CONFLICT AND CONTROL: HOW DOES THE BRAIN REGULATE COGNITIVE

CONTROL IN THE PRESENCE OF CONFLICT?

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DISSERTATION ABSTRACT

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Cognitive control refers to the brain's ability to control attention and other cognitive functions in the service of intention-driven behaviors; moreover, it is an essential aspect in cognition. Cognitive control is commonly evaluated through the so-called conflict adaptation effect, which is revealed through trial-to-trial changes in performance after experiencing cognitive conflict. The conflict monitoring theory is a prominent theory intended to describe conflict adaptation and explain how cognitive control might be engaged in the face of conflict. A passive carryover account, originally aimed at explaining task switching and based on parallel distributed processing models, may represent a superior alternative to the conflict monitoring account. In the carryover account, passive inertia of the cognitive control state explains the trial-to-trial modulation of conflict effects. One problem with conflict adaptation is that the typical paradigms used to create conflict adaptation often include trial-to-trial repetitions that mimic the same performance pattern through priming. Conflict monitoring theory also has difficulty explaining other issues such as whether conflict adaptation is task-specific. A meta-analysis of the so-called conflict adaptation effect suggests trial-to-trial repetitions do not entirely account for conflict adaptation effects, but these effects do appear to be

task-specific. The meta-analysis also suggests the withdrawal of control is episodic

rather than temporal and conflict adaptation may be sensitive to experimental session

length. A novel eye-tracking paradigm addresses the timing of control engagement. The

results suggest dynamic regulation of attention coupled with conflict detection. This

more tightly coupled detection and regulation process in the context of conflict adaptation

is more consistent with a carryover account than what would be expected from the

conflict monitoring theory. A subsequent eye-tracking paradigm further supported that

trial-to-trial modulations of control are generally more consistent with a carryover

account than they are with the conflict monitoring theory. Overall, the empirical

evidence points toward a carryover model of cognitive control.

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CHAPTER I

LITERATURE REVIEW

Our cognitive system must regulate conflict to mitigate the deleterious effect it can have in situations that range from something as simple as taking a new exit on a frequently used highway to taking the appropriate course of action when a warning system is activated while operating a commercial jet carrying hundreds of people. In recent years, several models have emerged that attempt to explain how we focus resources in the face of conflict. The main goal here is to discuss these models and the evidence they seek to explain, and to discuss the theoretical and empirical gaps in the literature.

Defining Conflict and Control

Simultaneous perceptual inputs or simultaneously activated responses can produce ambiguity or incompatible signals in the cognitive system (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Control in this context is broadly defined as the set of processes that focus our brains' resources to limit the negative effect of conflict so we can execute goal-relevant behavior (Posner & Snyder, 1975). When the yellow light from street lamps resembles the yellow color of a traffic light, the street lamps pull your attention away from the task-relevant traffic lights and may even trigger a response to slow down. Therefore, control must be exerted to ignore the task-irrelevant street lamps and focus on the relevant traffic signals to carry out the appropriate actions for driving.

In the laboratory, control and conflict are typically studied using experimental paradigms where two or more pieces of information are presented simultaneously, or very close in time, and that also compete for shared processing resources and/or are

associated with competing responses (e.g., Eriksen & Eriksen, 1974, MacLeod, 1991; Simon, 1969; Simon & Rudell, 1967; Stroop, 1935). Control over the conflict is required to reduce the influence of the irrelevant pieces of information, which allows the relevant piece to be used appropriately (Stroop, 1935). A high-conflict condition is compared to a low conflict condition in which no stimuli with mutually incongruent responses are presented. In principle, conflict could also arise strictly at the stimulus level without involving conflicting response tendencies, such as when a sudden stimulus onset results in exogenous capture of attention (e.g., Theeuwes, 1991). However, the literature on conflict adaptation has not extensively addressed this type of perceptual conflict. Therefore, the conflict referred to in this work is response conflict until Chapter V, where conflict is explicitly on the stimulus level.

To discuss cognitive control this paper will begin by describing the basic laboratory operationalization of cognitive conflict. These paradigms create conflict and therefore require control to manage it. The control is revealed through the modulation of conflict between transitions of conflict episodes. Models of cognitive control must explain the conflict effect and the modulatory effects that are used to indicate the presence of cognitive control. Gilbert and Shallice's (2002) parallel distributed processing (PDP) model of task switching, Botvinick, Braver, Barch, Carter, and Cohen's (2001) conflict monitoring model, and Holroyd and Coles' (2002) reinforcement learning model all provide explanations for behavioral and neural-level responses to conflict. The neural-level results are more easily understood in the context of the models and are therefore discussed in the next section.

Methods of Assessing Conflict and Modulations of Conflict

The various methods of studying cognitive conflict and control typically work by creating conflict on the level of incoming stimuli or outgoing response. For this discussion, the distinction between stimulus and response conflict is not as important as the discussion explaining how cognitive control resolves conflict on either the stimulus or response level. The Stroop, flanker, and Simon tasks are by far the most commonly used to create - and thus - study conflict.

The Stroop task presents a word in either the same or different font color than what the word spells out, such as "R-E-D" printed in green (see Figure 1c). The color of the ink and the text of the word are separate dimensions that vary independently, and they are possible sources of information to assign to separate text or color tasks (Stroop, 1935). Incongruence between the font color and the text of the word produce an increased need for control in two ways: (1) the ambiguity in defining the relevant dimension requires relatively more control than an unambiguous congruent word, and (2) relative to color naming, the greater automaticity of the word reading produces increased conflict for the color naming relative to the word reading (Cohen, McClelland & Dunbar, 1992; McCleod, 1991).

In the Eriksen flanker task (e.g., Botvinick, Nystrom, Fissel, Carter, & Cohen, 1999; Eriksen & Eriksen; 1976; Funes, Lupiáñez, & Humphreys, 2010; Gratton, Donchin, & Coles, 1992; Mayr, Awh, & Laurey, 2003) stimuli are assigned to a left and right response key – typically a left or right pointing arrow but sometimes letters or digits (Eriksen & Eriksen, 1976). Each trial consists of a target presented centrally while flanked by irrelevant distractors to its left and right. The task is to simply press the key

associated with the central target and ignore the flankers (see Figure 1a). An incongruent trial would be one where the target requires a different response than the flankers while a congruent trial would be one where both the target and flanker are associated with the same response.

The Erikson flanker task creates cognitive conflict with spatial flankers, but distractors that are presented very close in time rather than close in visual space also produce a similar conflict effect (Dehaene, et al., 2003). Dehaene et al. (2003) presented congruent or incongruent prime-flanker stimuli temporally close (e.g., 40-70ms) to a target. The incongruent temporal prime-flankers produced slower response times relative to congruent temporal prime-flankers. This so-called temporal flanker effect is a similar cognitive conflict effect to the spatial congruent effect typically observed in the Eriksen flanker task.

The Simon task (Simon, 1969; Simon & Rudell, 1967) induces cognitive conflict by presenting a stimulus such as a color patch or color shape that is arbitrarily associated with either a left or right response either on the left or the right side of the screen (see Figure 1b). Unlike the Stroop or Eriksen flanker tasks, the cognitive conflict in the target in Simon tasks does not come from the presence of distractors; rather, the conflict is created purely from the congruence, or lack of congruence, between the left or right correct response associated with the stimulus and the irrelevant location of the target in the left or right visual field where the stimulus is presented.
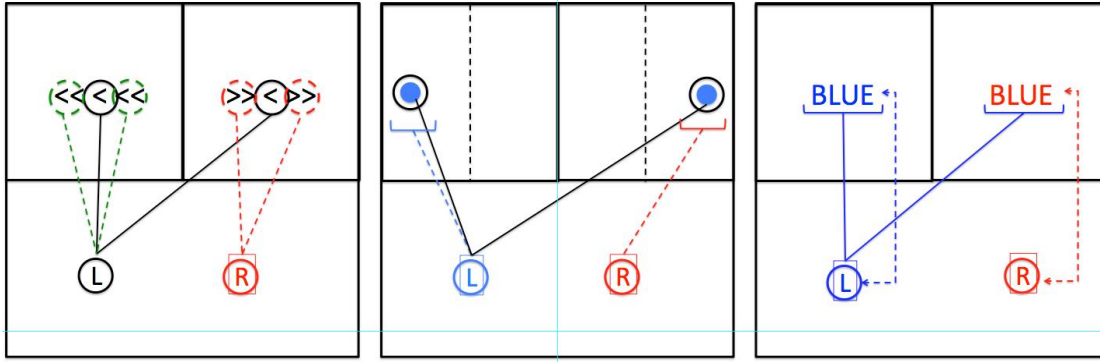
Figure 1. From left to right, (a) sample trials in an Eriksen flanker task, (b) Simon task, and (c) Stroop task. The distractor stimuli are shown in the dashed lines and targets in the solid lights. The congruent/non-conflict and incongruent/conflict trials in the left and right boxes, respectively, show how response conflict is created through the distractors.

Conflict and modulation of conflict.

In all of the above-described paradigms, conflict effects are defined as the differences in response times (RT) or accuracy between the high conflict (i.e., incongruent) and the low conflict (i.e., congruent) condition. The magnitude of the difference is assumed to reflect the amount of conflict and therefore the amount of control required to overcome the high conflict (i.e., incongruent) state compared to the low conflict (i.e., congruent) state.

The trialwise conflict adaptation effect.

Gratton, Coles, & Donchin (1992) are commonly credited as the first to report what they called the sequential congruency effect (SCE) in a flanker task, which is the difference in response times (RTs) or error rates between congruent and incongruent trials that follow an incongruent or congruent trial. RTs and error rates are lower in an incongruent (I) trial that was preceded by an incongruent (I) trial (trial II) compared to incongruent trials that are preceded by a compatible (C) trial (CI trials) (see Figure 2). Moreover, the conflict effect for sequences preceded by incompatible trials (i.e., II-IC) is

smaller relative to the conflict effect for sequences preceded by congruent trials (i.e., II-IC > CI-CC) (see Figure 2). The typical conflict adaptation effect is indicated through a statistically significant interaction between conflict on the current trial (N) and the N-1 trial (Gratton et al., 1992; Ullsperger, Bylsma, & Botvinick, 2005). Gratton et al. (1992) postulated that the trialwise conflict adaptation effect reflects the fact that conflict triggers the recruitment of control processes, which in turn leads to less susceptibility to conflict on the next trial.
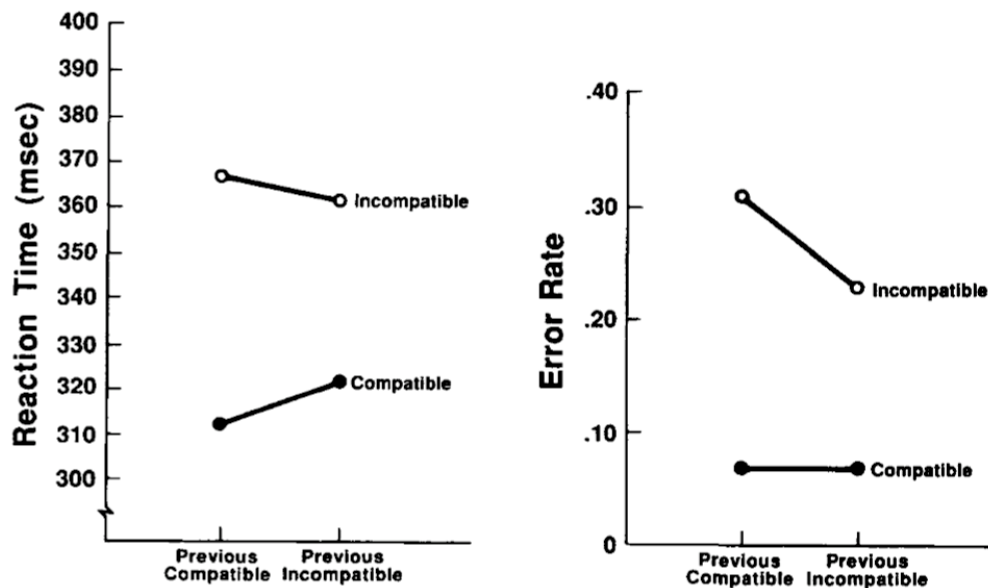
Figure 2. The conflict effect produces a reduction in RT (left) and error rates (right) for incongruent trials that follow an incongruent trial and the slowing in RT for incongruent trials following a congruent trial (Gratton, Coles, & Donchin, 1992).

Blockwise adaptation effect.

Sustained modulation of conflict also occurs on a slower scale than on the trial-to-trial modulation of the trialwise conflict adaptation effect. This sustained effect is sometimes referred to as the proportion congruency or the context effect. We refer to it here as the blockwise conflict adaptation effect in contrast to the trial-by-trial modulation.

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This effect can be observed when the proportion of incongruent relative to congruent or neutral trials is manipulated (Crump, Gong, & Milliken, 2006; Jacoby, Lindsay, & Hessels, 2003; Tzelgov, Henkik, & Berger, 1992). Typically, the conflict effect becomes larger when the frequency of incongruent trials is lower than non-incongruent and smaller when congruent trials are a higher proportion of the total trials than non-incongruent trials (Crump et al., 2006; Lindsay & Hessels, 2003; Mayr & Awh, 2009; Tzelgov, et al., 1992). This happens because as the number of instances of conflict from incongruent trials increases the conflict effect itself becomes smaller.

Similar to the trialwise conflict adaptation effect, the blockwise conflict adaptation effect has been argued to emerge from a cognitive control mechanism that modulates the interference from an irrelevant task (Jacoby et al., 2003). The logic behind this conclusion is simply that any reliable performance modulation in the conflict effect that is sensitive to the probability of conflict must come from some type of cognitive control. For example, Jacoby et al., (2003) attributed the blockwise conflict adaptation effect to reinforcement of task-goals.

Post-error slowing.

The final indicator of conflict that is discussed here is a modulation effect following errors. Post-error slowing is unlike the previously mentioned measures of control because it does not emerge as a direct result of conflict. Rather, it reflects the slowing of RTs immediately following an error response (Rabbitt, 1966; see also Laming, 1968; Verguts, Notebaert, Kunde, & Wühr, 2011). Rabbitt (1966) originally attributed post-error slowing to a conscious shift in cognitive control after participants noticed they

made a mistake. Because of the observation that post-error slowing occurs after noticing a mistake, it is useful for providing insight about the role consciousness plays in control.

