incorrect responses. Thus, while providing partial support for the model, our findings also dissociated incongruent and incorrect trials in a way that the model did not predict. This result has important implications for the conflict monitoring model and, more generally, for our understanding of human performance under conditions of distraction.

Experiment 1

Method

Participants

Thirty-nine participants from the University of Michigan community completed Experiment 1. Participants whose mean accuracy fell below 85% (two participants) or whose switch rates fell above 90% (four participants) or below 10% (one participant) were excluded from analysis. This yielded 32 participants with usable data. These participants had an average age of 20.1 years; 10 were male.

Apparatus and Stimuli

Participants performed a VTS version of the number Stroop task (Henik & Tzelgov, 1982). In each trial, they were cued by a central question mark to choose whether they would compare two upcoming digits in terms of their numerical size or their physical size (Figure 4.1). As in Arrington and Logan (2004), participants were instructed to choose each task an equal number of times and in a random order across trials. No pressure to choose quickly was given in the instructions, and the question mark remained on the screen until a choice was made. Task choices were indicated by using the index or middle finger of the left hand, respectively, to press the D or F key on a computer keyboard (task-key mappings were counterbalanced across participants).

Each task choice was followed by a 500 ms delay, after which two digits were presented. One digit appeared 1.7° of visual angle above fixation while the other appeared 1.7° of visual angle below fixation. One of the digits was numerically large (7, 8, or 9) while the other was numerically small (1, 2, or 3). Moreover, one digit was physically large (subtending 1.1° visual angle) while the other physically small (subtending 0.6° visual angle). In congruent trials (50%), the numerically large digit was also physically large. In incongruent trials (50%), the numerically large digit was physically small. The trial sequence was randomized such that exact stimulus repetitions were separated by at least three trials (i.e., a digit appearing in trial *n* could not be repeated until trial *n+3*).

Participants were instructed to indicate which of the two digits (top or bottom) was larger as quickly and as accurately as possible. If they chose to perform the numerical comparison task, they indicated which of the two digits was numerically

larger. If they chose to perform the physical comparison task, they indicated which of the two digits was physically larger. The digits remained on the screen until the participant responded, or until 3000 ms elapsed. Responses were made by using the index or middle finger of the right hand, respectively, to press the J or K key on a computer keyboard (task-key mappings were counterbalanced across participants). The next trial was presented after a short (100 ms) or a long (1000 ms) response-cue interval (RCI).

Participants viewed the stimuli on a 17" CRT monitor at a distance of 60 cm. A chin rest was used for head stabilization. Stimuli were generated and displayed using Presentation software (Neurobehavioral Systems Inc., Albany, CA).
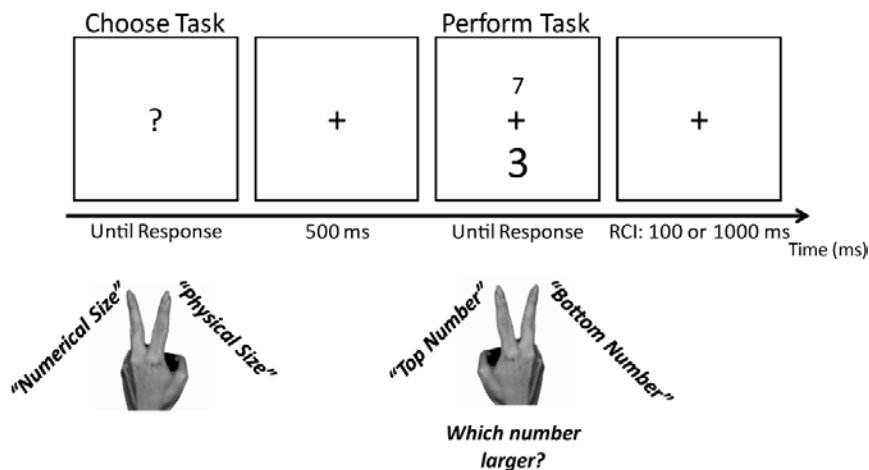

Figure 4.1. Experimental design.
A typical trial in Experiment 1. Participants performed a voluntary task switching version of the number Stroop task, which involved comparing two digits with respect to their numerical size or with respect to their physical size. Each trial began with the presentation of a question mark (?). This indicated that participants should choose which task to perform in the current trial by pressing a button with the middle or index finger of their left hand. Participants were not pressured to choose quickly, and the question mark remained on the screen until a choice was made. After a 500 ms delay, the two digits appeared. One was numerically large (e.g., 7) while the other was numerically small (e.g., 7). Further, one was presented in a large font (e.g., 3) while the other was presented in a small font (e.g., 7). In congruent trials, the numerically large digit was also physically large. In incongruent trials, the numerically large digit was physically small. Depending on the current task, participants decided which of the two digits (top or bottom) was numerically or physically larger. They were instructed to indicate their decision as quickly and as accurately as possible by pressing a button with their right index finger or their right middle finger. The next trial began after a 100 ms or 1000 ms response-to-cue interval (RCI).

Procedure

Participants first practiced the number and size comparison tasks separately. Next, they practiced one block of the VTS paradigm. If a participant's task choice proportions and switch proportion in this block were not both within $50 \pm 10\%$, then the instructions to choose each task equally often and in a random order were repeated and participants performed another practice block. This process was repeated until a participant's task choice proportions and switch proportion were both within $50 \pm 10\%$ (on average, each participant performed one practice block). Finally, participants performed 15 blocks of the VTS paradigm, each of which comprised 72 trials.

Data Analysis

Task choice data were analyzed with respect to the proportion of trials in which participants switched tasks (i.e., switch rates). Task performance data were analyzed in terms of mean reaction time (RT) and accuracy. Accuracy data were arcsine transformed prior to analysis in order to yield a more normal distribution (Cohen & Cohen, 1983). Omnibus tests were conducted using repeated measures analysis of variance (ANOVA); post-hoc pairwise comparisons were conducted using the Newman-Keuls test.

Unless otherwise noted, data from error trials and trials immediately following error trials were discarded (on average, 12.2% of trials). We also discarded trials in which either the current trial RT or the previous trial RT was (1) faster than 200 ms or (2) slower than three standard deviations from the participant's mean RT (on average, 5.7% of trials). In total, 16.7% of trials were discarded on average.

Results

Switch Rate Data

As instructed, participants chose the two tasks equally often [numerical task, 50.4%; physical task, 49.6%; $t(31) = 0.75$, *n.s.*]. Moreover, replicating previous findings (e.g., Arrington & Logan, 2004), switch rates fell below 50% [45.1%; 95% *CI*: 40.2% - 50.0%], indicating a bias to repeat the previously selected task [$t(31) = -2.0, p = 0.05$].

Our first main prediction was that switch rates would be lower after incongruent trials than after congruent trials. To test this prediction, the switch rate data were submitted to a repeated-measures ANOVA with four factors: previous congruency (congruent, incongruent), RCI (short, long), previous task alternation (repeat, switch), and previous task (numerical comparison, physical comparison) (see Table 4.1 for the mean switch rate in each cell of this design). The main effect of previous congruency did not achieve significance. However, we observed a significant interaction between previous congruency and RCI [$F(1,31) = 5.7, p < 0.05$; Figure 4.2a]. Participants repeated their previous task choice more often when the previous trial was incongruent than when it was congruent at the long RCI [2.4%; $F(1,31) = 5.9, p < 0.05$], but not at the short RCI [0.1%; $F(1,31) = 0.03$, n.s.]. This result is consistent with prior work indicating that the effect of enhancing a task's representation on subsequent performance can take time to develop (Notebaert, Gevers, Verbruggen, & Liefooghe, 2006). Thus, the switch rate data supported our first main prediction.

Three additional expected effects were also significant. First, in line with prior results (e.g., Arrington & Logan, 2004), there was a main effect of RCI because switch rates were lower at the short RCI (40.7%; 95% *CI*: 34.8% - 46.6%) than at the long RCI (47.0%; 95% *CI*: 41.2% - 52.7%) [$F(1,31) = 29.8, p < 0.001$]. Further analyses revealed

Table 4.1
Mean switch rates for Experiment 1 and Experiment 2.

RCI	Previous Task Alternation	Previous Congruency	Previous Task	*Experiment 1*	*Experiment 2*
100 ms	Repeat	Con	Numerical	50% (3%)	54% (5%)
			Physical	51% (4%)	54% (5%)
		Inc	Numerical	51% (4%)	54% (4%)
			Physical	51% (4%)	51% (5%)
	Switch	Con	Numerical	30% (4%)	42% (5%)
			Physical	32% (3%)	42% (5%)
		Inc	Numerical	30% (4%)	41% (5%)
			Physical	31% (3%)	38% (5%)
1000 ms	Repeat	Con	Numerical	57% (3%)	59% (4%)
			Physical	58% (4%)	56% (5%)
		Inc	Numerical	56% (3%)	56% (4%)
			Physical	56% (3%)	55% (5%)
	Switch	Con	Numerical	38% (3%)	41% (4%)
			Physical	40% (4%)	39% (5%)
		Inc	Numerical	35% (4%)	40% (5%)
			Physical	36% (3%)	40% (5%)

that the bias to choose the previously selected task (as indicated by a switch rate of less than 50%) was present at the short RCI [$t(31) = -3.2$, $p < .005$]. However, consistent with some prior results (Arrington & Logan, 2005, Experiment 6), it was absent at the long RCI [$t(31) = -0.76$, *n.s.*]. Second, there was a main effect of previous task alternation, such that switch rates were lower after switch trials (33.9%) than after repeat trials (53.8%) [$F(1,31) = 37.1$, $p < 0.001$]. This finding fits with prior data from the VTS paradigm indicating that participants often avoid returning to a task from which they recently switched away (Lien & Ruthruff, 2008), consistent with claims that switching away from a task is accomplished by inhibiting the associated task representation (c.f. Mayr & Keele, 2000). Third, there was an interaction between previous congruency and previous task alternation [$F(1,31) = 4.4$, $p = 0.05$]. Consistent with the view that conflict leads to an enhancement of a task's representation in working memory, the effect of previous task alternation on switch rates was larger when the previous trial was incongruent [20.7%; $F(1,31) = 38.2$, $p < 0.001$] than when it was congruent [19.0%;

$F(1,31) = 34.9, p < 0.001$]. In sum, these additional effects in the switch rate data both replicated prior work and further supported our hypothesis.

A.

Experiment 1

B.

Experiment 2

Figure 4.2. Effects of previous congruency and RCI on current trial switch rate.
A. In Experiment 1, switch rates were lower following incongruent (versus congruent) trials after the long response-cue-interval (1000 ms), but not after the short response-cue-interval (100 ms). B. In Experiment 2, switch rates were uniformly lower following incongruent (versus congruent) trials. Error bars represent one standard error of the mean.

Our second main prediction was that switch rates would be lower after incorrect than after correct responses. To test this hypothesis, switch rates were submitted to a repeated-measures ANOVA with two factors: previous accuracy (correct, error) and RCI (short, long). As hypothesized, there was a main effect of previous accuracy because

switch rates were lower after incorrect (25.9%) than after correct (45.1%) responses [$F(1,31) = 61.9$, $p < 0.001$]. We also observed a significant interaction between previous accuracy and RCI [$F(1,31) = 6.9$, $p < 0.001$; Figure 4.3a]. Mirroring the interaction between previous congruency and RCI described earlier in this section, the effect of previous accuracy on switch rates was larger at the long RCI [22.4%; $F(1,31) = 71.7$, $p < 0.001$] than at the short RCI [16.1%; $F(1,31) = 33.2$, $p < 0.001$]. This result suggests that the effect of previous accuracy on switch rates may be strategic in nature, as it takes time to develop (Notebaert, et al., 2006). In sum, the switch rate data supported our second main prediction.