Summary.

Each one of the above-described effects seems to capture the cognitive system's response to an impediment to goal-relevant behavior (i.e., conflict or errors). Thus, these empirical phenomena provide a test bed for theories of cognitive control that try to explain how our cognitive system regulates its activity to counteract such impediments.

Models and Theories of Cognitive Control

One goal and challenge for models and theories of cognitive control is to explain how cognitive control is engaged, modulated, and eventually recedes when it is no longer needed. The goal of most theories of control should be to "banish the homunculus" (Monsell & Driver, 1998). The homunculus here stands for the idea of some kind of central control agent (e.g., Atkinson & Shiffrin, 1968), which presents a problem of recursive logic: if a control system is required to engage and modulate attention or other resources, then what controls the controller? Models of control therefore have two broad requirements: first, the model must provide a plausible mechanism for how cognitive control engages and withdraws without a central control agent, and second the model must account for the observed qualities in the modulation of the conflict effect. Essentially all models of cognitive control have been formulated with the broad framework of Parallel Distributed Processing (PDP) models. Thus, we begin by presenting the basic assumptions of these types of models.

As a starting point we use Gilbert and Shallice's (2002) PDP model of task switching, which is a direct extension of the earlier Cohen, Dunbar, and McClelland's

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(1990) model of the Stroop task. Even though the model is more recent and was intended to explain task-switch costs, it is conceptually simpler and therefore provides a helpful framework for understanding Botvinick et al.'s (2001) conflict monitoring model, which will be the main focus of the paper. The conflict-monitoring model is the main focus because it has received a large amount of attention in the literature and is explicitly designed to describe control and conflict. Holroyd and Cole's (2002) reinforcement learning model also can account for many of the same behavioral and neural effects of conflict; more on the neural correlates of conflict will be discussed later. Moreover, the reinforcement-learning model also provides an alternative explanation to key physiological structures that are central to the conflict monitoring theory.

Parallel distributed processing models.

In parallel-distributed processing (PDP) models, information processing occurs through flow of activation within a network of interconnected simple processing units (Cohen, Dunbar, & McClelland, 1990; Gilbert & Shallice; 2002; see Figure 3). The activation begins at the input units that receive sensory stimulation. From the input units the activation spreads to all connected intermediate units, which are connected to all of the output units. A response is triggered when the output units' activity surpasses a predefined response threshold. In addition to input and output units these models also include task demand units. The task demand units represent the endogenous control element in the system. The task demand units bias the signals from the input units based on current task demands (e.g., name the color of the word in the Stroop task). When multiple inputs activate multiple output units, the task demand units modulate the signal from the input layers based on the current goal.

In the case of the Stroop task both color and word information are perceived simultaneously and registered in the input units (Gilbert & Shallice, 2002). This activation spreads to the output units. When the color information and word information are incongruent the system must bias the activation toward the direction of the goal-relevant task. The task demand units are the mechanism that biases the spread of activation away from the irrelevant dimension and toward the relevant dimension.
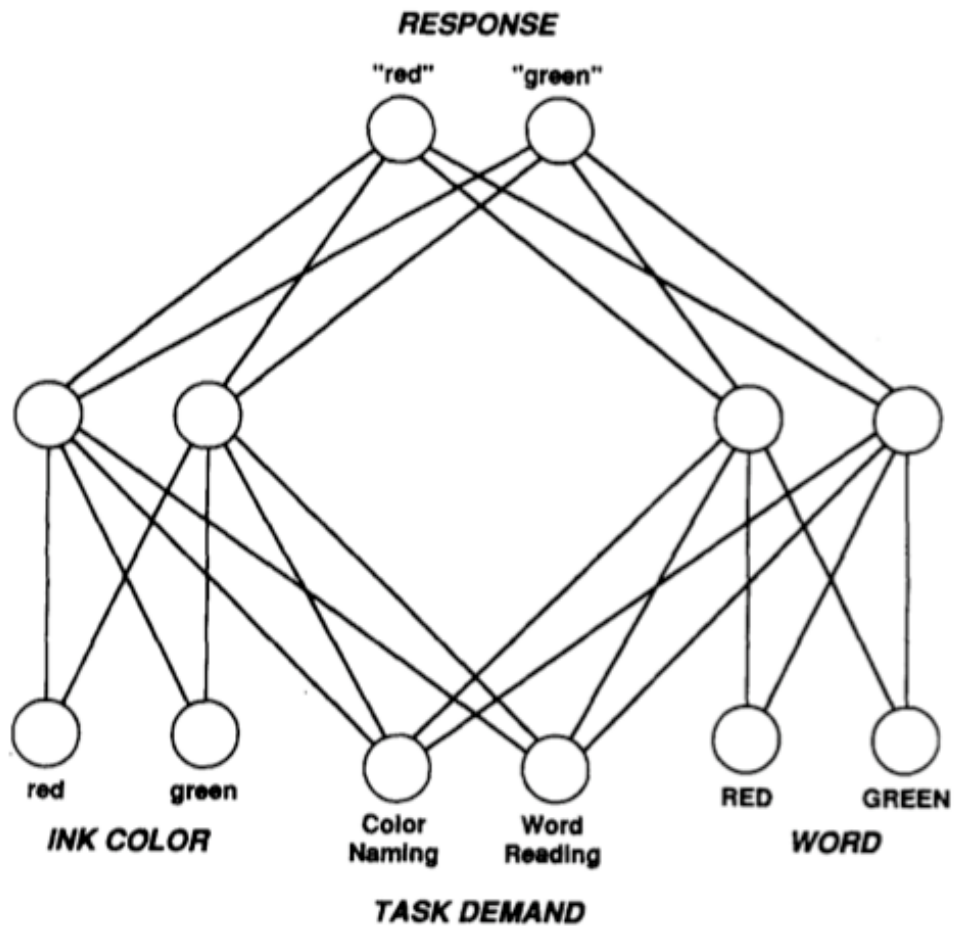
Figure 3. Cohen, Dunbar and McClelland's (1990) parallel distributed processing model showing the connections between the response layer, stimulus layer, and task demand units, which are all interconnected through the intermediate layer.

Gilbert and Shallice model: Adaptation without active regulation.

The Gilbert and Shallice (2002) model was originally designed to describe how task switching is executed; however, it can also be applied more generally to trial-to-trial conflict modulation effects. The Gilbert and Shallice PDP model features an additional number of inputs and output nodes from the Cohen et al. model and modifies the wiring between layers of the model to allow output layers to send information between task output modules. The Gilbert and Shallice model uses three colors and three response inputs that create six total inputs for word and color information in the Stroop task (see Figure 4). Additionally, the Gilbert and Shallice model contains a task-demand unit, which indicates which task is to be performed (i.e., supplies top-down information) and is also directly connected to stimulus layers for bottom-up activation.
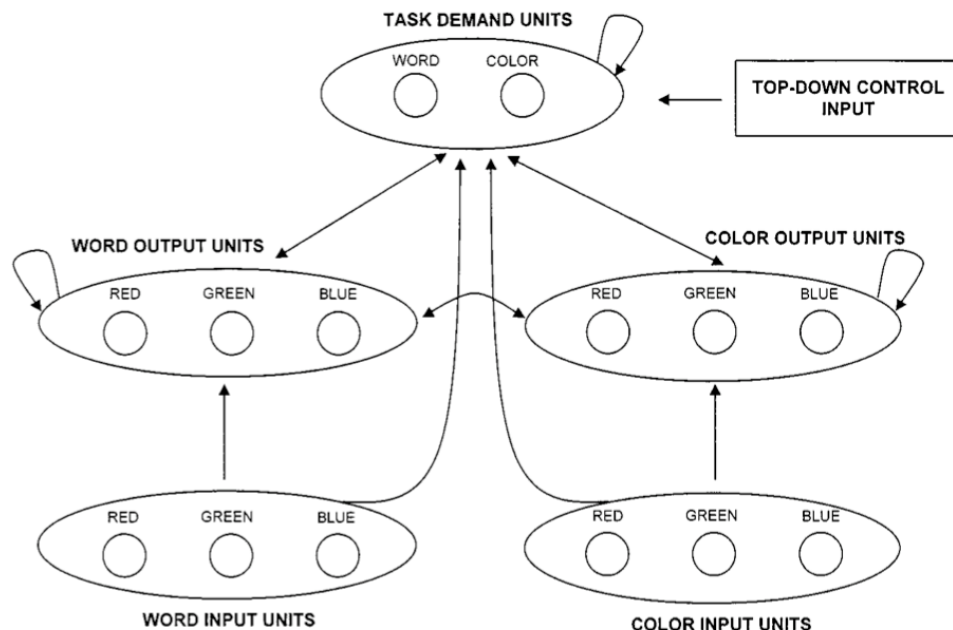
Figure 4. Gilbert and Shallice's (2002) model of cognitive control showing separate units for input, output, and task demands with reinforcing feedback in the output and task demand units.

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Most critically and different from the Cohen et al. (1990) model, the task demand unit has settings that passively carry over to the current trial from the previous trial. The carryover aspect of the model was intended to accommodate the data around so-called task-set inertia that suggests task-set activation on each trial carries forward the activation and inhibition from one trial to the next trial (Gilbert & Shallice, 2002; see also Allport & Wyllie, 2000). For example, if a task was inhibited on the previous trial, then it will remain inhibited to some degree on the current trial. This quality of the model also allows it to explain trialwise conflict adaptation by passively carrying over control settings that predispose the system to be set for the same level of conflict in the immediate future. Interestingly, the model achieves such adaptation phenomena without any active regulation or monitoring of conflict. This sets it apart from the models discussed below which do assume some kind of active monitoring process. It therefore serves as a kind of baseline model. Theorists who postulate active control and monitoring would need to provide evidence that such assumptions are in fact necessary to account for the observed effects.

The nature of this model configuration means the control settings that carry over from one trial to the next would be task-specific because task demand units for a particular task initiated the control settings. This fact creates clear predictions of expectations regarding the modulation of conflict when tasks change across trials – modulation should not be observed across task boundaries. On task switch trials the switched-to task set would have residual inhibition while the just-abandoned set would have residual activation. This fact could eliminate any conflict modulation or even produce a reverse conflict adaptation effect across task boundaries. This is for the same

reason that task switches in the Stroop task show asymmetric switch costs: larger switch costs when abandoning the dominant, reading task (Allport & Wyllie, 2000). Gilbert and Shallice's model offers no clear prediction about post-error slowing. However, one might speculate that the model can explain post-error slowing as the result of resetting the task-demand units after an error.

Conflict monitoring model.

The key component of Botvinick et al's (2001) conflict-monitoring model beyond the Gilbert and Shallice (2002) and the Cohen et al. (1990) model is the addition of an active conflict monitoring unit, which regulates cognitive control through a feedback loop between the task demand units and the conflict monitor (see Figure 5). The modulation of control comes from the conflict-monitor that connects the response units to the task-demand units. The conflict "measures" the amount of conflict between response units, and then the monitor passes a modulatory signal onto the task demand units, which provides more or less weight to activation on the level of the task-demand units. Therefore, control is still implemented through task-demand units as it is in the other models, however it is modulated, engaged, and withdrawn through a relatively simple feedback loop driven by the conflict-monitoring module.

Botvinick et al. (2001) hypothesized that the anterior cingulate cortex (ACC) carries out the conflict monitoring; additionally, the task demand units are located in the prefrontal cortex (PFC) that will allow the reduction of conflict through attention (Botvinick, et al., 2001; Botvinick, Cohen, & Carter, 2004; Botvinick, Nystrom, Fissel, Carter, & Cohen, 1999). Therefore, conflict at any given moment will be detected by the ACC, and then in reaction to the presence of conflict it will signal task demand units in

the PFC to engage attention toward task-relevant stimuli, which results in a reduction of

the negative effects of conflict.
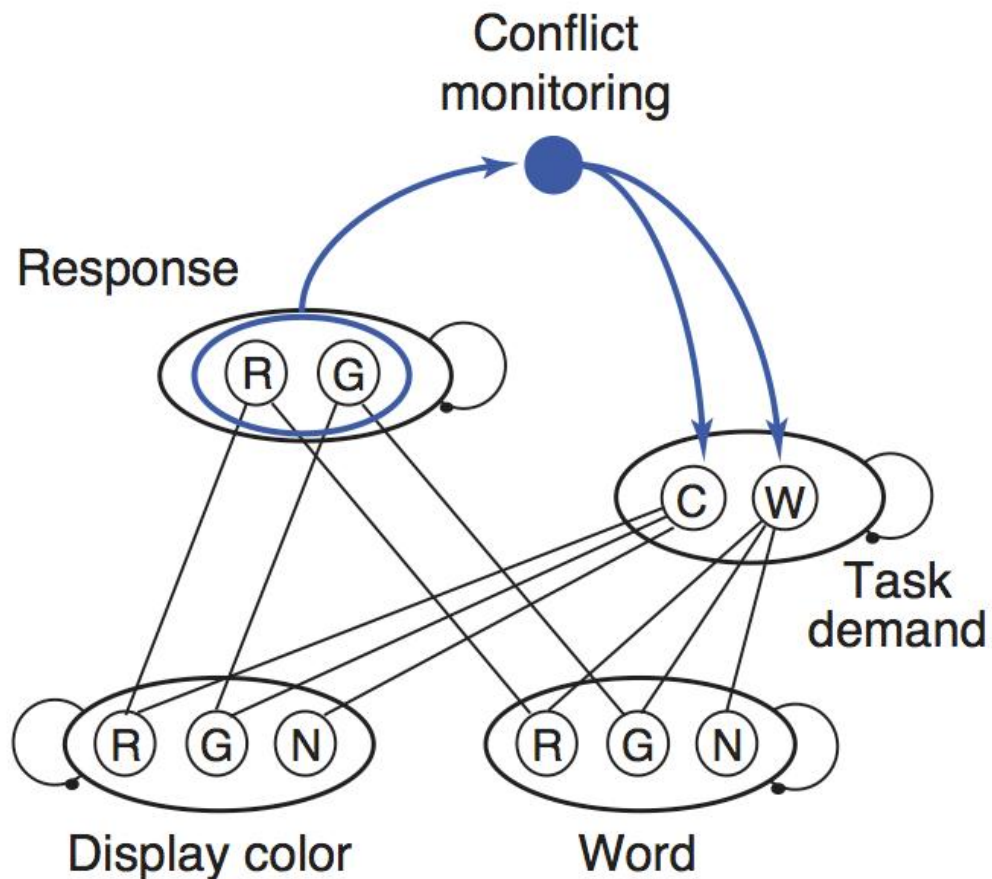
Figure 5. The conflict monitoring model showing the input and output notes and the connection between the conflict monitoring module to the response units and to the task-set units with the direction of information shown with arrows (Botvinick, Cohen, & Carter, 20014).