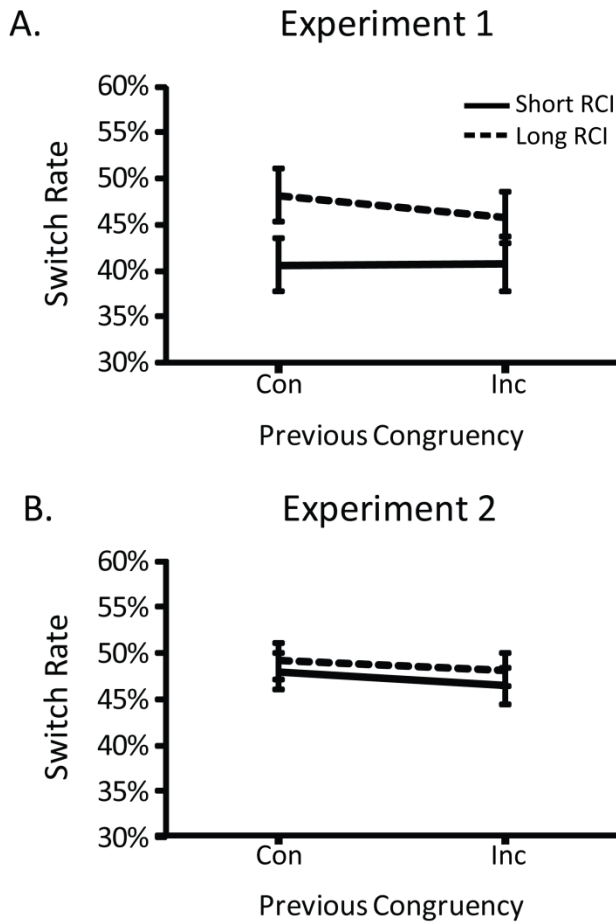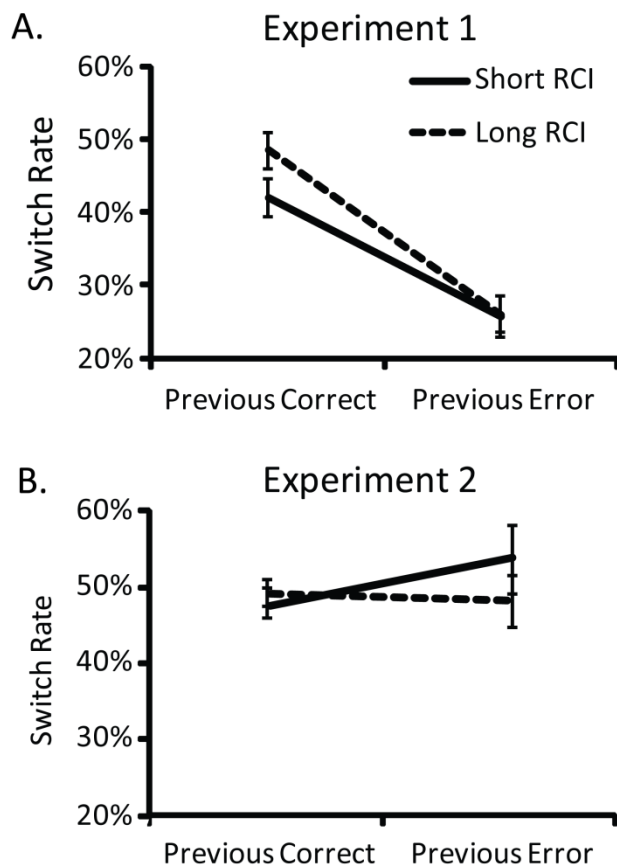**Figure 4.3. Effect of previous accuracy and RCI on current trial switch rate.**
A. In Experiment 1, switch rates were lower after incorrect than after correct trials, particularly at the long RCI. B. In Experiment 2, switch rates were higher after incorrect trials than after correct trials at the short RCI. At the long RCI, however, switch rates did not differ after incorrect and correct trials. Error bars represent one standard error of the mean.

Incorrect responses were more frequent in switch than in repeat trials (see *Accuracy Data* below). Therefore, we conducted an additional analysis to determine whether the lower switch rates following incorrect responses were simply a byproduct of the relatively low switch rates following switch trials that we described earlier in this section. To investigate this possibility, switch rates were submitted to a repeated-measures ANOVA with two factors: previous accuracy (correct, error) and previous task alternation (repeat, switch) (data from two participants were not included due to an insufficient number of error trials, i.e., less than five errors for any cell of the design). Ruling out this possibility, we observed a significant interaction between previous accuracy and previous task alternation [$F(1,29) = 7.3, p = 0.01$], which occurred because the effect of previous accuracy on switch rate was actually larger when the previous trial was a repeat (23.6%) than when it was a switch (15.5%). Moreover, the effect of previous accuracy was significant after both repeat trials [$F(1,29) = 55.1, p < 0.001$] and switch trials [$F(1,29) = 34.0, p < 0.001$]. Thus, the effect of previous accuracy on switch rate did not stem from the fact that incorrect responses occurred more often in switch than in repeat trials.

Reaction Time Data

The reaction time data were largely as expected, which was revealed by a repeated-measures ANOVA with four factors: RCI (short, long), current task alternation (repeat, switch), previous congruency (congruent, incongruent), and current congruency (congruent, incongruent) (see Table 4.2 for the mean reaction time in each cell of the design). For example, participants responded more slowly at the long RCI than at the short RCI [694 ms vs. 670 ms; $F(1,31) = 26.7, p < 0.001$], in switch than in repeat trials

[729 ms vs. 635 ms; $F(1,31) = 51.6$, $p = 0.001$], and in incongruent than in congruent trials [734 ms vs. 631 ms; $F(1,31) = 146.4$, $p < 0.001$].

Three additional findings further suggested that a task's representation in working memory was enhanced following an incongruent trial. First, there was a three-way interaction between current task alternation, previous congruency, and current congruency [$F(1,31) = 15.9$, $p < 0.001$]: conflict adaptation was greater in repeat trials [$F(1,31) = 51.0$, $p < 0.001$; Figure 4.4A] than in switch trials [$F(1,31) = 7.0$, $p < 0.05$; Figure 4.4B]. This result fits with previous reports suggesting that enhancing a task's representation to resolve conflict aids subsequent performance of the same task, but not of a different task (Brown, et al., 2007; Egner, 2008; Notebaert & Verguts, 2008). Second, there was a four-way interaction among all of the factors [$F(1,31) = 4.5$, $p < 0.05$]. Consistent with previous results (Notebaert, et al., 2006), post-hoc tests revealed that conflict adaptation in repeat trials was greater ($p < 0.05$) at the long RCI (68 ms) than at the short RCI (23 ms). In contrast, conflict adaptation in switch trials did not differ ($p = 0.67$) after the long (22 ms) versus the short (23 ms) RCI (see Table 4.2). Third, there was an interaction between previous congruency and current task alternation [$F(1,31) = 5.2$, $p < 0.05$] indicating that switch costs were higher when the previous trial was incongruent [103 ms, $F(1,31) = 48.9$, $p < 0.001$] than when it was congruent [86 ms, $F(1,31) = 47.6$, $p < 0.001$]. Put simply, as in prior studies (Brown, et al., 2007; Goschke, 2000), it was relatively difficult to switch away from a task following an incongruent trial, further suggesting that response conflict is resolved by enhancing a task's representation in working memory. In sum, the RT data were consistent with the conflict

monitoring model's claim that response conflict triggers a top-down enhancement of a
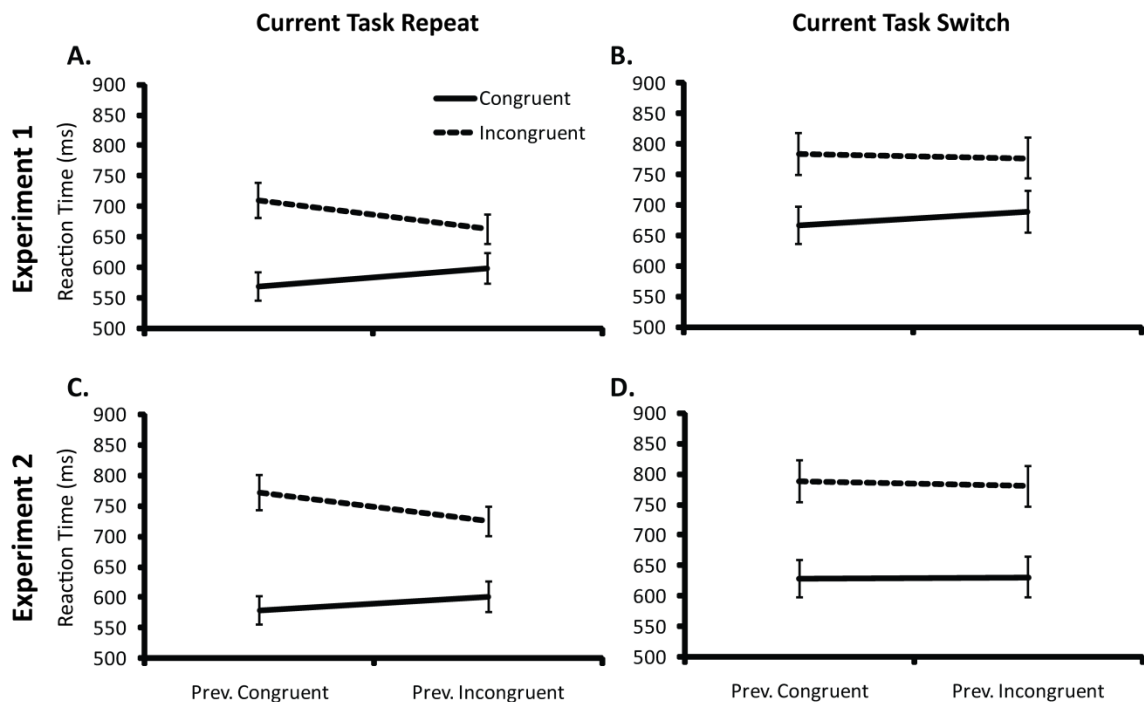
task's representation in working memory.

Figure 4.4. Effects of previous congruency and current congruency on response time.
In both Experiments 1 and 2, the effect of current congruency was reduced when the previous trial
was incongruent, relative to when it was congruent. Moreover, this effect was larger in repeat trials
(A, C) than in switch trials (B, D). Error bars represent one standard error of the mean.

Three effects that were less critical for testing our hypotheses were also

significant. First, RCI interacted with current task alternation $[F(1,31) = 7.4, p = .011]$

because switch costs were larger at the short RCI $[106$ ms, $F(1,31) = 59.3, p < 0.001]$

than at the long RCI $[83$ ms, $F(1,31) = 36.2, p < 0.001]$. This result fits with previous

work suggesting that proactive interference from the preceding task set diminishes with

increasing time between trials (Allport, Styles, & Hsieh, 1994; Meiran, 1996). Second,

RCI interacted with previous congruency $[F(1,31) = 6.5, p < 0.05]$ because RT was faster

after incongruent trials (667 ms) than after congruent trials (674 ms) at the short RCI,

while the opposite pattern was observed at the long RCI (incongruent, 697 ms; congruent,

691 ms). However, these simple effects were neither significant ($p > 0.10$ in both cases)

nor crucial for testing our hypotheses, so we will not discuss them further. Third, RCI

interacted with current congruency [$F(1,31) = 19.9$, p < 0.001] because congruency

effects were larger at the long RCI [113 ms; $F(1,31) = 171.7$, $p < 0.05$] than at the short

RCI [92 ms; $F(1,31) = 106.6$, $p < 0.05$]. This result replicates some previous findings

(Meiran, 1996; Rogers & Monsell, 1995) but not others (Goschke, 2000).

Finally, the conflict monitoring model predicts that a task's representation should

be enhanced after an incorrect response. Such enhancement is thought to involve raising

the threshold for selecting a response in the next trial, resulting in slower, more accurate

performance (Botvinick, et al., 2001; Yeung, et al., 2004). Consistent with prior data

(Laming, 1968; Rabbitt, 1966), participants responded more slowly after incorrect than

after correct responses [745 ms vs. 671.6 ms; $F(1,31) = 23.5$, $p < 0.001$]. As discussed

earlier with respect to the RT data, such enhancement is also thought to result in a

combination of smaller congruency effects and larger switch costs. However, separate

repeated-measures ANOVAs revealed no effect of previous accuracy (correct, incorrect)

on congruency effects ($F < 1$) or switch costs ($F < 1$) in the current trial. Thus, the RT

data provided little evidence to suggest that a task's representation was enhanced

following an incorrect response (see also Jentzsch & Dudschig, 2009).

Accuracy Data

The accuracy data mirrored much of the RT data, as revealed by a repeated-

measures ANOVA with four factors: RCI (short, long), current task alternation (repeat,

switch), previous congruency (congruent, incongruent), and current congruency

(congruent, incongruent) (the mean error rate for each cell of this ANOVA is presented in

Table 4.3. First, error rates were higher in switch than in repeat trials [7.3% vs. 4.1%; $F(1,31) = 60.9$, $p < 0.001$]. Second, error rates were higher in current incongruent than in current congruent trials [7.3% vs. 4.1%; $F(1,31) = 150.7$, $p < 0.001$]. Third, there was an interaction between previous congruency and current congruency [$F(1,31) = 21.2$, $p < 0.001$]. Replicating previous findings (Cho, Orr, Cohen, & Carter, 2009), the congruency effect in the current trial was smaller when the previous trial was incongruent (5.8%; $F(1,31) = 83.4$, $p < 0.001$) than when it was congruent (9.1%; $F(1,31) = 175.0$, $p < 0.001$). Moreover, this conflict adaptation effect remained significant even after we removed trials in which the response and/or the position of the numerically larger digit and/or the position of the physically larger digit was repeated from the previous trial [$F(1,31) = 22.2$, $p < 0.001$], suggesting that it could not be accounted for by repetition priming. Fourth, there was a three-way interaction between current task alternation, current congruency, and previous congruency because conflict adaptation was greater in repeat trials than in switch trials [$F(1,31) = 20.0$, $p < 0.001$; see Table 4.3].

Two additional effects were also consistent with the RT data and/or previous findings. First, as in the RT data, previous congruency interacted with current task alternation [$F(1,31) = 18.5$, $p < 0.001$]: switch costs were higher when the previous trial was incongruent [4.8%; $F(1,31) = 62.9$, $p < 0.001$] than when it was congruent [1.7%; $F(1,31) = 16.3$, $p < 0.001$]. This result further supports the hypothesis that a task's representation is enhanced following an incongruent (versus a congruent) trial. Second, current task alternation interacted with current congruency [$F(1,31) = 13.9$, $p < 0.001$]: the effect of current congruency was larger in switch trials [9.5%; $F(1,31) = 130.5$, $p < 0.001$] than in repeat trials [5.5%; $F(1,31) = 90.3$, $p < 0.001$]. This effect may index

residual activation of the previous task's representation in working memory (Goschke, 2000).

As discussed above, the conflict monitoring model predicts that a task's representation should be enhanced following an incorrect response. Inconsistent with this prediction, however, error rates were higher after incorrect (9.7%) than after correct (5.8%) responses [$F(1, 30) = 5.2$, $p < .05$]. Moreover, neither switch costs [$F(1,30) = 0.31$, *n.s.*] nor congruency effects [$F(1,30) = 0.64$, *n.s.*] in the current trial varied with previous-trial accuracy. Thus, similar to the RT data, the accuracy data provided no evidence to suggest that a task's representation in working memory was enhanced following an incorrect response.

Discussion

Our findings in Experiment 1 provided partial support for the conflict monitoring model's claim that a task's representation in working memory is enhanced following high-conflict trials. Consistent with this view, switch rates were lower after (1) incongruent (versus congruent) trials and (2) incorrect (versus correct) trials. Furthermore, the performance data revealed that following incongruent (versus congruent) trials, congruency effects were relatively small while switch costs were relatively large. The performance data following errors, however, were not consistent with the conflict monitoring model. First, congruency effects and switch costs in the RT data did not vary with previous-trial accuracy. Second, error rates were higher after incorrect than after correct trials. In sum, while the switch rate data supported the conflict monitoring model for both incongruent and incorrect trials, the performance data suggested that a task's representation was enhanced only after incongruent trials.

Table 4.2
Mean Reaction Time (ms) as a Function of RCI, Current Task Transition, Previous Congruency, and Current Congruency in Experiment 1 and 2.

	Short RCI (100 ms)								Long RCI (1000 ms)							
	Task Repeat				Task Switch				Task Repeat				Task Switch			
	Previous Congruent		Previous Incongruent		Previous Congruent		Previous Incongruent		Previous Congruent		Previous Incongruent		Previous Congruent		Previous Incongruent	
Current Congruency	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM
								Experiment 1								
Congruent	556	22	587	24	672	30	680	33	581	24	608	28	662	31	698	35
Incongruent	690	28	636	23	777	35	763	32	730	29	690	26	791	34	791	35
								Experiment 2								
Congruent	565	16	589	19	623	24	620	17	592	19	613	22	635	20	641	20
Incongruent	748	23	691	20	776	25	751	26	796	22	759	21	802	26	808	19

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Table 4.3
Mean Error Rate as a Function of RCI, Current Task Transition, Previous Congruency, and Current Congruency in Experiment 1 and 2.

	Short RCI (100 ms)								Long RCI (1000 ms)							
	Task Repeat				Task Switch				Task Repeat				Task Switch			
	Previous Congruent		Previous Incongruent		Previous Congruent		Previous Incongruent		Previous Congruent		Previous Incongruent		Previous Congruent		Previous Incongruent	
Current Congruency	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM	M	SEM
								Experiment 1								
Congruent	1%	0.3%	1%	0.3%	3%	0.6%	3%	0.6%	1%	0.3%	1%	0.4%	3%	0.6%	2%	0.5%
Incongruent	10%	1.0%	3%	0.4%	13%	1.4%	11%	1.4%	11%	1.1%	4%	0.5%	12%	1.3%	13%	1.5%
								Experiment 2								
Congruent	1%	0.3%	2%	0.5%	2%	0.4%	1%	0.4%	1%	0.3%	2%	0.6%	2%	0.5%	1%	0.4%
Incongruent	15%	1.8%	6%	0.8%	17%	1.9%	16%	2.5%	15%	1.6%	7%	1.0%	15%	1.9%	17%	2.0%

Experiment 2

In Experiment 1, the switch rate data suggested that a task's representation in working memory was enhanced after both incongruent and incorrect trials. However, the computer key that was used to choose a given task (e.g., the D key) did not vary across trials (even though task-key mappings were counterbalanced across participants). Thus, the relatively low switch rates following incongruent and incorrect trials may have resulted from a key-repetition bias, rather than a task-repetition bias. For example, the central question mark that appeared at the beginning of each trial had been recently associated with the previous task choice response. Therefore, its subsequent reappearance may have primed participants to repeat that response (Hommel, 1998), and this bias might somehow have been greater following incongruent and/or correct trials. The existence of such a bias would be consistent with previous findings suggesting an influence of stimulus-response priming on voluntary task choice (Arrington, Weaver, & Pauker, 2010; Demanet, Liefooghe, Verbruggen, & Vandierendonck, 2010; Mayr & Bell, 2006).

We conducted Experiment 2 to dissociate task-repetition and key-repetition explanations of the switch rate data. To distinguish between these accounts, we reversed the task-key mapping after each trial. For example, if the D key was associated with the numerical comparison task in trial n, then it was associated with the physical size task in trial $n+1$. We reasoned that if the switch rate results from Experiment 1 were driven by a task-repetition bias, then Experiment 2 should yield identical results: participants should repeat tasks more often after incongruent and incorrect trials. On the other hand, if the results from Experiment 1 were driven by a key-repetition bias, then Experiment 2 should

yield *opposite* results: participants should repeat tasks *less* often after incongruent and incorrect trials. Finally, if the results from Experiment 1 were due to some combination of task- and key-repetition biases, then these biases should tend to cancel each other out in Experiment 2. That is, previous congruency and previous accuracy should have smaller effects on switch rate than in Experiment 1.

Method

Participants

Twenty-seven participants from the University of Michigan community completed Experiment 2. None had participated in Experiment 1. Participants whose switch rates fell above 90% (two participants) or below 10% (one participant) were excluded from the analysis, yielding 24 participants with usable data. On average, these participants were 21.1 years old; 14 were male.

Apparatus & Stimuli

Experiment 2 was identical to Experiment 1 with two exceptions. First, the task-key mapping alternated across consecutive trials. Specifically, if on trial *n* the numerical size task was mapped to the D key and the physical size task was mapped to the F key, then on trial *n+1* the numerical size task was mapped to the F key and the physical size task was mapped to the D key. The D key is to the left of the F key on our computer keyboards, and we took advantage of this arrangement to remind participants of the correct task-key mapping during the choice phase of each trial. For example, when the numerical task was mapped to the D key and the physical task was mapped to the F key, the letters N and P, respectively, were displayed 1.7° to the left and 1.7° to the right of the central question mark.

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Second, to encourage participants to choose the two tasks equally often and in random order, we provided feedback after each task block. This feedback revealed the proportion of trials in which the participant (1) chose to perform each task and (2) switched tasks. The rest of the procedure and data analysis were identical to those in Experiment 1.

Results

Switch Rate Data

Two basic effects differed somewhat from those in Experiment 1. First, consistent with at least one prior finding (Arrington & Logan, 2005), overall switch rates did not differ significantly from 50% (mean switch rate: 48.4%; 95% CI: 44.6% - 52.2%)[1]. Second, participants chose to perform the physical comparison task more often that they chose to perform the numerical comparison task [51.0% vs. 49.0%; $t(23) = 2.5$, $p < 0.05$]. Recent data suggest that voluntary task choices favor tasks that require relatively little mental effort (Botvinick, 2007; McGuire & Botvinick, 2010). Thus, we investigated whether the physical comparison task was easier to perform than the numerical comparison task. Consistent with this view, responses in the physical comparison task were both faster [666 ms versus 697 ms; $t(23) = 4.2$, $p < 0.001$] and more accurate [6.6% versus 8.6%; $t(23) = 3.7$, $p < 0.001$] than responses in the numerical comparison task, replicating prior findings with these tasks (Henik & Tzelgov, 1982), but differing slightly from our findings in Experiment 1. Indeed, in Experiment 1, responses in the physical

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[1] The lack of an overall task-repetition bias is unlikely to have resulted from the end-of-block feedback, which indicated the proportion of trials in which a participant had chosen to switch tasks. Indeed, in a different study from our laboratory, we observed a task-repetition bias even when such feedback was given (Orr, Gehring, & Weissman, 2010). However, the lack of an overall task-repetition bias may have resulted from the variable task-key mapping that was employed.

comparison task were faster [700 ms versus 716 ms; $t(31) = 2.2$, $p < 0.05$] but not more

accurate [5.6% versus 5.5%; $t(31) = 0.75$, *n.s.*] than responses in the numerical

comparison task.

Our first main prediction was that switch rates would be lower after incongruent

than after congruent trials. To investigate this hypothesis, we submitted switch rates to a

repeated-measures ANOVA with four factors: previous congruency (congruent,

incongruent), RCI (short, long), previous task alternation (repeat, switch), and previous

task (numerical comparison, physical comparison) (the mean switch rate for each cell of

this design is presented in Table 4.1). As in Experiment 1, participants switched tasks

more often at the long RCI (48.5%) than at the short RCI (47.0%) [$F(1,23) = 4.3$, $p <$

.05]. Most important, we replicated our finding that switch rates were lower after

incongruent (47.1%) than after congruent (48.4%) trials [$F(1,23) = 6.7$, $p < .05$; Figure

4.2b]. This finding suggests that the effect of previous congruency on task choice in

Experiment 1 was driven by a task-repetition bias rather than a key-repetition bias (see

Between-Experiment Comparisons below for further evidence to support this view).

Our second main prediction was that switch rates would be lower after incorrect

than after correct responses. To investigate this prediction, we submitted switch rates to a

repeated-measures ANOVA with two factors: previous accuracy (correct, error) and RCI

(short, long); only two factors were included to ensure a sufficient number of errors per

condition. Unlike Experiment 1, we did not observe a main effect of previous accuracy

[$F(1,23) = 0.65$, *n.s.*]. As in Experiment 1, however, we observed an interaction between

RCI and previous accuracy [$F(1,23) = 6.8$, $p < .05$; Figure 4.3b]. At the short RCI,

participants switched tasks more often after incorrect than after correct responses ($p <$

.05); at the long RCI, however, no such difference was observed ($p = 0.67$, *n.s.*). This result replicates our finding in Experiment 1 that the task-repetition bias following errors was larger at the long RCI than at the short RCI. However, it also suggests that the effect of previous accuracy on switch rates in Experiment 1 was driven by a combination of task- and key-repetition biases.