Botvinick et al. (2001) propose the conflict monitoring as a general mechanism

monitoring for all conflict in the cognitive system. Therefore, the control settings created

from conflict should persist or withdraw depending on the amount of conflict detected

from one episode to the next, regardless of the task (Cho, Orr, Cohen, & Carter, 2009).

Unlike the Gilbert and Shallice (2002) model the conflict monitoring model's modulation comes through the feedback loop driven by the detection of any type of conflict detected within the cognitive system regardless of task.

The conflict-monitoring model accounts for block level context effects in the same way as the trial level conflict adaptation effect and post error slowing: an increased frequency of incongruent trials (i.e., more conflict) leads to an increase in cognitive control that subsequently reduces interference on incongruent trials and therefore the congruency effect as well (Botvinick et al., 2001). Moreover, the conflict-monitoring model assumes the mechanism that leads to trialwise reduction in the congruency effect is the same monitoring and feedback network that leads to the trialwise adaptation effect – the ACC and PFC network.

Holroyd & Coles' reinforcement learning model.

Holroyd and Coles' (2002) error-related negativity (ERN) and learning model is a model designed to account for cognitive control through reinforcement learning and error processing. Their model postulates that a control filter housed in the ACC acts as the main switching station and pass-through for motor signals from various motor control areas to the motor cortex (see Figure 6). The control filter/ACC learns which controller signal is appropriate through a midbrain mechanism that utilizes dopamine and then filters irrelevant controller signals from relevant controller signals to link the appropriate inputs to the appropriate outputs. This model explains modulation as the result of learning episodes that train the system for correct stimulus and response pairings.

In the Holroyd and Coles' model the various modulatory effects are all explained as learning through this network between midbrain and ACC mechanism. The trialwise

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conflict effect is the result of learning appropriate pairings. Early in the learning phase, conflict trials present negative feedback that increases efficiency in resolving irrelevant input signals from relevant ones. The blockwise effect is the result of a larger or smaller number of conflict episodes that equate to learning episodes. Holroyd and Coles (2002, p. 683) state, "During the early stages of learning, anterior cingulate motor areas appear specifically to use reward and error information to identify and select appropriate behaviors." The post-error slowing is therefore essential to the model because it should be a reflection of learning activity. Consistent with their account, post-error slowing is associated with error-related negativity (ERN) measured by EEG (Dehaene, Posner, Tucker, 1994). This model nicely accounts for the three main modulatory effects and places them in a physiological context that facilitates model testing.

The model integrates a larger body of literature on reinforcement learning rather than creating a model specifically aimed at cognitive control. The reinforcement-learning model also comes with clear predictions regarding the specificity of modulation within tasks and modulation of cognitive control over many trials or episodes. Because the ACC is focused around task specific input and output pairings, the conflict from one task should not generalize to stimulus-response pairings for other tasks. Moreover, the more trials the system encounters, the greater the strength between the pairings, which should result in a smaller trialwise conflict effect over time.
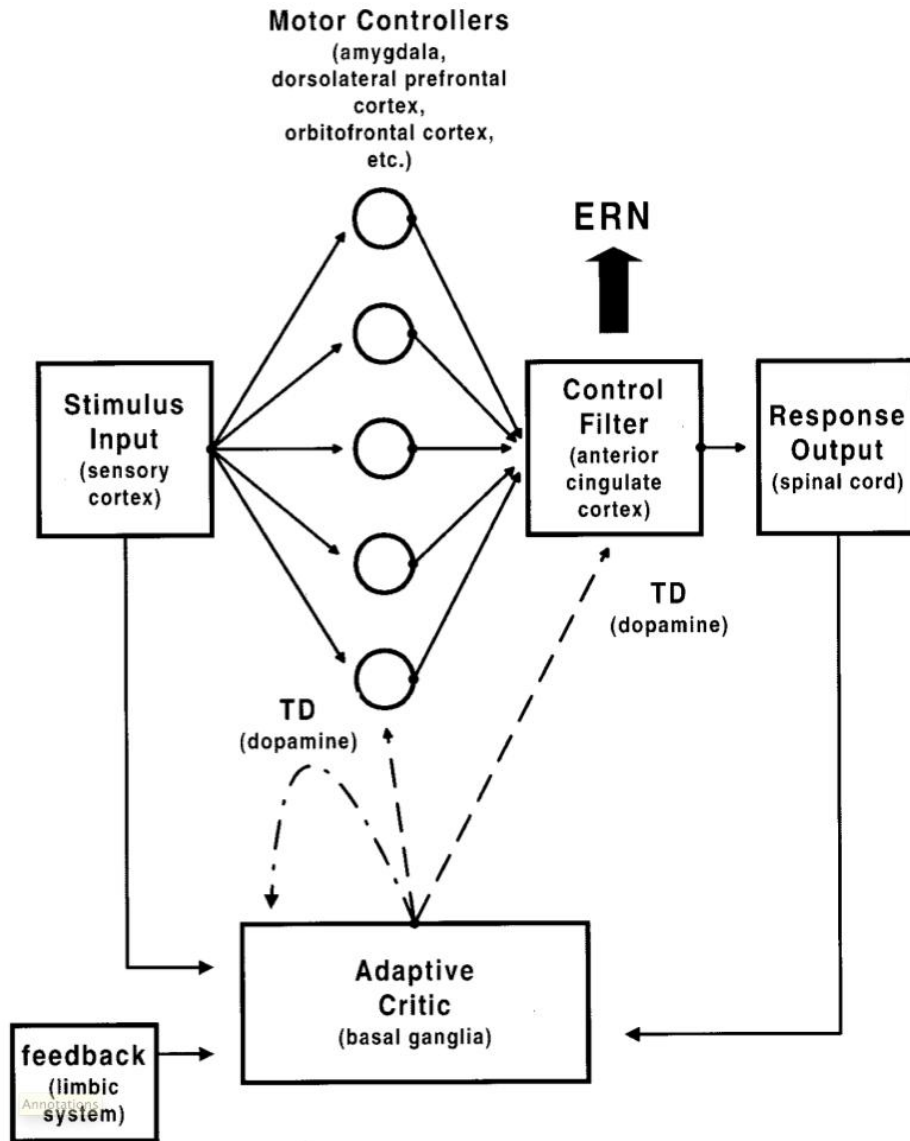
Figure 6. Learning model explaining ERN activity and learning (Holroyd & Coles, 2002)

Model summary.

All of the above models have the ability to account for performance modulation; however, the mechanisms for adjustments in the PDP models engage control through task-specific mechanisms. In contrast, the conflict-monitoring model accounts for

modulation through a general conflict monitor connected to task-specific units. Gilbert and Shallice's (2002) model was developed to account for task switching, but their architecture is suited to account for the control modulation. Holroyd and Coles' PDP model was designed to account for error-modulation, but it too can be extrapolated to explain more than post-error modulation. Botvinick et al., (2001) tested the conflict-monitoring model against simulated data to provide an explanation for the trialwise conflict adaptation, post-error slowing, blockwise effects, and neural correlates of conflict and attention in the anterior cingulate cortex (ACC) and prefrontal cortex (PFC), respectively. These simulations against behavioral and physiological observations, which appeared in the literature prior to the conflict-monitoring model, combine to provide the most unified model of control that accounts for a broad range of modulatory effects; all without implicitly or explicitly invoking the power of a homunculus. Following the proposal of the conflict-monitoring model a large number of empirical studies tested the model against its assumptions using both behavioral and neural-level effects (e.g., Kerns, Cohen, MacDonald, Cho, Stenger & Carter 2004; Mayr, & Awh, 2009; Mayr, Awh, & Laurey, 2003; Ullsperger, Bylsma, & Botvinick, 2005). This work has empirically confirmed some aspects in the conflict-monitoring model, but it has also revealed several problems with the model. In these cases the models by Gilbert and Shallice (2002) and Holroyd and Coles (2002) provide potential theoretical alternatives. In the end, the questions that emerge are: To what degree is the original conflict-monitoring model correct, can it be saved through adjustments or corrections, or does it need to be replaced by one of the theoretical alternatives?

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Physiological and Neuroimaging Evidence

Understanding the functions carried out by brain structures and their relationship in functional networks improves the ability to map models onto physiology and at times for physiology to motivate questions around the nature of cognitive control. In particular, the ACC and dorsolateral PFC areas are associated with aspects of control (Allport, 1987; Botvinick et al., 2001; D'Esposito, Detre, Alsop, Shin, Atlas & Grossman, 1995; Kerns, 2004; Posner, Peterson, Fox, & Raichle, 1988; Posner & Raichle, 1994).

Role of anterior cingulate cortex in control.

Research targeted at understanding how cognitive control is modulated and engaged has identified the ACC cortex as a key brain area associated with cognitive control (e.g., Allport, 1987; Barber & Carter, 2005; Botvinick, Cohen, & Carter, 2004; Botvinick, Nystrom, Fissel, Carter & Cohen, 1998; Bush, Luu & Posner, 2000; Carter, Braver, Barch, Botvinick, Noll, & Cohen, 1998; D'Esposito et al., 1995; Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004; Paus, Petrides, Evans, & Meyer, 1993; Posner, et al., 1988; Posner & Raichle, 1994). The ACC is found just anterior to the medial wall of the frontal cortex (see Figure 7). It is divided into ventral and dorsal sections that each are associated with emotion and cognitive processing, respectively (Bush, Luu, & Posner, 2000). In a meta-analysis of cognitive control data, Bush et al. (2000) demonstrated that the dorsal ACC is frequently activated in experiments that require cognitive control (see Figure 8). Both the reinforcement learning and the conflict-monitoring models indicate the dorsal ACC as a brain region with specific roles in cognitive control. However, between these two models the purported function carried out by the ACC is significantly different.
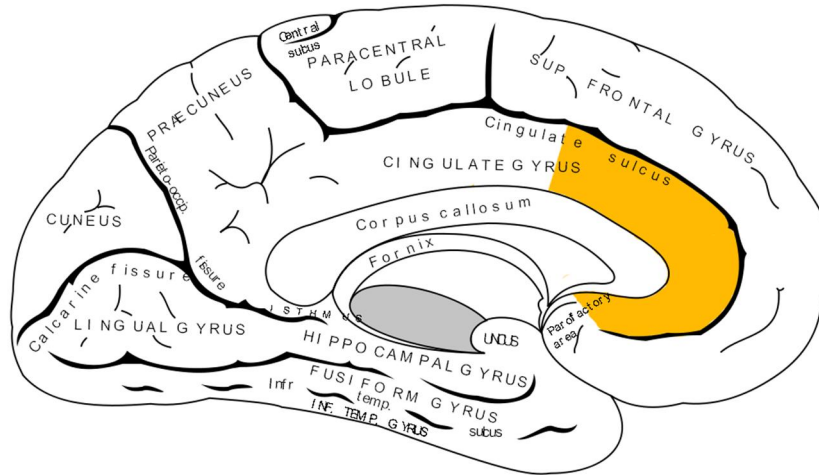
Figure 7. A medial view of the brain with the area in yellow showing the anterior cingulate cortex, which is located anterior to the medial wall of the frontal cortex. The ACC is hypothesized to be where the conflict monitoring functions are carried out.
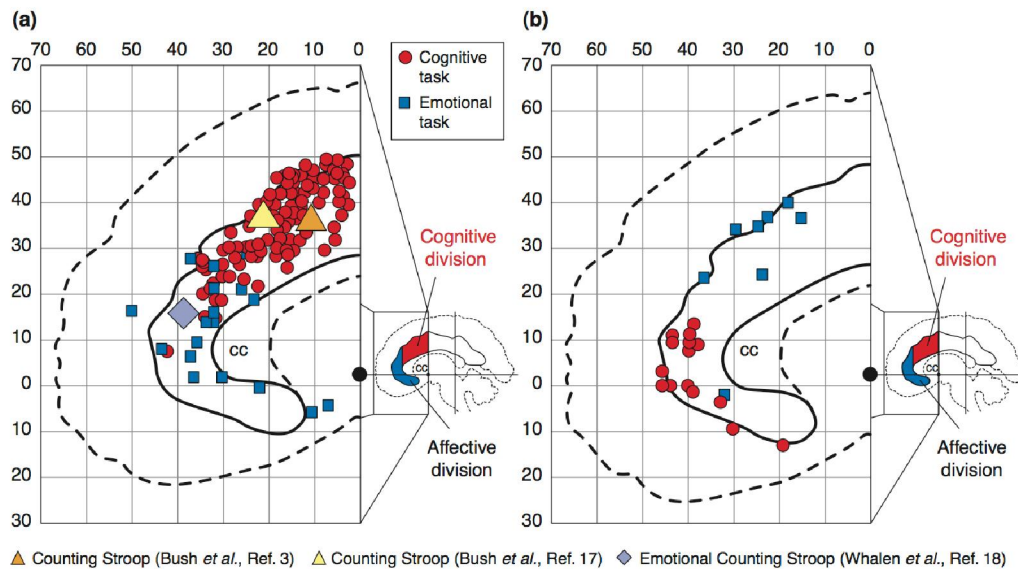
Figure 8. Meta-analysis of brain imaging studies showing a medial view of deactivations (a) and activations (b) in the ACC associated with cognitive tasks (red circles) and emotional tasks (blue squares) (Bush, Luu, & Posner, 2000).

Botvinick et al. (2001) and others hypothesized that the ACC is relevant for monitoring conflict (Botvinick et al., 2001; for review see also Carter & van Veen, 2007). The dorsal area in particular is the region associated with processing the broadly

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categorized "conflict" (Botvinick et al., 2001). According to Botvinick et al. (2001) conflict could be from two simultaneously activated responses, selection among many equally permissible responses, or the commission of errors. The two main sources of evidence for ACC function come from EEG source localization and functional neuroimaging work using positron emission tomography (PET) or fMRI.