Reaction Time Data

The RT data were largely consistent with those in Experiment 1 as revealed by a repeated-measures ANOVA with four factors: RCI (short, long), current task alternation (repeat, switch), previous congruency (congruent, incongruent), and current congruency (congruent, incongruent) (see Table 4.2 for the mean RT in each cell of the design). For example, participants responded more slowly at the long RCI than at the short RCI [705 ms vs. 670 ms; $F(1,23) = 32.8$, $p < 0.001$], in switch than in repeat trials [707 ms vs. 669 ms; $F(1,23) = 25.8$, $p = 0.001$], and in current incongruent than in current congruent trials [766 ms vs. 610 ms; $F(1,23) = 305.1$, $p < 0.001$].

The conflict monitoring model predicts that a task's representation should be enhanced following incongruent trials, and two findings supported this view. First, and consistent with Experiment 1, there was an interaction between current congruency and previous congruency [$F(1,23) = 25.1$, $p < 0.001$]: congruency effects in the current trial were smaller when the previous trial was incongruent (136 ms; $F(1,23) = 187.7$, $p < 0.001$) than when it was congruent (174 ms; $F(1,23) = 265.8$, $p < 0.001$). Moreover, this conflict adaptation effect remained significant even after removing trials in which the response and/or the position of the numerically larger digit and/or the position of the physically larger digit was repeated from the previous trial [$F(1,23) = 15.0$, $p < 0.001$].

Thus, this effect cannot be explained by repetition priming (Hommel, et al., 2004; Mayr, et al., 2003). Second, and also consistent with Experiment 1, there was a three-way interaction between task alternation, current congruency, and previous congruency [$F(1,23) = 8.5$, $p < 0.005$] because conflict adaptation was greater in repeat trials [$F(1,23) = 23.4$, $p < 0.001$; Figure 4.4c] than in switch trials [$F(1,23) = 0.55$, $n.s.$; Figure 4.4d].

Further replicating our findings in Experiment 1, two additional effects that were *not* crucial for testing our hypotheses were also significant. First, RCI interacted with previous congruency [$F(1,23) = 4.5$, $p < 0.05$]: RT was faster following incongruent (versus congruent) trials at the short RCI [15 ms; $F(1,23) = 9.8$, $p < 0.005$], but not at the long RCI [1 ms; $F(1,23) = 0.05$, $n.s.$]. Second, RCI interacted with current congruency [$F(1,23) = 10.2$, $p < 0.005$] because congruency effects in the current trial were larger at the long RCI [171 ms; $F(1,23) = 287.7$, $p < 0.001$] than at the short RCI [142 ms; $F(1,23) = 199.5$, $p < 0.001$].

As discussed in Experiment 1, the conflict monitoring model also predicts that a task's representation should be enhanced following an incorrect response, leading to slower, more accurate performance in the next trial (Botvinick, et al., 2001; Yeung, et al., 2004). However, mean RT following incorrect responses did not differ from mean RT following correct responses [$F(1,23) = 0.63$, $n.s.$]. Enhancing a task's representation following an incorrect response should also lead to a combination of smaller congruency effects and larger switch costs in the next trial. However, as in Experiment 1, previous accuracy influenced neither congruency effects [$F(1,23) = 2.1$, $n.s.$] nor switch costs [$F(1,23) = 1.1$, $n.s.$] in the current trial. Thus, inconsistent with the conflict monitoring

model, the RT data did not provide evidence to suggest that a task's representation was enhanced following an incorrect response.

Accuracy Data

The accuracy data replicated much of the RT data above and many of our findings in Experiment 1. This was revealed by an ANOVA with four factors: RCI (short, long), current task alternation (repeat, switch), previous congruency (congruent, incongruent) and current congruency (congruent, incongruent) (mean error rates for each cell of this design are presented in Table 4.3. First, as expected, error rates were higher in switch than in repeat trials [8.9% vs. 6.3%; $F(1,23) = 9.8$, $p < 0.005$] and in current incongruent than in current congruent trials [13.5% vs. 1.6%; $F(1,23) = 292.8$, $p < 0.001$]. Second, there was an interaction between previous congruency and current congruency [$F(1,23) = 26.5$, $p < 0.001$] indicating the presence of conflict adaptation. As predicted, the congruency effect in the current trial was smaller when the stimulus in the previous trial was incongruent [9.9%; $F(1,23) = 184.0$, $p < 0.001$] than when it was congruent [14.0%; $F(1,23) = 313.5$, $p < 0.001$]. Third, this conflict adaptation effect remained even after removing trials on which the response and/or the position of the numerically larger digit and/or the position of the physically larger digit was repeated from the previous trial [$F(1,23) = 15.9$, $p < 0.001$], suggesting it was not due to repetition priming (Hommel, et al., 2004; Mayr, et al., 2003). Fourth, there was a three-way interaction between current task alternation, current congruency, and previous congruency [$F(1,23) = 42.5$, $p < 0.001$] because the conflict adaptation effect was larger in repeat trials [$F(1,23) = 59.6$, $p < 0.001$] than in switch trials [$F(1,23) = 1.8$, *n.s.*; see Table 4.3].

Two additional effects were also consistent with our findings from Experiment 1. First, previous congruency interacted with current task alternation [$F(1,23) = 15.0$, $p < 0.001$]: switch costs were higher when the previous trial was incongruent [4.6%; $F(1,23) = 15.0$, $p < 0.001$] than when it was congruent [0.5%; $F(1,23) = 0.72$, *n.s.*]. In line with the conflict monitoring model, this finding further suggests that a task's representation was enhanced following incongruent compared to congruent trials (Botvinick, et al., 2001; Yeung, et al., 2004). Second, we observed an interaction between current task alternation and current congruency [$F(1,23) = 19.6$, $p < 0.001$]: the effect of current congruency was larger in switch trials [14.6%; $F(1,23) = 212.0$, $p < 0.001$] than in repeat trials [9.4%; $F(1,23) = 228.1$, $p < 0.001$]. As mentioned in Experiment 1, this latter effect may index residual activation of the previous task's representation in working memory (Goschke, 2000).

The conflict monitoring model predicts that a task's representation should be enhanced following an incorrect response, leading to slower, more accurate performance. However, previous accuracy (correct, incorrect) had no effect on error rates in the current trial [$F(1,23) = 0.03$, *n.s.*]. Moreover, as in Experiment 1, neither switch costs [$F(1,23) = 0.99$, *n.s.*] nor congruency effects [$F(1,23) = 1.4$, *n.s.*] in the current trial varied with previous-trial accuracy. Thus, similar to the RT data above and to our findings in Experiment 1, the accuracy data provided no evidence to suggest that a task's representation in working memory was enhanced following an incorrect response.

Discussion

In Experiment 2, we reversed the task-key mapping after each trial to determine whether effects of previous congruency and previous accuracy on switch rate

in Experiment 1 reflected a task-repetition bias, a key-repetition bias, or both. As in Experiment 1, both switch rates and congruency effects were lower after incongruent than after congruent trials, suggesting that effects of previous congruency reflected a task-repetition bias. Unlike Experiment 1, however, there was no overall effect of previous accuracy on switch rates. Indeed, previous accuracy influenced switch rates only slightly at the short RCI, and the nature of this effect was to slightly increase (rather than to massively decrease) switch rates after an incorrect (versus correct) response. These data suggest that the robust effects of previous accuracy in Experiment 1 were driven by a combination of task- and key-repetition biases, which tended to cancel each other out in Experiment 2. In sum, our findings suggest that effects of previous congruency were driven by a task-repetition bias while effects of previous accuracy were driven by a combination of task- and key-repetition biases.

Between-experiment comparisons

Our findings thus far suggest two conclusions: (1) previous congruency affected switch rates similarly in Experiments 1 and 2 and (2) previous accuracy affected switch rates differently in Experiments 1 and 2. However, to firmly establish these conclusions, it is necessary to directly contrast the effects of previous congruency and previous accuracy in Experiments 1 and 2. To accomplish this objective, we conducted a series of between-experiment comparisons using two mixed ANOVAs.

The first ANOVA assessed the effect of previous congruency on switch rates. It included experiment (Experiment 1, Experiment 2) as a between-participants factor and four within-participants factors: previous congruency (congruent, incongruent), RCI (short, long), previous task alternation (repeat, switch), and previous task (numerical

comparison, physical comparison). We observed a significant interaction between RCI and experiment [$F(1,54) = 11.0$, $p < 0.005$] because the degree to which switch rates were higher at the long RCI than at the short RCI was greater in Experiment 1 (6.3%) than in Experiment 2 (1.4%). Of greater interest, there was a main effect of previous congruency [$F(1,54) = 6.5$, $p = 0.01$] indicating lower switch rates after incongruent (45.2%) than after congruent (46.4%) trials. Critically, however, there was no interaction between experiment and previous congruency, [$F(1,54) = 0.034$, *n.s.*]. Thus, the degree to which participants switched tasks less often after incongruent than after congruent trials did not differ in Experiments 1 and 2. This result suggests that the effect of previous congruency is attributable to a task-repetition bias: participants are biased to repeat tasks, not key presses, after incongruent trials.

The second ANOVA assessed the effect of previous accuracy on switch rates. It included experiment (Experiment 1, Experiment 2) as a between-participants factor and two within-participants factors: previous accuracy (correct, incorrect) and RCI (short, long). As expected, the effect of previous accuracy on switch rate varied across Experiments 1 and 2 [$F(1,54) = 29.3$, $p < 0.001$]. Specifically, switch rates were reduced after errors (relative to correct responses) more strongly in Experiment 1 (19.2%) than in Experiment 2 (-2.7%). This result suggests that the effect of previous accuracy on switch rates was driven by a combination of task-repetition and key-repetition biases following incorrect responses, which tended to cancel each other out in Experiment 2.

General Discussion

The conflict monitoring model predicts that a task's representation in working memory is more highly activated following the experience of response conflict

(Botvinick, et al., 2001; Botvinick, et al., 2004; Brown, et al., 2007). In the present study, we used a voluntary task switching (VTS) paradigm to provide a novel test of whether two putative conflict-eliciting events—incongruent trials and incorrect responses—increase the activation of a task's representation in working memory. In the VTS paradigm, a bottom-up availability heuristic is thought to bias task choice toward the task whose representation is most highly activated in working memory (Arrington & Logan, 2005; Lien & Ruthruff, 2008; Mayr & Bell, 2006). Thus, the conflict monitoring model predicts that increasing the activation of a task's representation in an incongruent or incorrect trial should bias participants to repeat the same task in the next trial, leading to reduced switch rates.

Effects of previous congruency confirmed the conflict monitoring model's predictions. In Experiment 1, participants chose to repeat tasks more often after incongruent than after congruent trials. Experiment 2 revealed the same pattern even when the task-key mapping was reversed after each trial. Thus, effects of previous congruency on switch rate were likely driven by an increased bias to repeat the task chosen in the previous trial, rather than the key press that was made to choose that task. We also replicated prior findings regarding conflict adaptation. In particular, effects of current congruency on reaction time and accuracy were smaller after incongruent trials than after congruent trials. Critically, this conflict adaptation effect could not be accounted for by repetition priming. Thus, consistent with the conflict monitoring model, participants were both more likely to repeat the same task and better at performing that task after incongruent (versus congruent) trials.

In contrast, effects of previous accuracy confirmed the conflict monitoring model's predictions for switch rates, but not for task performance. With regard to switch rates, participants switched tasks less often after incorrect (versus correct) responses in Experiment 1, but not in Experiment 2, wherein the task-key mapping was reversed after each trial. Thus, it appears that incorrect responses resulted in a task-repetition bias in both experiments, but that this bias was canceled out by an opposing key-repetition bias in Experiment 2. With regard to the performance data, neither congruency effects nor switch costs varied with previous-trial accuracy. Moreover, participants responded more slowly and *less* accurately after incorrect than after correct responses. This latter result does not fit with the conflict monitoring model's claim that enhancing a task's representation after an incorrect response involves raising the threshold for selecting a response in the next trial, which should result in slower, *more* accurate performance (Botvinick, et al., 2001; Yeung, et al., 2004). In sum, effects of previous accuracy confirmed the conflict monitoring model's predictions for switch rates, but not for task performance.

The dissociation between switch rates and task performance following incorrect responses is difficult to reconcile with the conflict monitoring model. Indeed, the model predicts that increasing the activation of a task's representation in working memory should not only bias participants to repeat the same task, but also lead to better performance of that task in the next trial. An alternative account, however, is motivated by models in which a task's representation consists of two parts: (1) a task-level representation and (2) a parameter-level representation (Logan & Gordon, 2001; Rubinstein, Meyer, & Evans, 2001). The task-level representation is similar to the goal or

intention of performing a task. The parameter-level representation specifies the relevant stimuli, responses, and rules (e.g., stimulus-response mappings) that enable task performance. This distinction raises the possibility that errors increased the activation of the task-level representation in working memory (thus biasing participants to repeat the same task in the next trial), but not the parameter-level representation (resulting in the lack of a performance enhancement). Confirmation of this account in future studies would indicate an important difference in the way that control processes enhance the activation of a task's representation in incongruent and incorrect trials, which would need to be addressed by the conflict monitoring model.

Another finding that warrants further discussion is the key-repetition bias following errors in Experiment 2. We speculate that this bias resulted from a temporary depletion of resources needed by the representativeness heuristic to generate a random task sequence (Baddeley, Emslie, Kolodny, & Duncan, 1998). In particular, this depletion enabled the bottom-up availability heuristic to exert a greater influence on task choice. Two sources of evidence are consistent with this possibility. First, errors impair subsequent resource-demanding behavior. For example, errors are followed by elevated RT and reduced accuracy at short response-stimulus intervals (Jentzsch & Dudschig, 2009) and interfere with dual-task performance (Hochman & Meiran, 2005). Second, when participants try to generate random sequences under resource-limited conditions, they produce non-random sequences that are characterized by stereotyped, bottom-up transitions (Baddeley, et al., 1998). These findings are consistent with the view that, by depleting limited resources, errors could enable bottom-up processes to exert a heightened influence on voluntary task choice in the next trial.

But could bottom-up processes generate the key-repetition bias in Experiment 2? Recent work on event files suggests they could (Hommel, 1998, 2007). This work indicates that each time a stimulus is presented a temporary event file is created, which stores the stimulus-response association that was most recently linked to the stimulus. Further, the event file is automatically recalled from memory the next time the stimulus is presented, resulting in the activation of the previously stored stimulus-response association. For example, in each trial of the current study the question mark that prompted participants to make a random task choice was eventually linked to one of two possible responses (i.e., one of two key presses). This link was presumably stored in an event file, which was automatically recalled when the question mark appeared in the next trial.

Most important, when resources needed to randomly select a task were depleted after an error, recalling this event file may have enabled the task choice response from the previous trial to exert a heightened influence on task choice via the bottom-up availability heuristic. The result would have been an increased key-repetition bias. However, since choosing to repeat a task in Experiment 2 required making a *different* task choice response than in the previous trial, a key-repetition bias would have reversed the task-repetition bias observed in Experiment 1. Critically, we observed such a reversal at the short RCI. Further, this reversal was reduced at the long RCI, consistent with a *temporary* depletion of resources. We therefore conclude that bottom-up processes could have produced the key-repetition bias after errors in Experiment 2, in line with the claim that event files exert a greater influence in the voluntary task switching paradigm under resource-limited conditions (Demanet, et al., 2010).

More broadly, the present findings add to a growing literature indicating that a combination of top-down and bottom-up processes influences voluntary task choice. With regard to top-down influences, prior results indicate that the accessibility of resources to support top-down processes in the current trial strongly influences task choice. For example, switch rates are reduced in the presence (versus absence) of a concurrent working memory load (Demanet, et al., 2010) and in individuals with relatively inefficient top-down control (Arrington & Yates, 2009). Our finding that switch rates were reduced following incongruent (versus congruent) trials complements these previous results. Specifically, it indicates that the accessibility of resources to support top-down processes in the *previous* trial also influences voluntary task choice.

With regard to bottom-up biases, our findings extend prior results indicating that stimulus repetition influences task choice in the VTS paradigm. For example, when task choices are indicated by varying the hand that is used to respond to an imperative stimulus, switch rates are lower when the imperative stimulus from the previous trial repeats than when it does not (Demanet, et al., 2010; Mayr & Bell, 2006). Such findings suggest that an imperative stimulus can prime a task choice in a bottom-up fashion. As discussed above, the present results go one step further by suggesting that a cue to voluntarily choose a task can also prime a task choice in a bottom-up fashion, even in the absence of an imperative stimulus. Thus, the present findings not only fit with the current literature on voluntary task switching, but also extend that literature in important ways.

In conclusion, the present results illustrate the importance of response conflict for voluntary task choice, but also show that not all forms of conflict are created equal. In particular, they indicate a novel dissociation between previous congruency and previous

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accuracy that is not predicted by the conflict monitoring model. Thus, our findings

provide new constraints on the conflict monitoring model by indicating that different

sources of response conflict have distinct effects on subsequent task performance.

Acknowledgments

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Chapter 5
Amplitude of the P3 component predicts voluntary task choice

Abstract

Task choice in the voluntary task switching paradigm is thought to depend on a combination of top-down processes which generate a random task sequence and bottom-up processes which select the task with the strongest representation. Most tests of the latter process, known as the availability heuristic, have focused on whether stimulus aspects of the current trial bias task choice. However, task choices should also depend on prior task strength, independent of trial type. As the P3 event-related potential (ERP) component has been positively associated with the strength of a task's representation, we used P3 amplitude to test whether task strength in trial n predicted task choice in trial $n+1$. To test this hypothesis, participants performed a voluntary task switching version of the numerical Stroop task, while EEG was recorded. In line with our predictions, a larger P3 on the current trial was associated with choosing to repeat tasks (versus switch tasks) on the following trial. This finding demonstrates that bottom-up biases, such as the relative strength of task representations, influences task choice in the voluntary task switching paradigm. Moreover, our data demonstrate the use of ERP's to predict upcoming behavior.

Introduction

In our daily lives we often encounter multitasking situations, where we must manage multiple possible tasks and often alternate between these tasks quite frequently. Today's society encourages multitasking, with technology allowing us to check email during classes or meetings, search for the nearest gas station or restaurant from the wheel of a car, or follow a dizzying array of information across multiple computer monitors. Even when we are not actively trying to multitask, environmental information may distract us from the task at hand and cause us to multitask. It is no surprise, then, that there has been a recent surge of interest in understanding multitasking by both the public media (Hamilton, 2008) and the scientific community (Dux, et al., 2009; Neider, et al., 2011; Ophir, Nass, & Wagner, 2009).

Successfully completing one task in the face of competition from other possible tasks involves selecting and maintaining a task set, or the goals and rules relevant for performing the task (Rogers & Monsell, 1995). Doing so is thought to require cognitive control, a set of processes thought to maintain task goals in working memory and bias information processing of task-relevant stimuli (Miller & Cohen, 2001). However, such control must be flexible enough to quickly reconfigure the cognitive system to perform a new task whenever goals change, as is the case in multitasking environments (Monsell, 2003).

Arrington & Logan (2004) introduced the voluntary task switching paradigm in order to study the role of cognitive control in guiding task selection in multitasking environments. In each trial of a voluntary task switching study, participants are asked to voluntarily choose one of multiple possible tasks to perform while performing the tasks

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equally often and in a random order. Cognitive control is thought to be necessary to actively select the task in each trial. Random task selection in this paradigm would result in an equal proportion of task repeat trials and task switch trials; however, participants tend to be biased towards repeating tasks (Arrington & Logan, 2004, 2005; Mayr & Bell, 2006). This suggests that task selection in the voluntary task switching paradigm is not always under the guidance of cognitive control processes (Mayr & Bell, 2006).

Arrington & Logan (2005) have proposed that task choice in the voluntary task switching paradigm is driven by a combination of top-down and bottom-up processes. First, a top-down representativeness heuristic is thought to guide task choice by comparing a mental history of the recent task choices to a representative random sequence (Arrington & Logan, 2005), or by treating each trial as a discrete event and performing a mental coin flip (Mayr & Bell, 2006). Second, a bottom-up availability heuristic is thought to guide task selection by choosing the task with the strongest representation in working memory (Arrington & Logan, 2005). The most recently performed task is still the most active in working memory (Rogers & Monsell, 1995), thus, when task selection is guided by an availability heuristic, a task-repetition bias occurs.

Most previous studies have provided evidence for the availability heuristic by examining the effects of stimulus repetitions on task choice. The most prevailing finding is that when the task stimuli repeat from the previous trial, participants are biased to choose to repeat the task (Demanet, Liefooghe, Verbruggen, & Vandierendonck, 2010; Mayr & Bell, 2006). This finding is likely due to stimulus-response priming. When a stimulus is presented, it becomes associated with a response, and this association is stored

in what has been called an 'event file' (Hommel, 2004). When this stimulus repeats on the next trial, the event file is automatically retrieved and primes the automatic execution of the associated response. This response priming may simply lead to a response repetition which coincidentally signals a task repeat, without a task actually being chosen. Alternatively, stimulus repetition may prime the retrieval of a more abstract task representation (Arrington, Weaver, & Pauker, 2010; Demanet, et al., 2010; Waszak, Hommel, & Allport, 2003), which results in a given task being more available and more likely to be selected.

Relative task strength may also influence subsequent task choice, independent of trial type. Some theorists have proposed that in order to switch tasks, the most recent task must be inhibited (Mayr & Keele, 2000). This process weakens the representation of the most recent task. Following this logic, Lien and Ruthruff (2008) examined the effect of inhibition on voluntary task choice. They posited that if switching away from a task involved inhibiting that task, then participants would not quickly return to that task, and would wait until the inhibition weakened. Using three possible tasks (Task A, Task B, Task C), they examined the likelihood that participants would return to a task they just switched away from (e.g., an ABA task sequence). In line with their predictions, participants avoided returning to the task performed on trial *n*-2 in favor of performing a new task (e.g., an ABC task sequence). This suggests that Task A's representation was less active in WM than Task C's representation and that this difference influenced task choice. Thus, the likelihood of a choice to repeat tasks in the voluntary task switching paradigm appears to depend on the strength of a given task's representation on trial *n*-1.

By analyzing Event-Related Potentials (ERP's) we may be able to track task strength and predict subsequent task choices. ERP's reveal the temporal dynamics of brain activity related to different cognitive processes. A candidate ERP component for examining task strength is the P3 component. The P3 has been associated with resource allocation, attention, and working memory updating (for recent reviews, see Kok, 2001; Polich, 2007). By using the P3 to measure the strength of a task's representation on a given trial, we can test whether increased task strength in one trial is associated with choosing to repeat (versus switch) tasks on the next trial.

The P3 has often been studied in dual-task paradigms. In these paradigms, participants perform two tasks concurrently, with one task having priority over the other task. These paradigms assume that the two tasks rely on a shared pool of cognitive resources (Kahneman, 1973).When the primary task increases in difficulty, more processing resources are dedicated to it, which in turn, decreases the availability of resources available to the secondary task. The amplitude of the P3 elicited by the secondary task stimuli is decreased as demands of the primary task are increased (Isreal, Chesney, Wickens, & Donchin, 1980). This suggests that P3 amplitude tracks the availability of resources for the secondary task. Later studies showed a reciprocal relationship in the amplitude of the P3s elicited by the primary and secondary task, with larger amplitudes elicited by the primary task resulting in smaller amplitudes elicited by the secondary task, and vice versa (Sirevaag, Kramer, Coles, & Donchin, 1989). Thus, the amplitude of the primary task P3 is proportional to the amount of resources/ attention dedicated to processing the primary task.

Along these lines, the amplitude of the P3 elicited by the target in a task switching paradigm may reflect the amount of resources allocated to the current task, which we posit reflects the strength of the task representation. Task switching studies using ERP's have shown that target-locked P3 amplitude is reduced on task switch trials compared to on task repeat trials (Karayanidis, Coltheart, Michie, & Murphy, 2003; Kieffaber & Hetrick, 2005; Mueller, Swainson, & Jackson, 2007; Vandamme, Szmalec, Liefooghe, & Vandierendonck, 2010). However, this finding has received little notice in the literature, especially compared to the cue-evoked P3 (for a review, see Karayanidis, et al., 2010). Nevertheless, the consensus seems to be that the P3 is larger on repeat trials due to consolidation of stimulus-response associations, a key aspect of a task representation (Kok, 2001).