As the result of electrophysiological work using source localization of the error-related negativity (ERN), hypotheses about the role of the ACC have emerged (Dehaene et al., 1994). The ERN is a negative peak of electrical activity 50-100 ms following an error. Using a 64-channel electrode cap Dehaene et al. (1994) observed ERN following errors. Source localization determined the majority of electrical activity was coming from the midline in the prefrontal cortex, which is within the general area of the ACC. Due to the poor spatial resolution of EEG, the work was suggestive but by no means conclusive.

Some of the earliest functional neuroimaging data that associated response conflict with activity in the ACC with high spatial resolution was obtained using (PET). Pardo, Pardo, Janer, and Raichle (1990) found that interference during a Stroop task was associated with activation in the ACC. The ACC was not simply associated with interference, but the amount of activation in the ACC predicted the size of behavioral conflict effect on a given trial. Pardo et al. (1990) interpreted the association between conflict and ACC activity to possibly reflect attention processes that are essential for response selection. The association between conflict and ACC activity is very important, but there is more than one way to view this relationship.

The conflict monitoring theory is further supported through associated activity in the ACC and PFC, specifically, the inter-trial correlation between ACC activity on one

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trial and PFC on the following trial (Kerns, 2006; Kerns, Cohen, McDonald, Cho, Stenger, & Carter, 2004). Kerns and colleagues have shown that activation associated with conflict on a given trial predicts activation in the PFC on the subsequent trial. The association between conflict and ACC activity and the inter-trial association between ACC and PFC activity nicely fit with the conflict monitoring theory.

In contrast to the conflict monitoring theory, Holroyd and Coles (2002) promote the so-called selection for action theory of ACC function (see also Allport, 1987; Paus et al., 1993; Pardo, et al., 1990; Posner & Raichle, 1994). In the selection for action account the ACC is charged with creating the mappings between stimuli and responses. Pardo, et al. (1990) demonstrated through PET imaging that ACC activity is associated with the number of inputs and the difficulty of pairing inputs with outputs. From this view the incongruent trials are associated with more ACC activity because they present more incoming response information and therefore greater difficulty of pairing the correct input with the correct response output.

A point of divergence between the conflict monitoring theory and Holroyd and Coles's model is the nature of the ERN. The conflict monitoring theory postulates the ACC simply monitors conflict and the ERN is a product of conflict detection (Botvinick et al., 2001, Carter & van Veen, 2007). The so-called correct ERN is consistent with the ACC in this monitoring role (e.g., Van Veen & Carter, 2002; Vidal, Hasbourcq, Graperon, & Bonnet, 2000). Van Veen and Carter (2002) demonstrated through source localization with EEG that activity in the fronto -central scalp region was associated not only with errors (i.e., ERN), but also following correct, high-conflict responses. However, the

correct ERN may emerge from activity not associated with conflict monitoring activity (Coles, Scheffers, & Holroyd, 2001; Falkenstein, Hoorman, Christ, Hohnsbein, 2000).

The conflict-monitoring theory has a large amount of support for ACC as a conflict monitor and the ACC's relationship with the PFC. Evidence from EEG, PET and fMRI are consistent with the predictions made by the conflict monitoring theory. However, these data are also consistent with the so-called selection for action account proposed by the reinforcement-learning model (Holroyd & Coles, 2002). The conflict monitoring theory presents an account of cognitive control that is essentially regulated by a simple conflict-monitoring module that is connected to both response areas and task demand areas. The ACC is connected to several areas of the brain including motor areas, PFC and others (Bush, Luu, & Posner, 2000). Imaging work such as that by Kerns and colleagues (2006; 2004) demonstrate both a functional and temporal relationship between conflict associated with ACC activity and control associated with PFC activity that is consistent with the conflict monitoring theory.

Issues and problems with neuroimaging evidence.

Despite the empirical support for the ACC as the possible conflict-monitoring component, there are also some potentially inconsistent results. In particular, the variety of research that observes associations between behavior and activation in the ACC suggests that its function may be broader than only conflict monitoring. It may also be possible that the common thread between the varieties of tasks that lead to ACC activation is not conflict monitoring, but something more general.

The conflict monitoring theory proposes that a conflict detection signal originating from the ACC triggers cognitive control activity in the PFC. One of the

strongest pieces of evidence in support of the conflict monitoring theory and also the role of the ACC and relationship between it and PFC areas is the correlation between ACC activity on an N-1 conflict trial and the PFC activity on a current (i.e., N) conflict trial (Kerns, 2006; Kerns et al., 2004). Kerns and colleagues (2004) reported evidence for an inter-trial correlation between ACC activation in response to Stroop conflict on the previous trial and PFC activation on the current trial. However, these data must be viewed cautiously because the reported correlations did not take into account residual activation within brain areas. The key piece of evidence Kerns et al. presented was the correlation between ACC and PFC between conflict trials, but they did not report the correlation between ACC on the N-1 trial and ACC on the N trial or the same for PFC activity. It is reasonable to predict that activity within areas will correlate to itself between trials. For example, if the previous conflict trial has a high amount of PFC activation and ACC activation, then it is possible that PFC activation on trial N-1 will correlate with PFC activation on trial N. Similarly, if ACC activation is correlated to PFC activation within trials and also with itself between trials, then N-1 ACC activation will predict PFC activation on trial N. Therefore, because the activity within the two areas correlates to themselves between trials, ACC activity is also likely to correlate with PFC between trials. Kerns et al. (2004) did not report the partial correlation between ACC on the N-1 trial and PFC on the N trial after taking into account the within-area, between trial correlations.

In a later study Kerns (2006) replicated the same findings observed in Kerns et al. (2004) but using a Simon task. In Kerns (2006) the inter-trial correlations were partial correlations that removed the activation explained by inter-trial within brain area

correlations: "One set of partial correlations controlled for activity in a brain region also activated by response conflict. The other set of partial correlations controlled for baseline activity" (Kerns, 2006, p. 401). Despite the elimination of inter-trial within brain area correlations, the overall pattern of findings was the same as Kerns et al. (2004). These data suggest that some temporal relationship exists between the ACC and PFC. Due to the correlational nature of neuroimaging it is impossible to say conclusively that the relationship is the one hypothesized by the conflict monitoring theory, but it is consistent and suggestive with the ACC being a general conflict monitor and connected to the PFC in a feedback loop.

Botvinick et al. (2001) hypothesized that the common factor in ACC activation is a general reaction to any form of response conflict. This includes errors of commission, simultaneously activated responses, overcoming prepotent responses, or selecting one response from a large set of equally good responses. This means that the ACC and PFC should be associated with all forms of conflict in this manner and are critical to resolving and adapting to conflict. The ERN is commonly asserted as emerging from the ACC (Dehaene, et al., 1994). In the case of conflict monitoring, however, ACC and therefore possibly ERN activity should be observed during correct, conflict trials as well as error trials. Consistent with the ACC as a conflict monitor, the ERN activity has been argued to also emerge on correct trials producing the so-called correct ERN (Vidal, Hasbroucq, Graperon, & Bonnet, 2000). However, this correct ERN has alternative explanations such as contamination from non-error, post-response electrical activity (Coles, Scheffers, & Holroyd, 2001), a discrepancy in an expectation comparison process (Falkenstein,

Hoormann, Christ, & Honsbein, 2000), or the ERN may not actually emerge from the ACC at all (van Veen, Holroyd, Cohen, Stenger, & Carter, 2004).

Brain lesion research with patients who have ACC damage provides mixed results with regard to the association between ACC activity and conflict monitoring. For example, Fellows and Farah (2005) observed in three patients with lateralized dorsal ACC damage and one patient with bilateral dorsal ACC damage the ability to perform a Stroop and go/no-go task, where a go or no-go signal accompanies a stimulus to indicate a response or no response trial. Moreover, the ACC damage failed to significantly affect post-error. As mentioned many times throughout this paper and supported through consensus of research, the Stroop task and also the go/no-go task require overcoming the conflict from pre-potent response, which requires cognitive control. In direct contrast to Fellows and Farah's (2005) results, DiPelligrino, Ciaramelli, and Ládavas (2007) concluded the ACC is important for adaptation to conflict because trialwise conflict adaptation was not observed in 8 patients with ACC lesions but it was observed in normal controls and in patients with PFC but not ACC lesions.

The animal literature, too, does not provide clear answers to questions regarding ACC and PFC function. Mansouri, Buckley, and Tanaka (2007) observed the ACC was not critical for adjustments to conflict in monkeys; but the PFC was important. Furthermore, cross species extrapolation may not be justified between monkeys and humans because of unknown physiological differences between the species (Cole, Yeung, Freiwald, & Botvinick, 2009).

In the conflict monitoring theory the ACC - which is thought to be the conflict monitor - is the essential link for adapting control centers in the PFC that then allow for

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efficient resolution of conflict (Botvinick et al., 2001; McDonald, Cohen, Stenger, & Carter, 2000). Both DiPellegrino et al.'s (2010) and Fellows and Farah's (2005) results are therefore very difficult to resolve in conflict monitoring theory because a lack of consistent correlations with ACC or PFC indicates that response conflict would go undetected and therefore task-relevant attention would not be engaged or could not be engaged, respectively. Fellows and Farrah's (2005) failure to observe conflict modulation in patients with ACC lesions suggests that the ACC may not perform the functions hypothesized in the conflict monitoring theory.

Another account similar to Holroyd and Coles' (2002) reinforcement learning model is a theory in which ACC activity focuses on events that signal an increased need for learning through autonomic regulation (i.e., arousal; Verguts & Notebaert, 2009). In this account the ACC is a junction for intersecting sources of signaling conflict from various brain regions. Then inputs from the ACC are then sent to the locus coeruleus (LC), which releases noradrenalin that facilitates binding and learning throughout the brain. In the so-called adaptation by binding account, the ACC is not necessary for performing and resolving conflict, but it is important for adapting to conflict and improving performance.

The adaptation by binding account also fits with previous neuroimaging evidence showing a temporal relationship between ACC activity during a conflict trial and modulated PFC activity immediately following (Kerns, 2006; Kerns et al., 2004). The inputs received by the ACC trigger the LC to release a neurotransmitter that triggers learning in active brain areas such as the PFC. In a cognitive control task the PFC should

be active given its frequent association with cognitive control (Bush, Luu, & Posner, 2000).

Summary of physiological evidence for conflict monitoring theory.

A large number of studies have identified the ACC and PFC as critical regions in cognitive control. Some of the neruoimaging evidence is consistent with the conflict-monitoring model. However, ACC is not uniformly active in cognitive control studies (e.g., Egner & Hirsh, 2005) and patients with ACC lesions do not uniformly exhibit control deficits. Also, many of the existing neuroimaging studies are subject to the same criticisms regarding the basic experimental paradigms that we will discuss in the next sections. Therefore, at this point, neural-level evidence does not provide strong empirical constraints for theories of cognitive control.

Problems, Issues, and Open Questions

The conflict-monitoring theory provides a useful framework and a parsimonious explanation for several behavioral effects and neural correlates of cognitive control. However, there are several issues with this model that pose problems for it as a theory. One of the issues with cognitive control research threatens the construct validity of the trialwise conflict adaptation effect as a measure of control. Conflict adaptation is the most heavily used and studied indicator of control and also the most debated. Regarding the conflict-monitoring model, whether or not the trialwise adaptation effect generalizes across tasks or is task-specific, directly addresses the central tenet of the conflict adaptation model that conflict monitoring is a general function. The issues with blockwise adaptation effects are less controversial, more focused on details, but do present some problems for the validity of conflict monitoring theory. Post-error slowing

is not as heavily researched as the trialwise conflict adaptation effect, but research using

post-error slowing as a way of understanding the importance of consciousness in

cognitive control provides helpful insights into the models of cognitive control.

Issues and problems with trialwise conflict adaptation.

The trialwise conflict adaptation effect is one of the most heavily studied

indicators of control. However, the trialwise conflict adaptation effect may not entirely

reflect modulation in control settings from cognitive control. Mayr et al. (2003) were one

of the first to note that the trialwise conflict adaptation effect can also be explained by

priming. Similarly, the adaptation effect can also be explained by feature integration

(Hommel, Proctor, & Vu, 2004), which adds to Mayr et al.'s priming explanation with

the theory that visual and response information are integrated into event files that speed

processing when fully repeated or alternated, but slows processing when event files are

partially repeated. Both priming and feature integration are consistent with the patterns

observed in the conflict adaptation effect, but without the need of cognitive control.

Upon closer inspection of the flanker compatibility effect, Mayr et al. (2003) noticed that

a two-stimulus flanker task confounds the probabilities of target and distractor

configurations repeating with the congruent and incongruent transitions between trials.

When trial configurations are purely random and each trial condition appears with equal

probability, half of the transitions from congruent to congruent (CC) or incongruent or

incongruent (II) will be full target and distractor repetitions. But, none of the IC or CI

trial transitions will ever contain exact target-distractor repetitions. This is a problem

because the RTs on the second trial in a CC or II sequence may be faster simply because

half of the time the target and distractor were a repeat from what was just performed on

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the previous trial. Consistent with the hypothesis that the conflict adaptation effect is the result of target and distractor repetitions and not cognitive control, the interaction between congruency and transition types loses its significance (i.e., no adaptation effect) when the stimulus repetition trials are removed (Davelaar & Stevens, 2009; Exp. 1 Fernandez-Duque & Knight, 2008; Mayr & Awh, 2009; Mayr et al., 2003; Niewenhuis et al., 2006; Wendt, Heldmenn, Munte, & Kluwe, 2007).

In elaboration to Mayr et al. (2003), Hommel et al. (2004) further argued that the feature integration account explains conflict adaptation by the binding of stimuli and responses in so-called event files. The event files create a complete snapshot of stimuli and responses where both relevant and irrelevant elements in the environment are grouped together with any response activation made on a given trial. In this account, an incongruent trial would be faster if it followed another incongruent trial because elements of the event on the previous trial facilitate performance on the current trial. Using a Simon task with a simple color discrimination task, Hommel et al. (2004) demonstrated that transitions between full repetitions and full alternations where nothing is repeated resulted in faster performance than partial repetitions or alternations where events on the previous trial appeared on the current trial with new or different elements. Repeating events speeds processing because the elements on the previous event that were bound together simply repeat and the pre-existing binding provides a benefit. Somewhat counterintuitive, full alternations of events also speed processing because there is no interference between the binding of elements from the previous event to new elements not present in the previous event; undoing binding is costly. Thus, combinations of elements from the previous event and the current event slow processing. Hommel's

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feature integration account is consistent with Mayr, et al.'s (2003) findings with repetition benefits in the flanker task.