Perhaps the most direct evidence that P3 amplitude may reflect the strength of a task's representation in working memory comes from an ERP study with the Wisconsin Card Sorting Task (Barceló, Muñoz-Céspedes, Pozo, & Rubia, 2000). In the Wisconsin Card Sorting Task, participants must categorize the current stimulus based on its stimulus features (e.g., quantity, color, shape) according to the current rule. The current rule will occasionally change without any external signal, and the participant must determine the new, current rule via response accuracy feedback. These set shifts require cognitive control processes to reconfigure the cognitive system for the new rule. Barcelo and colleagues (2000) found that the amplitude of the P3 was markedly reduced on set switch trials compared to non-switch trials. Further, P3 amplitude showed a gradual return to baseline two to three trials after the shift. The authors posited that this post-shift build-up reflected the strengthening of the task's representation in working memory. Thus, by

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examining P3 amplitude, we can test the hypothesis that the strength of a task's

representation in one trial predicts whether participants will choose to repeat or switch on

the next trial.

<div align="center">**Method**</div>

Participants

Fifteen healthy participants (three males) completed this study, with a mean age

of 20.1 years. All participants were right-handed. Participants received $30 for their

participation. Informed consent was obtained in accordance with the University of
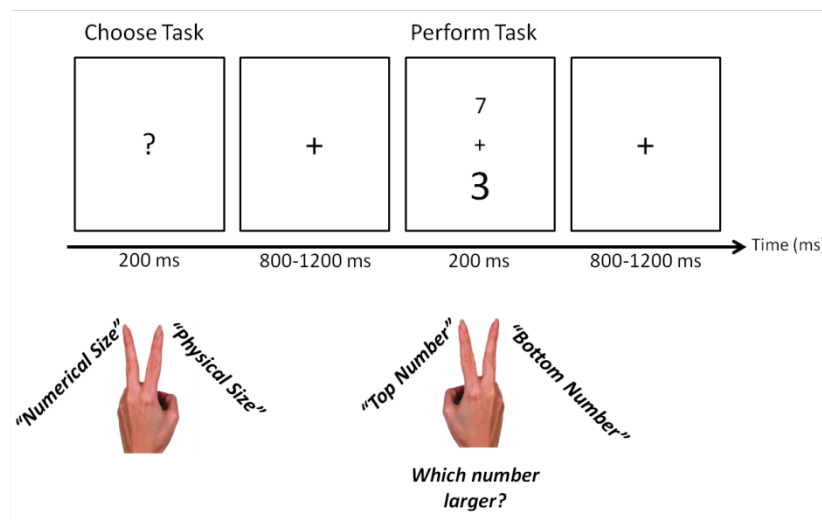
Michigan Institutional Review Board.

Figure 5.1. Experimental Design.
Participants performed a voluntary task switching version of the number Stroop task, which involved comparing two digits with respect to their numerical size or with respect to their physical size. Each trial began with the presentation of a question mark (?) for 200 ms. This indicated that participants should choose which task to perform in the current trial by pressing a button with the middle or index finger of their left hand. Participants were not pressured to choose quickly. The two digits appeared 800-1200 ms after participants chose the task. One digit was numerically large (e.g., 7) while the other digit was numerically small (e.g., 7). Further, one was presented in a large font (e.g., 3) while the other was presented in a small font (e.g., 7). In congruent trials, the numerically large digit was also physically large. In incongruent trials, the numerically large digit was physically small. Depending on the current task, participants decided which of the two digits (top or bottom) was numerically or physically larger. They were instructed to indicate their decision as quickly and as accurately as possible by pressing a button with their right index finger or their right middle finger. The next trial began 800-1200 ms after the task response.

Behavioral Paradigm

The behavioral paradigm was adapted from a previous study (Orr, Carp, & Weissman, 2011), with the timing adapted for use in an ERP study. Participants performed a VTS version of the number Stroop task (Henik & Tzelgov, 1982). In each trial, they were cued by a central question mark to choose whether they would compare two upcoming digits in terms of their numerical size or their physical size (see Figure 5.1). The instructions emphasized that participants should choose each task an equal number of times and in a random order across trials (Arrington & Logan, 2004). The question mark remained on the screen for 200 ms, and was then replaced with a fixation cross. No pressure to choose quickly was indicated in the instructions. Task choices were indicated by using the index or middle finger of the left hand, respectively, to press the D or F key on a computer keyboard (task-key mappings were counterbalanced across participants).

Each task choice was followed by a variable delay between 800 and 1200 ms, after which two digits were presented. One digit appeared 1.7° above fixation while the other appeared 1.7° below fixation. One of the digits was numerically large (7, 8, or 9) while the other was numerically small (1, 2, or 3). Moreover, one digit was physically large (subtending 1.1°) while the other physically small (subtending 0.6°). In congruent trials (50%), the numerically large digit was also physically large. In incongruent trials (50%), the numerically large digit was physically small. The trial sequence was randomized such that exact stimulus repetitions were separated by at least three trials (i.e., a digit appearing in trial *n* could not be repeated until trial *n+3*).

Participants were instructed to indicate which of the two digits (top or bottom) was larger as quickly and as accurately as possible. If they chose to perform the numerical comparison task, they indicated which of the two digits was numerically larger. If they chose to perform the physical comparison task, they indicated which of the two digits was physically larger. The digits remained on the screen for 200 ms, and were then replaced with a fixation cross. Responses were made by using the index or middle finger of the right hand, respectively, to press the J or K key on a computer keyboard (task-key mappings were counterbalanced across participants). The next trial was presented after a variable delay between 800 and 1200 ms.

Participants viewed the stimuli on a 17" CRT monitor at a distance of 60 cm. A chin rest was used for head stabilization. Stimuli were generated and displayed using Presentation software (Neurobehavioral Systems Inc., Albany, CA).

EEG Acquisition & Analysis

The EEG was recorded at 512-Hz using an ActiveTwo Biosemi system (Amsterdam, the Netherlands) from 64 Ag/AgCl electrodes relative to a Common Mode Sense (CMS) active electrode and Driven Right Leg (DRL) passive electrode. The CMS-DRL electrodes form a feedback loop, which drives the average potential close to the amplifier zero, as per BioSemi's standard design (http://www.biosemi.com/faq/cms&drl.htm). The data were downsampled to 256 Hz with a low-pass filter of 52 Hz, and referenced off-line to two mastoid electrodes. Electrooculogram (EOG) was recorded from electrodes placed above and below the left eye and on the outer canthi of both eyes.

Data was analyzed offline using EEGLAB (Delorme & Makeig, 2004) and

ERPLAB (http://www.erpinfo.org/erplab). Oculomotor movements were corrected with

an automated Blind Source Separation algorithm using the Automated Artifact Removal

toolbox for EEGLAB (Gómez-Herrero, et al.). The current analyses focused on three

components: the CNV during the response-to-cue interval, the target stimulus-locked P3,

and the target response locked ERN. To examine the CNV, we created epochs consisting

of a window 500 ms before the target response to 2500 ms after the target response.

These epochs were baseline corrected with a -50 to 50 ms response-locked interval, and

then averaged separately as a function of the upcoming choice to repeat or switch tasks.

To examine the P3 component, we created epochs consisting of a window 200 ms before

stimulus target onset to 800 ms after stimulus target onset. These epochs were baseline

corrected with a 200 ms prestimulus interval, and then averaged at each level of current

trial and next trial task transition (repeat, switch). Epochs were excluded if they contained

amplitudes larger than $\pm$ 500 μV or had power in the 0-2 Hz or 20-40 Hz frequency

ranges that was larger than $\pm$ 50 dB. The remaining epochs were inspected visually for

movement artifact, drift, or any other impurities.

Results

Behavioral Data

Switch Rate Data

As instructed, participants performed the two tasks equally often [numerical task,

50.3%; physical task, 49.7%; $t(14) = 0.57$, *n.s.*]. As in previous studies with relatively

long inter-trial intervals (Arrington & Logan, 2005; Orr, et al., 2011), participants did not

show a task repetition bias: the confidence interval for the mean switch rate (50.4%) contained 50% [95% CI: 43.3% - 55.9%].

The switch rate data were submitted to a repeated measures ANOVA with two within-participants factors: previous trial task (numerical, physical) and previous trial task transition (repeat, switch). In line with our previous studies (Orr, et al., 2011; Orr & Weissman, 2011), participants were more likely to switch tasks following a repeat trial (62.5%) than following a switch trial [36.3%; $F(1,14) = 29.1$, $p < 0.001$]. No other effects in this analysis were significant.

Reaction Time Data

Reaction time data were entered in to a repeated measures ANOVA with within-participants factors of task transition (repeat, switch) and task (numerical, physical). As expected reaction times were longer for switch (697 ms) compared to repeat trials [624 ms; $F(1,14) = 29.5$, $p < 0.001$]. In line with previous studies (Henik & Tzelgov, 1982), reaction times were also longer in the numerical task (681 ms) compared to the physical task [640 ms; $F(1,14) = 15.1$, $p= 0.001$]. In addition, task interacted with task transition [$F(1,14) = 8.1$, $p < 0.05$]: the switch cost was larger for the physical task [88 ms; $F(1,14) = 36.6$, $p < 0.001$] than for the numerical task [57 ms; $F(1,14) = 18.2$, $p < 0.001$]. This is in line with previous studies demonstrating that it is harder to switch to the easier of two tasks, presumably because switching away from a hard task requires greater cognitive control to inhibit the harder task than does switching away from an easy task (Monsell, Yeung, & Azuma, 2000; Yeung, 2010). However, unlike Yeung (2010), participants did not paradoxically choose the harder task (numerical) more often than the easy task (physical), as there was no effect of task in the switch rate data presented above (see

Liefooghe, Demanet, & Vandierendonck, 2009 for a similar result). No other effects were significant.

ERP Data

Previous studies using both cued and voluntary task switching have observed a greater CNV leading up to the onset of the imperative stimulus in task switch versus repeat trials (Lorist, et al., 2000; Vandamme, et al., 2010). This CNV difference is thought to reflect the recruitment of cognitive control processes in preparation of a task switch. In a previous voluntary task switching study by Vandamme and colleages (2010), the task choice was indicated when the target stimulus was presented, meaning that the CNV actually predicted whether participants would choose to repeat or switch tasks. This is somewhat unsurprising, as the task design permitted the participants to choose the next task before the stimuli were presented. However, task choice and the imperative task response were indicated by a single button press. Thus, it is unclear whether the greater CNV leading up to a switch reflected processes related to preparing for an upcoming change in task choice or an upcoming change in task performance. In the current design, participants were first cued to choose the next task, and then they were presented with the task stimuli, so this may allow us to shed some insight on what preparatory processes the CNV reflects.

In line with these previous studies, a CNV was observed during the response-to-cue interval which was larger for upcoming task switches versus repeats. The CNV was maximal over right central electrode sites, maximal at channel C4. The grand-averaged waveform is shown in Figure 5.2. The waveforms appear to differentiate starting at around 400 ms. In order to determine when the CNV began to differentiate between an
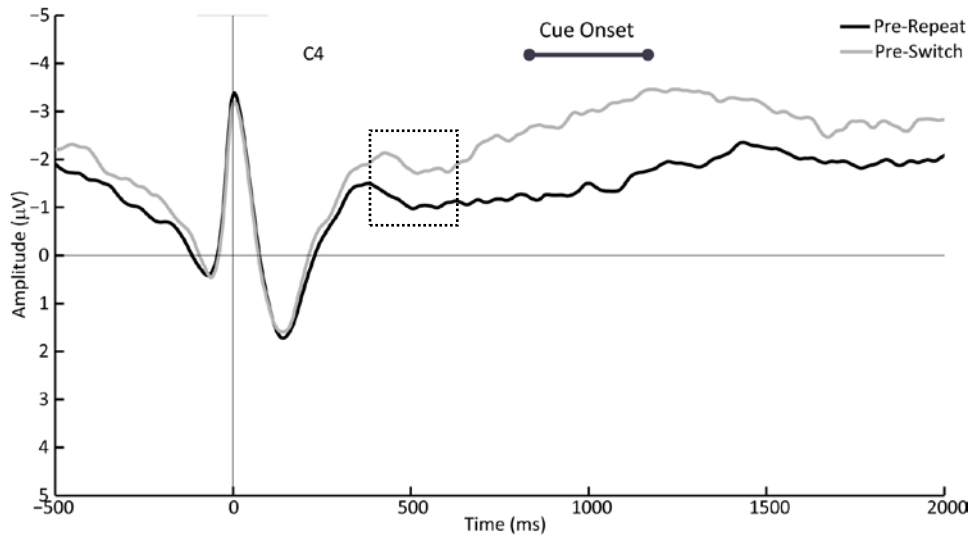
Figure 5.2. CNV as a function of next trial task transition.
Grand-averaged waveforms at channel C4 showing activity during the response to cue interval as a function of whether the next trial was a task repeat or switch trial. Time zero represents the onset of the target response. The time range of the choice cue onset is denoted by the gray line. The waveforms were significant different 400-600 ms after the response, with a more negative Contingent Negative Variation (CNV) leading up to the choice to switch tasks than leading up to the choice to repeat tasks. The dashed rectangle marks the 400-600 ms time range on which analyses were performed. The waveforms were baseline corrected with respect to the period of 50 ms pre-response to 50 ms post-response.

upcoming task switch or repeat, for each participant we extracted the mean CNV

amplitude at channel C4 between 400 and 600 ms after the response in the previous trial,

separately for upcoming task switches and repeats. The mean amplitudes were entered

into a paired t-test. In line with previous studies, the CNV was greater for upcoming task

switches than for upcoming task repeats [$t(14) = 3.1$, $p < 0.01$]. This suggests that the

CNV reflected preparatory processes for choosing a new task, and not choosing a new

task.

We next tested the hypothesis that P3 amplitude reflected the current strength of a

given task representation. We first sought to replicate the previous finding of larger

target-stimulus locked P3 amplitude on repeat compared to switch trials (Karayanidis, et

al., 2003; Kieffaber & Hetrick, 2005; Vandamme, et al., 2010). The grand-averaged

waveform is shown in Figure 5.3. A P3 component is apparent between 400 and 500 ms

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after stimulus onset. For each participant, we entered the mean amplitude between 400

and 450 ms into a repeated measures ANOVA with two within-participants factors:

current trial task transition (repeat, switch) and next trial task transition (repeat, switch).

Replicating previous studies, there was a main effect of current trial task transition

$[F(1,14) = 10.2, p < 0.01]$: the P3 was larger for current trial repeats than for current trial

switches. If the P3 reflects task strength, then in line with previous work on the

availability heuristic (Lien & Ruthruff, 2008), larger P3 amplitude on trial n should

predict the decision to repeat tasks on trial n+1. In line with our predictions, there was

also a main effect of next trial transition $[F(1,14) = 10.0, p < 0.01]$, as a larger P3 on the

current trial was associated with repeating on the next trial as opposed to switching on the
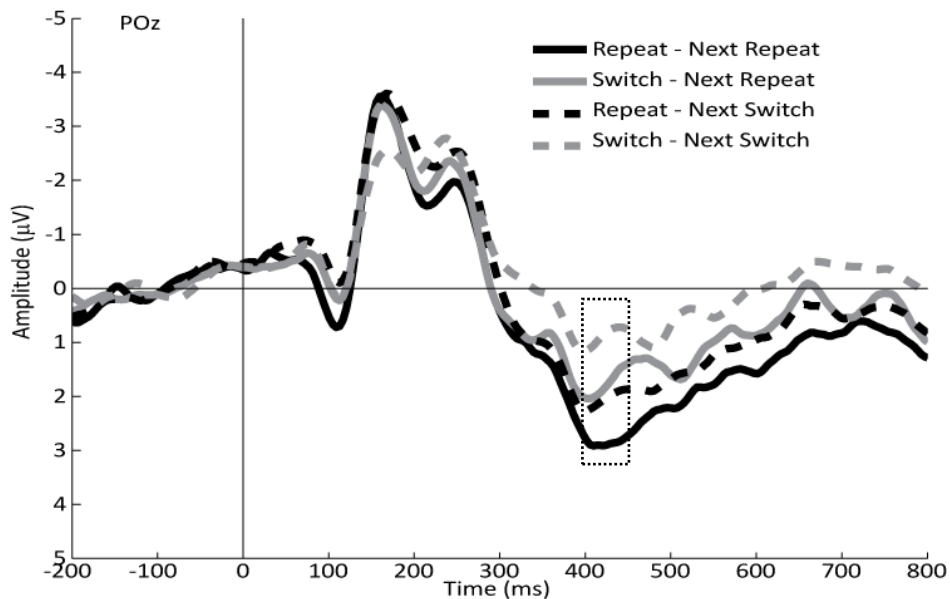
next trial.

Figure 5.3. P3 as a function of current and next trial task transition.
Grand-averaged waveforms at channel POz showing target stimulus-locked activity as a function of current and next trial task transition (response, switch). There was a P3 component evident around 400 ms post-response. P3 amplitude differed as a function of current trial and next trial task transition. The P3 was more positive on current trial task repeats versus current trial task switches. Further, the P3 was more positive when participants subsequently chose to repeat tasks than when they subsequently chose to switch tasks. The dashed rectangle marks the 400-450 ms time range on which analyses were performed. The waveforms were baseline corrected with respect to the 200 ms preceding the response.

Discussion

The current findings demonstrate that the P3 can be used as a measure of task strength. These findings are in line with previous findings suggesting that relative task strength is an important influence on task choice in the voluntary task switching paradigm (Arrington & Logan, 2005; Lien & Ruthruff, 2008; Mayr & Bell, 2006; Orr, et al., 2011). Moreover, we show that relative task strength in one trial predict task choice in the next trial.

We also found a larger CNV leading up to choice stimuli on task switch (versus repeat) trials. The one previous voluntary task switching study that examined ERPs used a variant of the voluntary task switching paradigm where a single response during stimulus presentation represented both the current task choice and the current task performance (Vandamme, et al., 2010). They found that a greater CNV leading up to stimuli presentation was associated with choosing to switch rather than repeat tasks. As this study did not temporally separate task choice and task performance, it is not clear whether their finding was associated with preparing to choose to switch or preparing to perform a task switch. The current study suggests that the CNV is involved in preparing to choose to switch.

However, the exact function of the CNV is not very clear. Most previous ERP task switching studies have only discussed the CNV as reflecting preparatory processes (Karayanidis, et al., 2003; Karayanidis, et al., 2010; Vandamme, et al., 2010). However, one previous study identified a CNV-like switch negativity that they attributed to overcoming response inhibition (Astle, Jackson, & Swainson, 2006). Mayr and Keele (2000) have suggested that switching requires inhibiting the most recent task. This

inhibition appears to occur at the level of the response set, as switch costs are eliminated when switching away from a no-go task (Schuch & Koch, 2003). Thus, the CNV may reflect overcoming inhibition of a task's response set.

If the inhibition account of the CNV is correct, it suggests that when a task choice was made, the response set for performing the task was activated. The task performance response set of the previous task would need to be inhibited before the next task is chosen. The CNV in the current study was localized over right frontal sites. Task choice responses were made with the left hand, while task performance responses were made with the right hand. Thus, the CNV was contralateral to the task choice response, so is unlikely to have been related to processing task performance responses. This weakens support for the claim that the CNV is associated with overcoming response set inhibition. Furthermore, as there was only one response set active for the task choices, no inhibition of the choice response set would be required in order to choose to switch tasks.

Further, we replicated previous findings that the P3 is larger on current trial repeats than current trial switches (Karayanidis, et al., 2003; Kieffaber & Hetrick, 2005; Vandamme, et al., 2010). This finding is thought to reflect greater attention to the current task stimulus features or a stronger configuration of the current task rules (Barceló, et al., 2000). These aspects make the P3 an ideal measure of task set strength, which is thought to influence task choice in the voluntary task switching paradigm through the availability heuristic (Arrington & Logan, 2005).

Perhaps the most novel finding from this study was that P3 amplitude in one trial predicted whether participants chose to repeat or switch in the next trial. This is in line with our hypothesis that the P3 represents task strength. Participants in the voluntary task

switching paradigm are biased to choose the task whose representation is the strongest; this is often the most recently performed task (Mayr & Bell, 2006). The present findings suggest that participants are more likely to switch away from a task (versus repeating a task) when it has a weaker representation, indexed by P3 amplitude.

An alternate account of the function of the P3 has been proposed, the context updating theory (Donchin, 1981; Donchin & Coles, 1988; Donchin & Coles, 1998). According to this account, the P3 reflects cognitive control processes responsible for updating the contents of working memory, such as the representation of the current task. Accordingly, the amplitude of the P3 has been shown to be proportional to the amount of revision required to working memory contents. In line with this finding, the P3 should be larger on task switch trials, where it necessary to load a new task representation in to working memory, compared to task repeat trials, where the task representation merely needs to be maintained. Conversely, however, the P3 is typically larger on task repeat trials than on task switch trials (Gehring, Bryck, Jonides, Albin, & Badre, 2003; Karayanidis, Coltheart, Michie, & Murphy, 2003 & Murphy, 2003; Kieffaber & Hetrick, 2005; Mueller, Swainson, & Jackson, 2007 2007; Vandamme, Szmalec, Liefooghe, & Vandierendonck, 2010 & Vandierendonck, 2010).

Of the previous studies to have investigated the P3 in switching studies, only Gehring and colleagues (2003) discussed how this finding may relate to context updating. They argued that the reduction in P3 amplitude on switch trials may reflect a breakdown of the processes maintaining the task representation in working memory. Further, these authors found that the P3 on switch trials was reduced when the previous trial was a switch compared to a repeat. This is similar to our finding that the P3 was reduced on

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current switch trials that preceded a task switch versus a task repeat. This further supports the hypothesis that the P3 reflects the strength of a task's representation in working memory.

The present findings do not speak to the factors that determine the strength of a task representation, but inhibition may be one key factor. Switching to a new task requires inhibiting the previous task, and this inhibition weakens the representation of the task and decays slowly over the course of several trials (Mayr & Keele, 2000). This results in participants not returning to a task they recently switched away from for several trials (Lien & Ruthruff, 2008). One possible extension of the current study would be to examine how the P3 changes when there are three possible tasks, as in Lien and Ruthruff.

Previous studies have shown that several factors influence the extent to which the availability heuristic guides task choice, including stimulus repetitions (Demanet, et al., 2010; Mayr & Bell, 2006), learned associations of specific stimuli and tasks (Arrington, et al., 2010), and the presentation of irrelevant stimuli associated with a specific task (Orr & Weissman, 2011). If the finding of a larger P3 associated with choosing to repeat (versus switch) on the next trial is related to the availability heuristic, then the P3 may be useful in examining other factors thought to influence task choice through the availability heuristic. While stimulus repetitions do have a large influence on task choice, participants do not always choose to repeat tasks when the stimuli repeat. It may be possible to predict whether participants will follow the stimulus repetition bias from the P3 on the trial preceding the stimulus repeat. If fewer resources are allocated to stimulus processing on the initial trial, then participants may be less likely to follow the stimulus repetition

bias. Accordingly, smaller P3 amplitudes may be associated with choosing to switch (versus choosing to repeat) tasks when the stimulus repeats on the next trial.

Arrington and Logan (2005) described the voluntary task switching paradigm as involving two, sometimes competing, cognitive control processes. First, cognitive control processes are required to choose tasks in a random order, as random sequence generation has been shown to rely heavily on these processes (Baddeley, 1996; Baddeley, Emslie, Kolodny, & Duncan, 1998). Second, task switching is thought to rely on cognitive control processes (Meiran, 1996; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). When both of these executive processes are activated there will be a high mental workload. This will deplete the availability of resources for cognitive control, which allows the availability heuristic to have a greater influence on task choice. The P3 has been implicated in reflecting mental workload, with reduced P3 amplitudes being associated with increased mental workload (Kok, 2001). However, reduced P3 amplitudes in the current study were associated with switching tasks, which is not associated with the availability heuristic.