Subsequent follow-up of Mayr et al.'s (2003) study has had mixed success in replicating the same absence of trialwise conflict adaptation when stimuli repetitions are removed (Akçay, & Hazeltine, 2008; Akçay, & Hazeltine, 2011; Kerns et al., 2004; Ullsperger, Bylsma, & Botvinick, 2005; Verbruggen, Notebaert, Liefooghe, & Vandierendonk, 2006). In other words, the trialwise conflict adaptation effect remains to some extent even after stimulus and/or response repetitions are removed. For example, Ullsperger, Bylsma, and Botvinick (2005) used the same flanker task as Mayr el al. (2003) with the same arrow stimuli and also with digit stimuli. Using digit stimuli increased the number of target and distractor combinations, reducing the probability of exact repetitions. With both the arrow stimuli and number stimuli Ullsperger et al. (2005) observed a trialwise conflict adaptation effect even for conflict trials with stimulus alternations; however, the adaptation effect was reduced when using the digit stimuli. Kerns et al. (2004) reduced the stimulus repetition problem by using a Stroop paradigm that also increased the number of possible target and distractor combinations. Changing the number of target and distractor combinations means more variety of incongruent trial configurations and that fewer II trials will include exact target and distractor repetitions relative to paradigms with two target and distractor combinations; in addition to this, Kerns et al. (2004) eliminated stimuli repetitions from analysis. Despite the lower proportion of trials containing repetitions and the elimination of the remaining repetitions from analysis, Kerns et al. still observed a trialwise conflict adaptation effect.

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Mayr et al.'s (2003) work highlighted clear problems with the standard methodology of assessing trialwise conflict adaptation using a flanker task. One solution to the repetition problem noted by Mayr et al. (2003) is to remove repetitions from trial sequences entirely. Although removing stimulus repetitions solves one problem it can introduce another problem of contingencies in trial sequences (Mordkoff, 2012). Many studies avoid the problem of creating contingencies by removing repetitions post-hoc during analysis. Other studies such as Akçay and Hazeltine (Exp. 2, 2011) use pseudorandom sequences that carefully retain randomness without introducing sequence contingencies. In a paradigm that included both a Simon and a flanker task, Akçay and Hazeltine (2011) eliminated response repetition trials but allowed stimulus repetition trials. They still observed a reliable trialwise conflict adaptation effect for flanker transition trials and Simon transition trials even when analyses, post-hoc, excluded the stimulus repetition trials.

Dissociation between trialwise and blockwise conflict adaptation.

Both the trialwise and blockwise adaptation effects arise in conflict paradigms, but an open question and issue for conflict monitoring theory is whether or not performance adjustments that are triggered by the overall block context are emerging from the same source as trial-level adjustments. In the conflict monitoring theory the blockwise and trialwise effects are both hypothesized to come from the same control areas in the PFC through the general conflict monitor in the ACC. However, Mayr and Awh (2009) used a six-color Stroop task that reduced the frequency of trial-by-trial color and word repetitions. They excluded stimulus repetitions and failed to observe any trialwise conflict adaptation effects. But, despite the lack of trialwise adaptation there

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was still a blockwise adaptation effect. The presence of a blockwise adaptation effect in the absence of a trialwise effect suggests that trialwise and blockwise adjustments may be separate reactions to the presence of conflict. This is currently the only study to include both a trial and blockwise investigation of conflict adaptation. More work is needed to examine to what degree these two phenomena are truly dissociable.

Short-term dynamics of conflict adaptation: Inter-trial intervals.

The two competing accounts of how control is withdrawn focus on either the episodic or temporal decay of control settings. Botvinick and colleagues (2001) proposed that down-regulation of control is triggered by non-conflict episodes or events. In other words, control remains at its current state until non-conflict episodes or events are encountered and signal a withdrawal of control. On the other hand several researchers have suggested that control gradually decays over time and thus is not episodically graded, but temporally graded (Egner, Ely & Grindband, 2010; Notebaert, Gevers, Verbruggen, & Liefooghe 2006; Wühr & Ansorge, 2005).

Few studies have explicitly investigated the withdrawal of control. The conflict-monitoring model posits each new non-conflict episode signals a so-called episodic withdrawal of control. Gilbert and Shallice's (2002) carryover model describes control as temporally graded, fading as the control state is not reinforced. There are some cases where the trialwise conflict adaptation effects appear to decrease with an increasing inter-trial interval (ITI) (Egner, Ely, & Grindband, 2010; Wühr & Ansorge, 2005). Wühr and Ansorge (2005) noticed a smaller trialwise conflict adaptation effect for trials with a shorter (1.5 second) stimulus onset asynchrony (SOA) relative to ones with a longer (6 second) SOA. Egner and colleagues (2010) investigated the timing question more

thoroughly by manipulating ten different inter-trial or inter-stimulus intervals (ISI) or response stimulus intervals (RSI) that ranged between 500 ms up to 7,000 ms within blocks, between trials. In both cases the trialwise conflict adaptation effect decreased over time, which seemingly suggests temporal withdrawal or decay.

Even though the literature explicitly investigating the timing and withdrawal of control suggests temporal withdrawal, the evidence from the current literature is not robust. The two studies that looked at timing compared two relatively long intervals (Egner, Ely, & Grindband, 2010; Wühr & Ansorge, 2005). In contrast, Notebaert and colleagues (2006) compared two very short RSI (50 ms) to another still relatively short 200 ms RSI. Notebaert et al. (2006) observed a smaller, not reliable trialwise conflict adaptation effect at the shorter RSI. Notebaert inferred that attention has some delay before it can be deployed in an effective way. The broader range of ISI in other areas of the literature opens the possibility of the meta-analysis revealing some additional information regarding this question. The carryover model suggests ISI should be inversely related to conflict adaptation, but the conflict-monitoring model would suggest no such relationship.

Longer-term dynamics of conflict adaptation: Intra-session effects.

The blockwise adaptation effect is somewhat related to the longer-term changes in trialwise adaptation effect throughout an experimental session. The blockwise effect emerges as the result of sensitivity to the number of conflict events encountered. Mayr & Awh (2009) noted a decrease in the trialwise conflict adaptation effect in later blocks compared to earlier blocks within a session. Similar to the blockwise effect, this intra-session effect is sensitive to the number of conflict episodes encountered.

This long-term, within session dynamic change in trialwise conflict adaptation

could mean that conflict adaptation only happens during an initial, deliberately controlled

phase of task processing and fades once a task is fully automatized. This may also fit

with the fact that adaptation disappears for unconscious conflict (see below, Dahaene,

Artiges, Naccache, Martelli, Viarde, Schürhoff, Recasens, et al., 2001; Kunde, 2003). An

automization account is also supported by the work of Gilbert and Shallice showing a

decrease in Stroop conflict with increasing experience (Gilbert & Shallice, 2002).

However, the decrease could also be the result of Holroyd and Coles' reinforcement

learning model because each conflict episode results in learning between stimulus and

response pairings; more episodes means more learning, which results in better reinforced

stimulus-response pairings.

Generality or specificity of adaptation in control settings.

Conflict adaptation could result from a general adjustment of control that

improves performance for any goal-focused behavior, it could be limited to the specific

task where the increased control is needed, or it could be constrained by some other

properties (e.g., (Kornblum, Hasbroucq, & Osman, 1990). Whether or not the trialwise

or the blockwise conflict adaptation is general or specific is an important theoretical issue

because of how control is engaged. In conflict situations these predictions provide clear

hypotheses to whether or not control and adaptation should be a task-general or task-

specific mechanism. In the case of a carryover account, control is implemented through

task demand units that are applied to a particular task (e.g., Gilbert & Shallice, 2002). In

contrast, the conflict-monitoring model describes an engagement of control that is

through a task-general conflict monitor. So, the question of generality or specificity is an

important one because the implementation of control is a large piece of these models. The theoretical model must accurately reflect whether control is either general or specific.

An important question that remains is whether or not the cognitive control processes that lead to trialwise conflict adaptation or blockwise conflict adaptation generalize across tasks and contexts, or if conflict adaptation is limited to only the specific tasks or contexts. The main method of testing the generality or specificity of trial level control is to create situations where trial transitions include both combinations of conflict transitions (e.g., II, CC, etc.) and also transitions of either the source of conflict, tasks, or other forms of context changes. In this method the key piece of evidence used to demonstrate the generality or specificity is the cross modulation of control on an II trial where the N-1 trial was from a different domain, task or context. In situations where trialwise conflict adaptation facilitates performance within a task, the modulation of conflict across tasks is taken as evidence for generality while a failure of it is taken to show the specificity of control. Blockwise adaptation typically emerges from changes in the conflict adaptation from the proportion of incongruent, congruent or neutral items (e.g., Jacoby et al., 2003). In some cases, manipulating individual items within a set of possible incongruent items will create a blockwise conflict adaptation effect, but in other cases item-specific manipulations are either ineffective or an ambiguous cause of blockwise conflict adaptation.

In trialwise conflict adaptation research, incongruent and congruent trials may vary along with either tasks or context changes across trials to test for cross modulation of conflict adaptation across these specific trials where the task or context changes. Within this debate it is important to distinguish between generality of tasks and also of

contexts. In general, tasks include a set of stimuli and rules for responding, which together make up a so-called task set (Rogers & Monsell, 1996). Several studies have combined conflict paradigms to test for cross modulation between combinations of a conflict task like Stroop, Simon, or flanker tasks (e.g., Akçay, & Hazeltine, 2011; Egner, Delano, & Hirsch, 2007; Funes, Lupiáñez, & Humphreys, 2010). Changes can also be categorized as context changes when the task remains the same across trials but the context in which the task is performed changes across trials (Akçay, & Hazeltine, 2008; see also, Cho, Orr, Cohen, & Carter, 2009). In these examples, context changes could be location, stimuli, or other aspects of the task that manipulate the context in which the conflict is presented and resolved without changing the actual task itself.

A variety of evidence that ranges from neuroimaging, Stroop, flanker and Simon tasks all support that the adaptation effect is specific to the task that is the source of conflict (Akçay, & Hazeltine, 2011; Egner, Delano, & Hirsh, 2007; Fan Flombaum, McCanddlis, Thomas, & Posner, 2003; Fernandez-Duque & Knight, 2008; Stürmer, Seiss, & Leuthold, 2005; Funes, Lupiáñez, & Humphreys, 2010; Wend, Kluwe, & Peters, 2006). For example, Fernandez-Duque and Knight (2008) had participants switch between a word and number Stroop task. The typical sequential conflict benefit of repeating an incongruent task did not produce a cross-task modulation from trial to trial, but showed within-task modulation from the same task on the n-2 trial. The failure to see cross-task modulation between two different types of Stroop tasks demonstrates the specificity of conflict adaptation.

Similarly, conflict from a Simon task does not seem to modulate performance in a flanker task (Stürmer, Seiss, & Leuthold, 2005; Wend, Kluwe, & Peters, 2006). Imaging

studies support the same conclusion, showing also that conflict from either a Stroop or a Simon task produces activation in separate brain areas (Egner, Delano, & Hirsch, 2007).

It would seem that the question about a general conflict adaptation mechanism is mostly answered. The frequent failure of cross-task modulation of conflict suggests task-specific control. However, some aspects of control do seem to generalize between tasks; aspects that range from within-task, context changes to between –task cross modulation.

Conflict adaptation does show the ability to generalize within tasks in specific circumstances. In one of Fernandez-Duque and Knight's (2008) experiments pre-cues indicating the level of conflict did generalize across tasks. However, in a follow-up Rünger, Schwager, and Frensch (2010) failed to observe the same general cuing effect. Despite the ambiguity with this issue, other factors support the idea that some general mechanisms of conflict adaptation can show cross modulation within tasks but not across task contexts. Cho, Orr, Cohen and Carter (2009) had participants perform a simple spatial judgment task where the stimuli appeared in the left, right, top or bottom regions and the response was either congruent with the location or opposite (e.g., a stimulus in the top, but a bottom response). The task was the same (congruent or opposite spatial judgments), but the context of the task changed. Half of the trials appeared along a vertical axis while half appeared along a horizontal axis. In addition to the spatial locations of the task changing, each axis had separate, unique color cues. Finally, because the judgments were spatial the vertical and horizontal axes required vertically aligned or horizontally aligned responses with separate keys. Despite the change in context, a trialwise conflict adaptation effect was nevertheless present across contexts.

Cho et al.'s (2009) results are open to some interpretation. They concluded their evidence supported general mechanisms of control, but the same task was used throughout the study, merely with a different set of explicit and implicit cues: separate axes and different color cues for the axes. Overall, it is unclear how much of the design is explained by task switching or cross-task modulation. The type of response rule change used in the experiment is similar to task changes found in task switching literature (Mayr & Bell, 2006). Thus, the trialwise conflict adaptation effect observed in their study could either be conflict adaptation or a task repetition benefit.

The bulk of the current evidence suggests that trialwise conflict adaptation is specific to a given task, but not all of the evidence is consistent. The work showing a general cuing benefit and cross modulation between contexts like cues or locations suggests there are aspects of control that are general. The lack of consistency also suggests there is more to be learned about what aspects of conflict adaptation are general and which are specific. The work by Cho and colleagues (2009) is suggestive, but leaves several open questions. Specifically, it is unclear how much the two tasks in Cho's experiment represented two distinct tasks with separate task sets or a single task with multiple response rules.

The current research on the generality of conflict adaptation has so far focused on trialwise conflict adaptation. The extant literature provides very little explicit evidence regarding cross-modulation for blockwise conflict adaptation. Given the dissociation between trialwise and blockwise conflict adaptation observed by Mayr and Awh (2009) it is reasonable to also expect a dissociation in the factors that influence trialwise and blockwise conflict adaptation. Specific stimulus configurations do generalize to

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influence blockwise adaptation (Crump et al., 2005). These examples of specific stimuli configurations influencing performance on the block level are perhaps a clue that blockwise conflict adaptation may be general and not specific to a single task.

Conscious or unconscious detection of conflict.

In the conflict monitoring theory the so-called conflict monitor simply detects the presence of response conflict in the information-processing stream and then sends a signal to the PFC where control is implemented. Within this model, there is no explicit place for conscious awareness of conflict. Interestingly, a subliminal distractor that will interfere with response selection (Dehaene, et al., 2001; Kunde, 2003) allows a direct test to investigate the degree to which awareness is in fact necessary of conflict adaptation (see also Mayr, 2004).

For example, Dehaene et al., (2001) demonstrated that subliminal distractors produce a conflict effect similar to what is typically observed in an Eriksen flanker task. To do this, Dahaene et al. (2001) presented supraliminal and subliminal primes immediately preceding a probe task while recording anterior cingulate cortex activity with functional MRI. Only the supraliminal, but not subliminal primes resulted in ACC activation while both types of distractors produced a compatibility effect in a two-choice number task; the ACC is the purported neural correlate of the conflict monitoring module in the conflict monitoring theory. Moreover, Dehaene et al. (2001) observed that schizophrenia patients who have impaired ACC and PFC function showed impaired conscious, but not subliminal priming in the number task. Furthermore, Kunde (2003) reported a conflict-adaptation effect only for conscious but not the subliminal prime-

probe sequences. The combination of these two studies provides compelling evidence that conscious processing of conflict stimuli is required to trigger conflict adaptation.

Another reason to believe that conscious recognition of conflict is required is because error-related activity (ERN) is modulated by the awareness of a commission error (Niewenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). The ERN is related to conflict detection in brain areas that are or were connected to conflict monitoring in the ACC (Carter & van Veen, 2007; Holroyd & Coles, 2002; van Veen & Carter, 2002). Niewenhuis et al. (2001) did not observe ERN activity following errors that participants did not notice they had committed.

In contrast to these trial-by-trial effects, the blockwise effects may in some instances be based on unconscious processes. Specifically, the manipulations of item-specific associations with context by Jacoby et al. (2003) and Crump et al. (2006) were likely too subtle to be noticed by participants. Again, this suggests that blockwise and trial-by-trial effects are based on different processes.

Blockwise effects and generality of conflict adaptation.

Two important issues that remain to be resolved are the general or specific nature of conflict adaptation and the dissociation between trialwise and blockwise adaptation. We have covered the two independently, but it is likely that these issues are related. The seemingly task-specific nature of trialwise conflict adaptation may be true for trial-level conflict adaptation, but it may not be the case for blockwise conflict adaptation. There may be some insight from the so-called item specific proportion congruent effect (ISPC) that is argued to lead to general, blockwise improvements in dealing with conflict from specific items (Crump et al., 2006). This evidence is by no means direct, but it is

suggestive that perhaps blockwise adaptation occurs at a general level while trialwise adaptation occurs at a task-specific level. However, the ISPC was originally shown to be task specific (Jacoby et al., 2003).

Probing deeper into the blockwise/trialwise and generality issues will have greater importance beyond the immediate empirical question. Whether or not a single mechanism is or multiple mechanisms are responsible for regulating processing in order to produce conflict adaptation, may require separate mechanisms for operating at a faster trial-to-trial level and a slower block level.

The next step is to establish (1) that two separate mechanisms exist, (2) the properties of the separate systems, and (3) the generality or specificity that the non-trial level mechanism operates on. The blockwise effect can be present in the absence of a trial-level effect (Mayr, Awh, & Laurey, 2001). The dissociation between the blockwise and the trialwise effect in Mayr and Awh could simply be because the blockwise effect is more robust. But, it could certainly be that the trialwise-blockwise relationship emerges from two mechanisms with a short, attentional mechanism producing the trialwise effects and a slower, memory based mechanism producing the blockwise effects. If that is the case the trialwise effect should be relatively unaffected by experience, which would modulate learning and memory systems.

Summary of issues, problems and open questions.

Several possible explanations exist that account for trialwise conflict adaptation, blockwise conflict adaptation, and post-error slowing. Which of these is the answer has yet to be determined, but the likely conclusion will be some mix of two or more. The question of priming in conflict adaptation research presents a significant problem.

Although some evidence suggests a trialwise conflict adaptation effect persists even after repetition priming is accounted for, others do not. The simplicity and amount of support for the conflict monitoring theory make a compelling case for how regulatory processes might be engaged, modulated, and withdrawn. However, there are several core issues that suggest an alternative may be a better characterization. The difficulty in accounting for the dissociation between blockwise and trialwise conflict adaptation, the task-specific nature of conflict adaptation, and the question of consciousness all pose problems for conflict adaptation. The carryover model of task-switching by Gilbert and Shallice (2002) and Holroyd and Coles' (2002) reinforcement learning model have common characteristics that present these models as compelling alternatives. The conflict adaptation literature offers several important insights into the fundamental mechanics of cognitive control, but additional research is required to address some of these issues and open questions. Next I will integrate the literature review and motivate the next steps for understanding conflict and control.

Adjustments and Alternatives to Conflict Monitoring-Theory

One alternative to the conflict monitoring theory is that the adaptation effects on either the trial or block level result from a carryover of control settings. The trial level adaptation effect could simply be explained by inertia of control states that regulate attention and action (Gilbert & Shallice, 2002). In the task-switching literature a just-abandoned task-set will maintain some so-called task-set inertia that carries over from one trial to the next and interferes with a new task (Allport, Styles, & Hshieh, 1995; Meiran, 1996).

Following this assumption, the blockwise frequency effects, therefore, could simply be the momentum of the control settings that build as high control events/episodes are repeatedly encountered and reinforce a particular state of control. A greater frequency of episodes would mean either more push to build momentum and less time to put on the brakes, or some combination of both. In this account the blockwise and trialwise effects emerge from a common mechanism that gains and loses momentum from moment to moment growing over time. That could also be consistent with the decrease in trialwise conflict adaptation with intra-session length and conflict probability because the settings become calibrated as the number of events increases. This would not affect the blockwise effect, but it would decrease the trial-to-trial sequential modulation in the trialwise effect. Shorter inter-trial effects would be associated with temporal factors such as RSI or ISI, which would provide more or less time for trial-to-trial dissipation carryover.

Another important alternative to the theory of ACC activity explains activity as learned predictions of error probabilities and not conflict itself. Brown and Braver (2005) demonstrated that ACC activity is associated with learned predictions of error likelihood. Using a stop-signal task with high and low conflict situations, Brown and Braver showed that ACC activity increases throughout an experiment, consistent with an error-prediction account that is tuned as experience builds. This model is more task-general and also may inform why the number of trials in a session predicts decreases in trialwise conflict adaptation. The theory would also be consistent with the evidence that trialwise conflict adaptation is not general, because the probability that one task would predict an error is irrelevant for another task predicting an error.

The Present Research

The next three chapters summarize three studies that each focus on understanding and answering select issues and open questions that the introduction reviewed and discussed above. The broad goal of all of these chapters is to (1) better understand the fundamental nature of cognitive control and, in general, (2) produce evidence in support for the conflict monitoring theory or an alternative account, and, finally, (3) to advance the methodologies used to study cognitive control.

Perhaps the most important question regarding trialwise conflict adaptation research is resolving the ambiguities in current research and validating the trialwise conflict adaptation effect as an indicator of control rather than repetition priming. To this end, the first study is a meta-analysis of trialwise conflict adaptation research. The meta-analysis first addresses the most basic question in cognitive control research – namely is the trialwise conflict adaptation effect the result of cognitive control or repetition priming? In addition, we will try to examine to what degree the conflict-adaptation effects is modulated through the various other, theoretical important factors that have emerged within our literature review, such as the role of task switches or of within-session experience.

Between-trial measures provide a valuable, convenient indicator of control, but one limit to between-trial effects is the fact that they occur as consequences to conflict events after the conflict episode. The first empirical experiment sought to develop a new technique for assessing and understanding conflict adaptation within a trial when the conflict event is first detected. Eye movement analyses present an opportunity to evaluate cognitive events as they occur (Mayr, Kuhns, & Rieter, 2012). An application

of eye-movements in this context would allow for the possibility to observe and understand the within-trial dynamics of cognitive control when conflict is first detected. Information about when conflict is first detected and reacted to is also relevant to evaluate the conflict monitoring theory, which makes specific predictions regarding the time course of conflict detection and adaptation.

The final chapter addresses the relationship between within-trial dynamics and between-trial effects. Eye movement analyses could also be useful to gain information regarding conflict processing that could begin to inform how events in the preceding trial triggers control updates and adjustments between trials. Spieler, Mayr, and LaGrone (2006) have provided initial evidence that cue checking events may reflect control attempts. Such control attempts may reflect updating processes that predict subsequent control adjustments. The final study will describe a novel paradigm that uses the same type of cue display from Spieler et al. (2006) to test specific predictions from the conflict-monitoring theory and carryover account based on control attempts and conflict.

CHAPTER II

META-ANALYSIS OF CONFLICT ADAPTATION

A large amount of work has focused on the trialwise conflict adaptation. However, it has not yet produced an unambiguous answer to questions about the theoretical interpretation of this effect. For example, the relative contribution of priming and cognitive control remains up for debate. Due to the mixed empirical evidence, a clearer answer requires looking across studies to gain a better insight into the larger trends that can only be seen when quantitatively looking at the literature as a whole. Meta-analyses allow for better estimates of the true effect size and how it might be modulated through potentially critical factors than would be possible within single studies. From the literature review in Ch. I, we have selected a few questions and issues as both critical to test and suited to be tested through a meta-analysis.

Before any theoretical debate can continue, an important question to answer is whether or not the trialwise conflict adaptation effect reflects adaptation from cognitive control or if it is simply a consequence of priming. Any model that relies on the trialwise conflict adaptation effect is gravely threatened if repetitions of stimuli or responses eliminate trialwise conflict adaptation (Mayr et al., 2003; Niewenhuis, Stins, Posthuma, Polderman, Boomsma, & De Geus, 2006). Given the large number of mixed results there is likely a reduced trialwise conflict adaptation effect that persists after direct repetitions are removed, but it is likely to be significantly smaller than reported by early studies (e.g., Gratton et al., 1992).

The empirical data concerning whether conflict adaptation is general or specific are also mixed. Therefore, this is another question where looking across studies is useful

to estimate the degree to which task-switches modulate the conflict adaptation effect. Whether cognitive control is general or specific is central to identifying which model best describes cognitive control or what parameters a new model must contain. The conflict-monitoring model makes a clear prediction regarding the generality of control, which must hold true to confirm the validity of the model.

Another question regards the longer-term dynamics of conflict adaptation. Mayr et al. (2009) observed an absence of the trialwise conflict adaptation effect in the second half of their experiment. This suggests the possibility the conflict-adaptation is contingent on early, deliberate phases of processing, and disappears once processing has become automatized. While there are no studies (aside from Mayr et al., 2009) that had tested this factor explicitly, we can use experimental session length as a modulating variable that might allow us to indirectly address the question of intra-session dynamics. In this meta-analysis we looked at session length to see if experimental session length predicted any reliable decrease in trialwise conflict adaptation across studies.

Finally, certain issues like whether adaptation withdraws temporally or episodically have not been thoroughly examined within studies, but when looking across studies we can obtain a clue as to the possible role ISI plays in conflict adaptation. Any trends that emerge in the meta-analysis regarding inter-trial intervals would begin to clarify ambiguities where empirical data have mixed findings or have simply not been studied thoroughly.

We compiled data from papers that reported trialwise conflict adaptation data or data where it could be computed. The papers considered for inclusion ranged in age from Gratton, et al. (1992) to empirical papers published through the end of 2012. These

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studies included any cognitive control research that sampled from equivalent populations where we might begin to estimate the true conflict adaptation effect.

Methods

The inclusion criteria for the meta-analysis were any empirical, peer-reviewed conflict regulation journal article or book chapter using human participants and that reported the RT trialwise conflict adaptation effect or other RT data where the trialwise conflict adaptation effect could be computed from reported data or were provided by the corresponding author. The RT data of interest were the RT differences between the conflict effect following incongruent and following congruent trials - in other words, the RTs for II, IC, CC, and CI trials. Studies that did not meet these initial criteria were not considered for analysis.

From the set of included papers we then excluded from final analyses data that came from non-healthy populations, had more than two independent factors that were not reported or could not be inferred from the publication, or reported study details in a way that independent factors could not be categorized from the information available in the publication or through author correspondence. Also excluded from analysis were entries that produced redundant data such as when a study reported omnibus data in addition to individual conditions that were already accounted for in the omnibus data. In these cases we included either the omnibus or the individual data, but never both. From the 59 independent source publications, a total of 140 samples remained for the final analysis following the exclusion of non-qualified data.

Moderator and mediator analyses.

The data that was included was then categorized by (1) whether it included task switches or was exclusively from task-switch trials, (2) the proportion of conflict trials to total trials, (3) the number of unique target and distractor stimuli, (4) whether or not complete stimulus and response repetitions were included, (5) the inter-stimulus interval (ISI), (6) the number of experimental blocks, and (7) the number of trials in the experimental blocks. In addition, the overall RT across all conflict level transition times, and the size of the overall trialwise conflict effect were included. Prior to running the regression model, the number of blocks and trials were transformed and computed into a single variable that was the log transformation of the number of trials multiplied by the number of blocks, standardized around the mean number of total trials ($M = 732.40$ ms, $sd = 404.30$). The ISI was taken from direct reporting of ISI or where ISI was not reported it was estimated from the RSI by adding the grand averaged of RT from the given entry to its RSI. Conflict adaptation was computed from individual reports of transitions between incongruent and congruent trials. The trialwise conflict adaptation effect was also computed as the sum of the difference between CI-II and IC-CC transitions. Conflict probability was computed as the number of conflict trials out of the total number of trials within a block. Finally, the proportion of direct repetition trials was estimated from the average probability of direct trial-to-trial repetitions weighted by the proportion of conflict and non-conflict trials. The average probability was weighted because the probability of a direct repetition for non-conflict decreases when there are more than two unique targets and two unique distractors; this difference is irrelevant

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when the probability of conflict is 50% because each conflict and non-conflict stimuli are sampled with equal probability.

Literature search strategies.

We extensively searched the literature to identify any study published through December 2012. First, we searched ISI Web of Knowledge, PsycINFO, and Google Scholar using keywords such as "conflict adaptation", "sequential conflict effect", "sequential congruency effect", "Gratton effect", "conflict monitoring", and "conflict adaptation effect". Second, we searched for papers that cited some of the most frequently cited conflict adaptation papers: Botvinick et al. (2001), Gratton et al., (1992), and Mayr et al. (2003). The search strategy yielded a total of 59 articles and dissertations.