The current study demonstrates how ERP data can used to generate predictions of upcoming task choices. ERP activity can used to track the engagement of mental processes over time, and these fluctuations may result in varying strategies. Similarly, previous studies have used P3 amplitude to predict upcoming instances of mind wandering (Smallwood, Beach, Schooler, & Handy, 2008). P3 amplitude was reduced prior to behavioral and subjective measures of mind wandering, reflecting reduced attention to the current task. In addition, EEG synchrony power may be another way to track the efficiency of mental processes. Increased synchrony is associated with greater

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communication between brain regions. When synchrony decreases, this may indicated

decreased efficiency of brain networks. Accordingly, decreased synchrony in the medial

prefrontal cortex, which is thought to generate the ERN, has associated with upcoming

errors (Cavanagh, Cohen, & Allen, 2009).

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Chapter 6
General Conclusions

The studies in this dissertation explored how mechanisms of adaptive cognitive control influence task selection in multitasking situations. In multitasking environments, it is sometimes crucial to flexibly switch from one task to another, while at other times, it is crucial to focus on just one task. This dissertation explored the mechanisms involved in the latter, where the current task is enhanced in order to minimize distraction or conflict. My first two studies demonstrated that successfully resolving conflict during task selection lead to better performance in the form of reduced interference from distracters (Chapter 2) or reduced switch costs (Chapter 3). Chapter 4 demonstrated that resolving response conflict involved a task enhancement which influenced subsequent task choices. Chapter 5 demonstrated that the amount of attention (or resources) allocated to processing a task could be tracked with the P3 ERP component, and this information could be used to predict subsequent task choices.

Chapter 2 dissociated between two accounts of the role of the ACC in detecting and resolving interference. Posner and DiGirolamo (Posner & DiGirolamo, 1998) suggested that the ACC is directly involved in allocating control, particularly in demanding, distracting situations. A group led by Jonathon Cohen proposed a model that shifted the locus of control from the ACC to the DLPFC. They proposed that the ACC monitors for conflicts in information processing, and signals the DLPFC to up-regulate control (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Nystrom, Fissell,

Carter, & Cohen, 1999; Carter, et al., 1998; MacDonald, Cohen, Stenger, & Carter, 2000). As loci of functional activations in the ACC had previously been shown to be heterogeneous (Bush, Luu, & Posner, 2000; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004), we proposed that different subregions within the ACC may be subserve attentional control (or resolving conflict) and detecting response conflict.

The results in Chapter 2 demonstrated a double dissociation for resolving and detecting conflict. A dorsal subregion of the ACC responded more when resolving cue/task conflict (and to a lesser extent during response conflict), and a rostral subregion of the ACC responded more when detecting target response conflict and did not respond during cue conflict resolution. Participants responded faster to targets following incongruent versus congruent cues, and this effect was correlated with the degree to which participants activated the dorsal subregion more for incongruent versus congruent cues. Furthermore, the pattern of activation in the dorsal subregion closely resembled that in the DLPFC, suggesting that these regions may both serve to up-regulate control. However, future studies should examine whether the dorsal subregion and the DLPFC act in concert, or whether there is a more unidirectional relationship between these regions.

The dorsal subregion consisted of voxels in area 32' of the ACC as well as in the pre-SMA. Rushworth and colleagues (Rushworth, Walton, Kennerley, & Bannerman, 2004) have proposed that the pre-SMA is involved in action selection, so it may be the case that the DLPFC is implementing a more abstract task set and it directs the pre-SMA (and possibly area 32') to implement or maintain a response set. While we argued against a similar response selection account of our findings in Chapter 3, there is a need for future research on this matter.

Chapter 3 followed up on Chapter 2, by examining the role of control in overriding distraction during voluntary task selection. In the real-world it is often the case that we encounter environmental cues that might seize our attention and bias our task choices. For instance, we may have the top-down goal of dieting and we encounter a cue, such as seeing the dessert menu at a restaurant. This cue may dominate our goals to diet, and we may give in and order dessert. The findings of Chapter 3 demonstrate that environmental information may bias even simple task choices. In addition, participants switched tasks more often when their task choices were biased by the distracter letters. At first we thought that maybe participants used the distracter letters to help them to switch tasks; perhaps they used the distracter letters to automatically activate the next task (Demanet, Liefooghe, Verbruggen, & Vandierendonck, 2010; Waszak, Hommel, & Allport, 2003). However, participants showed increased switch costs relative to when their task choice was not biased by the distracter letters. This was the case when comparing congruent task choices to incongruent or to neutral task choices. So it was not only resolving conflict on incongruent choices that was associated with better performance compared to congruent choices. The act of going along with the distracter letters reflected a reduction of top-down control, and this reduction persisted to influence task performance. This study suggests that exerting volitional control during task choice may in fact save mental effort later on during task performance.

In Chapter 4 we presented a novel test of the conflict monitoring model (Botvinick, et al., 2001). Some instantiations of the conflict monitoring model simulate conflict-driven control with units that increase attention to task relevant stimuli (i.e., the flanker task simulation). However, others model such control with units that represent

task goals (i.e., the Stroop task simulation), and along these lines, Botvinick, Cohen, and Carter (2004) state more directly that conflict-driven control acts to enhance the representation of a task in working memory. However, studies have suggested that conflict is resolved by enhancing the representation of task-relevant stimuli and/or responses (Banich, et al., 2000; Egner, 2008; Egner & Hirsch, 2005; King, Korb, von Cramon, & Ullsperger, 2010; Milham, et al., 2001). Behaviorally, there is no direct evidence that conflict-driven control enhances a more abstract task representation as opposed to enhancing lower-level stimulus/ response representations. Enhancing the goals or rules for a task would have the same effect on RTs as enhancing stimuli or responses: generally faster responses with reduced congruency effects. The voluntary task switching paradigm introduced a new dependent measure—switch rate—that we could use to test whether conflict was resolved by enhancing an abstract task representation. People are biased to choose the task with the strongest representation; if conflict strengthens a given task's representation, it followed that there would be a greater bias to repeat a task following trials high versus low in conflict. This is precisely what we found.

While Chapter 4 confirmed a key prediction of the conflict monitoring model—response conflict is resolved by enhancing a task's representation—this study failed to support the hypothesis that errors drive similar control adjustments (Yeung, Botvinick, & Cohen, 2004). While we did find that errors led to a bias to repeat tasks—in fact, this was a much larger effect than that observed for response conflict—this bias did not seem to stem task enhancements. The conflict monitoring model posits that errors should trigger a strategic adjustment of control that results in more cautious, slower yet more accurate

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responding. However, we found that responses following errors were no slower than responses following correct responses; further, responses following errors were significantly less accurate than responses following correct responses. The repeat bias following errors appears to be better explained by alternate accounts of behavioral adjustments following errors. Notebaert and colleagues (Notebaert, et al., 2009) have proposed that because errors are typically rare events, they may orient attention away from the current task. Jentzch and Dudschig (Dudschig & Jentzsch, 2009; Jentzsch & Dudschig, 2009) have suggested that error monitoring is a time-consuming process that interferes with subsequent processing. Thus, errors may have depleted resources available at the time of the task choice, so an availability heuristic may have biased task choice, rather than a representativeness heuristic. However, a recent study suggests that the presence of post-error improvements in behavior depend on the nature of the error (Maier, Yeung, & Steinhauser, 2011). These authors found that behavior improved when the errors resulted from failures of selective attention, but not when errors occurred for other reasons (e.g., impulsive responding). Chapter 4 was not designed to dissociate between errors of different types, so it is not clear whether post-error task choice was biased by control processes on some trials and bottom-up process on other trials.

Chapter 5 examined whether the strength of a task's representation (independent of trial type) in one trial predicted whether participants would repeat or switch on the next trial. The P3 ERP component has previously been associated with the amount of attention and/or resources allocated to a task (Kok, 2001; Polich, 2007), therefore, we used the P3 to track task strength. Choosing to repeat (versus switch) tasks was associated with a larger P3 on the prior trial. This provides novel evidence to support the

hypothesis that an availability heuristic sometimes guides task choice (Arrington & Logan, 2005).

Matthew Botvinick and his group have recently started a line of work examining how the ACC may use conflict detection as an aversive learning signal. People typically avoid exerting mental effort, and in multitasking situations, they may use conflict to guide their task choices to the easier task (Botvinick, 2007; Kool, McGuire, Rosen, & Botvinick, 2010). Chapter 4 appears to show the contrary: participants were biased to repeat tasks after trials high in conflict. However, there are several differences in our study and the paradigms used by Botvinick. First, participants in our voluntary task switching paradigms are instructed to choose the tasks equally often, and in Chapters 3-5 they successfully followed this instruction. On the contrary, there are no constraints on task choice in Botvinick's studies. Second, the two tasks in our studies were always associated with the same amount of conflict, whereas Botvinick's group uses tasks with unequal levels of conflict. Botvinick's studies examined trends in behavior over the course of a series of trials, whereas our studies examined trial-to-trial adjustments in behavior. It would be interesting to see whether participants in Botvinick's studies showed similar small-scale task choice biases, or whether such biases existed only early in the experiment, but disappeared once participants learned which task was associated with more effort.

Chapter 3 suggests that participants may have avoided effort by choosing the task congruent with the distracter letters more often than they chose the alternate task. Yet, when participants made congruent task choices, they switched tasks more often than when they made incongruent or neutral task choices. Further, task switches on congruent

choice trials were slower than task switches on incongruent or neutral choice trials. This suggests that exerting less effort while choosing the task was associated with more effort during task performance than when more effort was made while choosing the task. One way to test this claim would be to use P3 amplitude to track mental effort, as was similarly done in Chapter 5. One possibility would be that the P3 associated with the target is larger following congruent versus incongruent or neutral choices.

Future studies may examine the brain networks involved in voluntary task selection. There has been a recent focus on demonstrating that the frontal cortex may be organized in a hierarchy based on the level of abstraction (for a review, see Badre, 2008). More abstract processes, such as subgoaling and task switching, are carried out by rostral regions of frontal cortex, and more specific processes (e.g., representing stimulus-response associations) are carried out by more caudal regions of frontal cortex. The paradigm used in Chapter 4 could be carried out in an fMRI scanner to see if conflict in one trial was associated with subsequent activation in rostral regions of the later frontal cortex that maintain abstract goal representations.

Recently, it has been demonstrated that the medial frontal cortex (including the ACC) has a similar hierarchical organization as the lateral frontal cortex (Kim, Johnson, Cilles, & Gold, 2011). Thus, we might predict that resolving task conflict during voluntary task selection (as in Chapter 3) would be associated with activity in rostral regions of the medial frontal cortex, whereas resolving response conflict (as in Chapter 4) might be associated with activity in caudal regions of the medial frontal cortex. However, in Chapter 2, we found that the rostral subregion detected response conflict, whereas the caudal/ dorsal subregion resolved task conflict. Thus, it is unclear how different regions

of the medial frontal cortex might be involved differentially in processing task conflict

and response conflict, and future research will be needed to understand how the ACC is

involved in these processes.

Chapter 3 suggested that task choice depends on a balance of bottom-up and top-

down processes. Future studies may examine if the trade-off between bottom-up and top-

down influences on task choice depends on the strength of task-related functional

connectivity between frontal control regions and posterior sensory and association

regions. Weaker functional connectivity may be associated with congruent task choices,

and stronger functional connectivity may be associated with incongruent and neutral task

choices.

The studies in my dissertation suggest that resolving distraction during task

selection in multitasking situations leads participants to focus more on the current task,

making them more likely to continue performing a given task. This suggests that

distraction actually makes participants less likely to multitask. But would conflict or

distraction lead to a repeat bias in real-world multitasking environments? As suggested in

Chapter 1, we may use conflict to detect when one task needs more of our attention than

other possible tasks. When we are driving in a more demanding environment (e.g., a busy

highway) we focus more on the current task. However, in a situation such as this, the task

of driving has a clear priority over other possible tasks. In the current studies, the tasks

were given equal priority, and there was no reward. Future studies should examine how

manipulating relative priority or reward of tasks influences the effect of conflict on task

choice. While participants would likely show a bias of choosing the task with the higher

reward/ priority, it is unclear whether experiencing conflict during a low priority/ reward

task would lead to a repeat bias. It may be that the conflict-driven repeat bias is not strong

enough to overcome a bias towards reward. Answering these questions would provide

insight on how we manage task choices in the real world.

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