Statistical methods.

The final regression model of the trialwise conflict adaptation effect came about from a stepwise approach testing the significance of the predictors of (1) the log transformation of the standardized total number of trials, (2) inclusion of stimulus repetitions, (3) the standardized conflict probability, and (4) whether task switches were included or excluded. The final regression model explained 24% of the variability of the trialwise conflict adaptation effect reported in the final dataset, ($R^2 = .243$, $F (5, 83) = 637$, $p < .001$, see Table 1 for summary of final model). No other factors significantly predicted the trialwise conflict adaptation effect. To address concerns that the trialwise conflict adaptation effect may vary between tasks we also included overall RT and the conflict effect as predictors, neither of which predicted the size of the trialwise conflict adaptation effect. Therefore, all data regardless of the type of task, was included

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irrespective of the type of task. Moreover, task type was not included as a predictor in the model.

Results

The meta-analysis of the trialwise conflict adaptation effect suggests there is a trialwise conflict adaptation effect even after repetitions are removed. These combined data reveal an average baseline trialwise conflict adaptation of 28 ms ($t = 6.58, p < .001$); the stimulus repetitions alone account for an additional 13 ms of the trialwise conflict adaptation effect ($t = 2.46, p = .016$; see Table 1). These data clearly suggest that some of the trialwise conflict adaptation effect may be caused in part by repetitions (e.g., Davelaar & Stevens, 2009; Exp. 1 Fernandez-Duque & Knight, 2008; Mayr & Awh, 2009; Mayr et al., 2003; Niewenhuis et al., 2006; Wendt, et al., 2007). However, the fact that a trialwise conflict adaptation effect remains even after repetitions and contingencies are removed supports that there is a real adaptation effect reflecting control processing.

Table 1. Summary of regression analysis predicting trialwise conflict adaptation (N = 140 conditions) from the standardized and log transformed number of total trials, the inclusion of stimulus repetitions (not included or included), the standardized probability of conflict, and the inclusion of task-switch trials (not included or included).

Variable	B	SE(B)	Beta	t	p
Constant	27.90	4.24			<.001
Zscore: (Log of total trials)	-9.61	2.85	-.35	-3.37	.001
Stimulus Repetitions	13.35	5.43	.24	2.46	.016
ZScore: P(Conflict)	-6.86	2.60	-.26	-2.65	.010
Switch	-21.68	7.04	-.30	-3.08	.003

The issue of the general or specific nature of control also seems to suggest trialwise conflict adaptation is task specific. Data that included task switches predicted nearly a 22 ms drop in the trialwise adaptation effect, which virtually eliminates the baseline adaptation effect entirely. This observation lends support to the task-specificity of adaptation because a general conflict monitor should lead to control adjustments that are insensitive to task changes.

The number of trials in an experiment predicts a decline in trialwise adaptation effect throughout an experimental session. The standardized log transformation of the total number of trials was calculated by standardizing the number of trials multiplied by the number of blocks in a session. The mean number of trials was 738 ($SD = 403$). This standardized and log transformed total trials variable predicted nearly a 10 ms decrease in the adaptation effect for every 1 standard deviation from the mean number of trials ($B = -9.61, t = -3.37, p < .001$). The drop in the conflict adaptation effect with increasing trials supports some form of learning. This intra-session change is primarily associated the trialwise conflict adaptation effect and not the within-trial conflict effect. To test this hypothesis the trialwise conflict adaptation effect was replaced with the conflict effect. The same model predicted no significant decrease in the baseline conflict effect as the number of trials increased ($B = -0.877, t = -0.183, p = .855$).

The data do support a reliable blockwise conflict adaptation effect. As the probability of conflict increased above the mean probability of conflict ($M = 45.81, sd = 10.06$), the 28 ms trialwise adaptation effect is predicted to increase by nearly 7 ms for each standard deviation above the mean (see Table 1 for full summary). This establishes

a blockwise conflict adaptation effect that emerges as a context-dependent trialwise conflict adaptation effect.

The analysis of conflict adaptation papers suggests that the ISI does not significantly explain the size of the conflict adaptation effect. The mean ISI was 1770 ms ISI ($sd = 948$, range = 5,053 ms). Although very few studies have intentionally investigated the time course of conflict adaptation, the range of ISI across studies provides a reasonable outlook on the time course of conflict adaptation. It appears that the observed range combined with the handful of studies specifically investigating the issue (e.g., Egner et al., 2010), the conflict adaptation is stable across the typically studied time courses. As far as the passive carryover account is concerned, these two findings about the timing of trialwise conflict adaptation provide suggestive evidence in favor of an episodic over a temporal account. If trialwise conflict adaptation were a passive carryover from one trial to the next, you would expect some correlation of the effect with inter-trial interval. The fact that the trialwise conflict adaptation is seemingly not modulated by ISI is, instead, suggestive of decay process occurring over trials as posited by Botvinick et al. (2001).

Discussion

Overall, the meta-analysis provides several important insights regarding what factors do and do not influence the trialwise conflict adaptation effect. The regression model estimates the baseline trialwise conflict adaptation effect to 28 ms before removing repetitions. The duration of the experiment, presence of repetitions, probability of conflict, and whether or not a given trial was a switch trial all significantly accounted for the trialwise conflict adaptation effect. The impact of some of these factors will be

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discussed in the sections below where they inform relevant questions and issues in conflict adaptation research.

Some trialwise conflict adaptation comes from control.

However, a reliable trialwise conflict adaptation is present even when stimulus repetitions are removed (Kerns et al., 2004; Ullsperger et al., 2005). The meta-analysis of the conflict adaptation effect supports this conclusion estimating a baseline trialwise conflict adaptation effect to be approximately 28 ms. It would seem, perhaps ostensibly, that a portion of the adaptation effect is actually associated with a cognitive control process.

Conflict adaptation seems to be specific.

The data suggested that conflict adaptation is in fact task specific and not generalized to all tasks. For this reason, this evidence in the meta-analysis points away from the conflict-monitoring model to one of the alternatives, for example, the PDP model, carryover model account, or reinforcement-learning model. However, given the limited available evidence this conclusion is not a strong one. Less than 20% of the entries in the meta-analysis came from studies that included task-switches. This fact reinforces the need to further investigate this issue more thoroughly to better identify the full extent of how specific or general conflict adaptation is. Conflict could be specific or general to bottom-up features of conflict like those defined by Kornblum's conflict taxonomy (Kornblum, et al., 1990). Or, conflict could be specific based on top-down features of task structure (Akçay, & Hazeltine, 2008).

Temporal vs. episodic.

The fact that in the meta-analysis the conflict adaptation effect was not associated with the length of the inter-trial interval speaks against any time-based decay of control states. The data suggest the effect is not associated with short-term inter-trial intervals. Instead, control states may be weakened or occluded through intervening trial episodes. Unfortunately, this question of how control states decay either over time or episodes is not a frequently researched one. It would be important to specifically manipulate the amount of interference between episodes. For example, what effect would interference have on N-2 conflict adaptation? As it stands this is a question that needs to be addressed more systematically.

Long-term dynamics of conflict adaptation.

These long-term dynamics do not appear to be the result of improved cognitive control over time because the basic conflict effect does not decrease, which would be expected if cognitive control improved. These facts require an explanation that is not currently provided by any of the models discussed here.

The intra-session dynamic could be due to practice, learning, or the role of consciousness. During the early phase of an experiment conscious effort may be high, but as experience and expertise increases throughout a session conscious control may decrease. Cohen et al. (1990) describe the process of automization for Stroop tasks where control and attention withdraw over time. The same could be possible for effortful control states that shift from deliberate to more automatic (Logan, 1988). This account would also fit to the conscious/unconscious distinction, which poses a problem for the current models that make no distinction regarding the role of consciousness (Mayr, 2004).

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Mayr (2004) pointed out that conscious and non-conscious processing may be carried out

in separate brain areas (e.g., Dehaene, et al., 2003).

CHAPTER III

USING EYE MOVEMENTS

TO ASSESS WITHIN-TRIAL CONFLICT REGULATION DYNAMICS

The conflict monitoring theory and its primary alternative, the carryover account of adaptation, make similar predictions regarding the trialwise conflict adaptation effect. However, most work on conflict adaptation focuses on the trialwise conflict adaptation effect while the question of how or if regulation occurs within-trials has been largely ignored (cf. Scherbaum et al., 2011). Moreover, looking only at conflict adaptation after the initial conflict event does not reveal any possible relationship between the detection and the resolution of conflict that may occur within a trial with the adaptation to conflict between trials.

Because the conflict monitoring and carryover accounts of the trialwise conflict adaptation make different predictions regarding the trigger of the trialwise conflict adaptation effect, looking at the effect of conflict within trials is a way to test which of these accounts better explains cognitive control. The conflict monitoring theory proposes that conflict detection and subsequent adjustments to cognitive control are independent processes (Botvinick et al., 2001; Kerns, 2006; Kerns et al., 2004). According to the theory, the ACC detects the conflict on the previous (N-1) trial, then sends the conflict information to prefrontal areas where these areas make adjustments in attentional settings (Kerns, 2006; Kerns et al., 2004; Verguts & Notebaeart, 2008). In contrast, a carryover account predicts within-trial adjustments of control that passively carry over into subsequent trials. The carryover of attentional control from the previous trial would lead to similar levels of control on the subsequent trial. Unfortunately, both accounts make

similar predictions regarding performance adjustments between trials. Thus, the standard trialwise conflict adaptation paradigms that evaluate behavioral measures of adaptation across trials cannot distinguish between the two accounts.

An important next step in advancing cognitive control research is to use online measures of conflict resolution within a conflict trial to observe control processing as it actually occurs, rather than after the trial ends, as is the case with RT and accuracy data (Mayr, Kuhns, & Rieter, 2012; Scherbaum, Fischer, Dshemuchadese, & Goschke, 2011). Eye-movements are one possible measure of online allocation of attention to visual stimuli. Mayr et al. (2012) demonstrated how eye-movements can be used to reveal the online resolution of relevant and irrelevant visual stimuli based on task switching. According to the conflict monitoring theory this type of resolution should occur in a two-stage process of detection on the N-1 trial and then adjustment on the current trial. In contrast, a carryover account predicts the detection and resolution to occur within the same trial.

In the present study described in this chapter we used standard behavioral measures of RT and accuracy rates, used eye-movements to probe allocation of attention within a trial as a function of distractor response congruency in a task-switching paradigm. In this paradigm participants switched between two tasks in the presence of distractors, which created conflict. One stimulus was neutral with respect to the two possible tasks, while the distractor could share either a congruent response with the target or an incongruent response: a congruent distractor was considered a low conflict trial while a high conflict trial is considered to be a trial with an incongruent distractor. Previous work in task switching has demonstrated that eye-movements are associated

with complex and dynamic control processes; moreover, they can reveal valuable information about control changes as they occur between stimulus onset and a manual response (Mayr et al., 2012). According to the conflict monitoring theory the high and low conflict trials should trigger control adjustments that are detectable following the conflict event; thus, no within-trial conflict adjustments would be expected for eye movements within a trial. In contrast, the carryover account would predict within-trial adjustments that are then associated with improved control.

Methods

Participants.

Seventy-two students from the University of Oregon participated in exchange for partial credits for introductory psychology courses.

Tasks, stimuli, and procedure.

Participants viewed task stimuli on a 17-in. Dell CRT monitor set to 1024 x 768 resolution. Eye movements were recorded using a desk-mounted SR Research Eyelink 1000 camera, controlled with Matlab and the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002).

On each trial, there were three vertically oriented bars present, each subtended visual angles of 1.7° high and .34° wide. One bar was either a lighter or darker color than the other two bars, a second bar had a small gap near either the top or the bottom, and the third bar was neutral with no gap and color matched to the bar with the gap (see Figure 9). Depending on the currently relevant task, these bars either served as the target or the distractor, whereas the third object always served as the neutral object. The three bars were presented equally spaced in three of 12 possible positions on a virtual circle (circle

radius = 100 pixels or 3.4°; see Figure 9), thus constituting four possible rotations of an equilateral, virtual triangle. On each trial, stimulus positions were constrained to fall on the vertices of one of four possible equilateral triangles necessary to capture all 12 possible positions on the circle. Triangle constellations never repeated from trial-to- trial, and assignment of target, distractor, or neutral object to positions within the triangle was random. Thus, there was neither trial-to-trial predictability nor repetitions of stimulus locations.
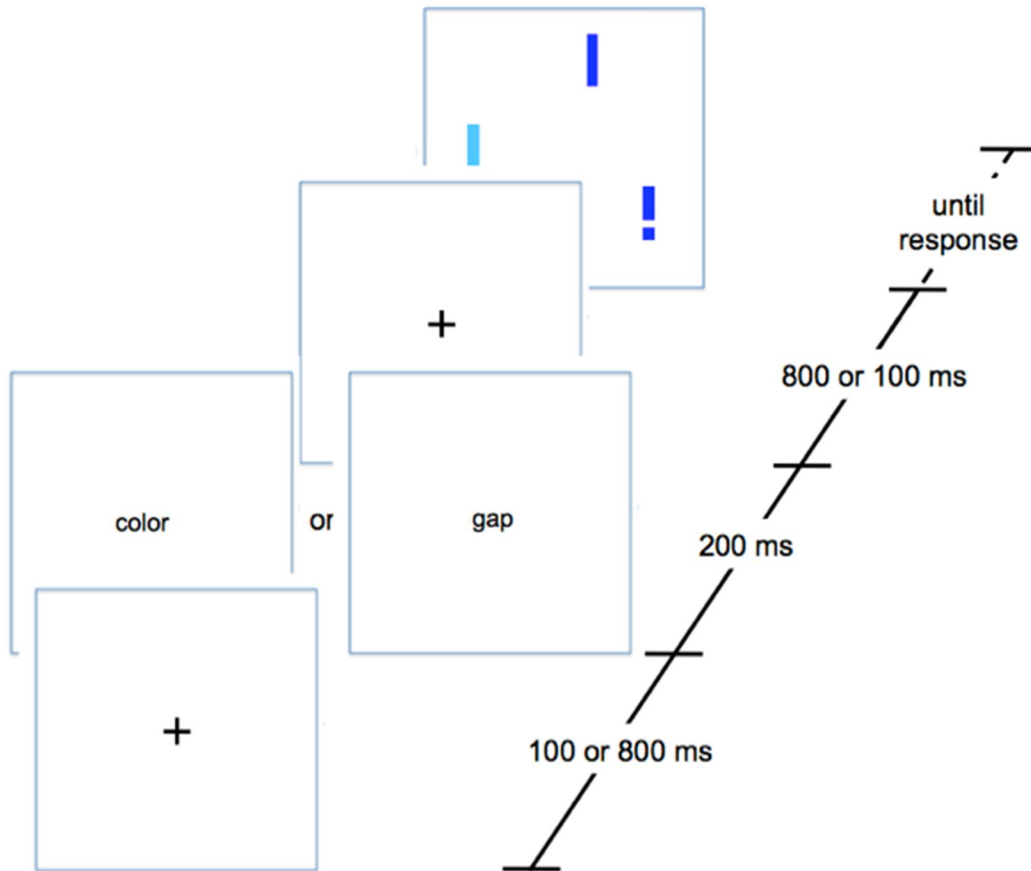
Figure 9. Sample trial sequence showing one example trial for each task beginning with a fixation cross, then a text cue for one of the two tasks, a fixation cross during the CSI, and finally stimulus all shown with timing between events.

The task cues instructed participants to perform either the "gap" task, where they made a left response when the gap was on the bottom of the bar or a right response when the gap was on the top of the target object. For the "color" task, light blue color meant a left response and dark blue meant a right response. Participants responded by pressing the left or right arrow keys on an English keyboard.

For each trial, the relevant task was signaled by text, task labels presented visually at the center of the screen. As explained above, the cue was selected from pairs ("gap" vs. "color", "space" vs. "hue") to avoid immediate cue repetitions. Tasks were selected randomly with the constraint that a task switch occurred with a 25%, 50%, or 75% probability manipulated between three randomly assigned groups of participants (n = 24 per group).

The interval between the start of each trial and the stimulus was 1,100 ms. Within that interval, the cue was presented for 200 ms either after 100 ms, leaving a cue–stimulus interval (CSI) of 1,000 ms, or after 800 ms, which created a CSI of 300 ms. Participants sat with their eyes approximately 50 cm from the screen with their head supported by an adjustable chin rest. The session began with three 40-trial practice blocks during which participants received error feedback. Incentives were used to motivate participants to use the preparatory interval. Participants earned $0.01 for each trial with an RT that was faster than the average across all previous blocks, as long as their proportion of correct trials remained at or above 90%. Participants were not informed of this incentive scheme until the completion of the 4th block of the experiment. During Block 4, the overall average RT was computed separately for no-switch and switch trials, and this average was updated for each new block. Participants were

instructed that no-switch and switch transitions were averaged separately in order to avoid any selective bias for the one or the other. At the end of each block, participants saw how much additional money they had earned (if any) along with average accuracy and RT (across no-switch and switch trials), and at the end of the experiment they were paid the amount earned (usually between $3 and $4). Blocks 5–20 were used for data analysis. Eye-gaze registration was calibrated at the beginning of the experiment and recalibrated every four blocks. Each block's average eye positions during the presentation of the task cue were used to correct for possible calibration drift across the experimental session.

Analysis of eye movements.

Eye-gaze data was sampled at 1000 Hz. Fixations were defined as the absence of either a blink or a saccade, where a saccade was identified for each pair of successive samples in which the eye movement's velocity surpassed 30°/s or the acceleration surpassed 8,000°/s^2. Fixations before or after blinks were not excluded from the data - doing so would not affect the results. Around each object center, 1.7° (i.e., half the distance between cue and object) non-overlapping circles were defined. Fixations within these circles were categorized as being directed toward that object. In the present analyses, we focused on the initial 700 ms within a trial, which are most likely to reflect attentional selection processes, rather than later rechecking. In fact, inspection of individual eye movement probability curves revealed that within these initial 700 ms, the pattern was relatively consistent across individuals, whereas later probability curves were much more idiosyncratic and varied. In part, this simply reflects the fact that given average RTs of around 800 ms, data density strongly decreased beyond 700 ms.

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Across all conditions, the probability of trials with target, distractor, and neutral fixations within the first 700 ms of a trial was .54 (SD = .22), .18 (SD = .11), and .07 (SD = .05), respectively. These numbers changed only slightly when looking at the entire trial duration: .61, .22, and .10. The remaining trials did not have any fixations. The fact that target fixations remained close to 50% might appear surprisingly low at first. However, this reflects the two opposing criteria we needed to optimize in the stimulus display. On the one hand, we needed to achieve sufficient stimulus-driven task competition, which decreases as object-to-object distance increases. On the other hand, we simultaneously needed to ensure that eye movements to the target and the distractor are in fact indicative of the efficiency of attentional control. We could have easily enforced near 100% eye movements by moving the objects even further apart. But, doing so would have turned the paradigm into a visual search task and eliminated much of the between-task competition. The goal was that the fixations we observed are meaningful indicators of attentional selection— overall, our results indicate that.

To reduce overall complexity of the present chapter, the considerable differences in overall fixations found across the two task dimensions are ignored. The color deviant object generally attracted more eye movements than the gap deviant. This was true when it was a target (.72 vs. .35) and a distractor (.24 vs. .11). However, we made sure that the general pattern of results to be reported below replicated across both task dimensions. In addition, for the analysis of between-trial dynamics, the effect of task dimension was statistically controlled.

Finally, the effect of specific value repetitions (e.g., when the color deviant carried the exact same color across trials) was also ignored, but only after ensuring that including this factor would not affect the present conclusions. Finally, the analyses reported indicate that there were more than twice as many fixations to the distractor than fixations to the neutral stimulus. This suggests that competition during attentional selection was mainly about selecting the potentially task-relevant objects, and little additional information was contained in the eye fixations to the neutral object. Therefore, in the data analysis only data regarding target and distractor fixations are reported.

Results

Overall, as expected, more eye movements went toward the current target and away from the current distractor. This pattern of eye fixations distinguishing between relevant and irrelevant objects begins as early as 300 ms following stimuli onset (see Figure 10). Figure 10 shows the difference in probability of eye fixations to the target and the distractor over time from the onset of the stimuli until the manual response. Here, 0 means there was an equal probability of fixating on either target or distractor, with greater probabilities reflecting improved attentional selectivity. The effect of response congruency goes in the opposite direction of the switch effect: switch trials were associated with fewer target fixations; incongruent trials were associated with more target fixations (see Figure 10). This counterintuitive result is consistent with conflict-driven adjustments of control where the presence of conflict requires greater control to successfully complete the currently relevant task.
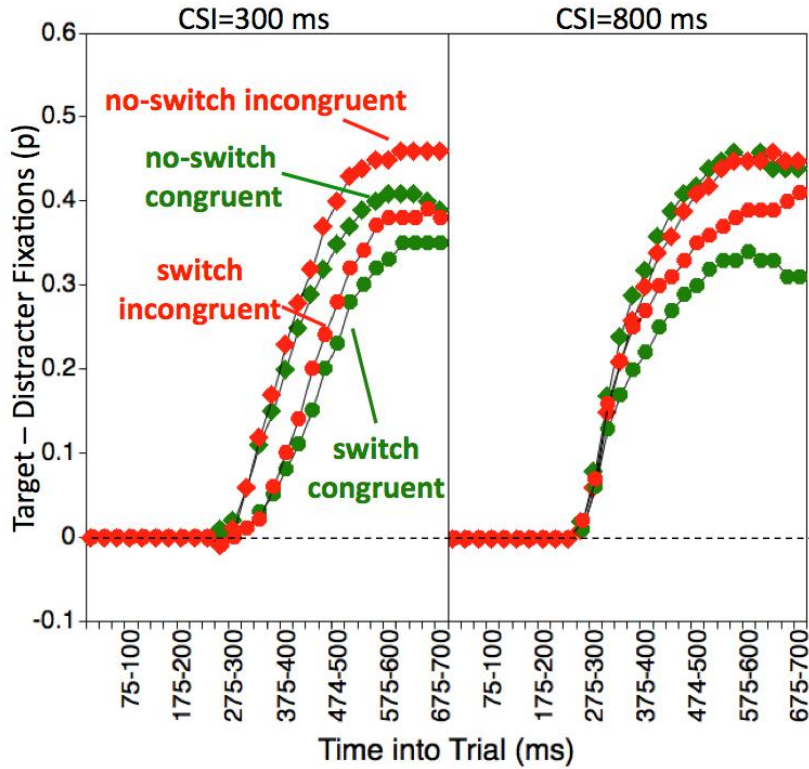
Figure 10. Difference in probability of eye fixations on target relative to the probability of eye fixations on the distractor as a function of time in the presence of conflict (red) or no conflict (green) during no-switch trials (squares) and switch trials (circles) on trials with a short preparation interval (left) or long preparation (right) (Kuhns, Viale, & Mayr, 2011).

We used congruency, task switch, and eye-fixations on the target and on the

distractor as predictors (as well as all interactions, all effects coded as 0/1) in a

hierarchical linear model of individual trials' error rates and RT.

High conflict trials resulted in congruency effects on errors (2.1 %, $t = 7.5$) in the

absence of target or distractor fixations. The congruency effect was eliminated for target

fixations trials (-2.1%, $t = 6.7$), but increased for distractor fixations (2.6%, $t = 4.9$). In

the absence of target or distractor fixations, congruency effects further increased on

switch trials by 2.6%, $t = 4.87$, and again this effect was reversed for target fixation trials

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by 3.3%, $t = 4.94$, but further increased for distractor fixation trials by 2.8%, $t = 3.17$ (see

Figure 11). There were no consistent RT results. These results suggest fixations to the

target object and away from the distractor help to avoid errors. In other words, the

conflict-induced increase in selectivity improves performance exactly as would be

expected. When the conflict-induced selectivity is ineffective (i.e., eye movements first

to the distractor), the result is a decline in performance.
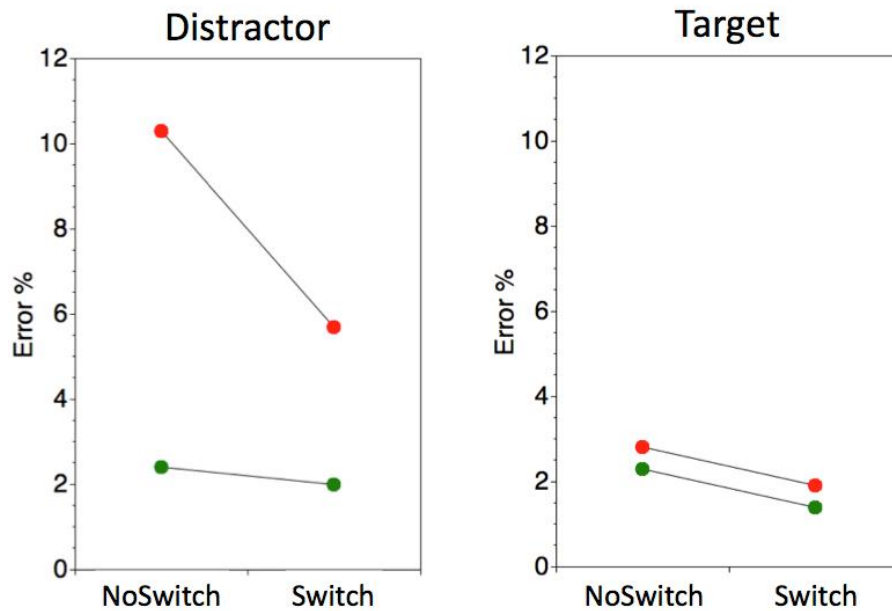
Figure 11. Error rates on no-switch and switch trials for incongruent (red lines) and congruent (green lines) trials when eyes first look at either the distractor (left panel) or the target (right panel); no-switch trials are shown on the left half of each panel, with switch trials shown on the right sides.

Discussion

The eye-movement results as a whole demonstrated they hold valuable insights

regarding conflict adaptation and eye-movements. Eye-movements revealed an improved

efficiency for attention to resolve relevant from irrelevant stimuli in the presence of

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conflict. Moreover, these within trial adjustments improved in the presence of increased conflict. This finding is not only important for cognitive control research but also for demonstrating the usefulness of eye-movements in cognitive control research.

The higher probability of fixations to the target on high conflict relative to low conflict trials suggests that conflict boosts the allocation of eye-movements that are assumed to reflect allocation of attention; a pattern that begins relatively early within a trial. This type of conflict-driven adjustment suggests dynamic control that proactively adjusts attentional settings to meet current demands.

The allocation of attention to the target eliminated the congruency effect on error rates. When participants made eye-movements to the distractor error rates significantly increased relative to when eye-movements were first made to the target. The increase in error rates also significantly interacted with no-switch and switch trials resulting in the highest error rates when fixations were most likely first made on the distractor on high conflict, no-switch trials.

Another important result is the demonstration that eye-movements as an indicator of early, input-selection appeared to be affected by response-congruency as an indicator of late, response selection. This suggests parallel processing of early and late-stage information, and feedback from late to early processes.

The pattern of results obtained in this study reveals dynamic, within-trial adjustment to control that is more consistent with a carryover account of cognitive control rather than the conflict monitoring theory. Moreover, these results replicate previous findings that show similar, dynamic, within-trial control adjustments using so-

called steady state visually evoked potentials (SSVEP) obtained through EEG (Scherbaum, et al., 2011).

These conclusions rely on the use of accuracy rates rather than RT. This is atypical with respect to cognitive control research. In principle, this lack of consistent RT results could be due to selective survival: participants make more errors on incongruent than congruent trials. If errors trials are excluded, as is typically done in RT analysis, then it is likely that relatively more incongruent trials "survive" on which participants happened to look at the target. For this reason, the Figure 11 contains all trials (no error and error).

The next step is to relate our observed within-trial regulation to between-trial adaptation effects. The carryover account suggests that the settings from one trial carry over to the next. Does adaptation to within-trial conflict then predict conflict resolution on the next trial? Within the current experimental design between-trial effects could not be adequately addressed, because the overall response congruency effects on RTs were small to non-existent. However, within the paradigm used in the next chapter, we have an opportunity of revisiting related issues.

CHAPTER IV

USING EYE MOVEMENTS TO IDENTIFY

BETWEEN-TRIAL CONFLICT ADAPTATION IN A CAPTURE TASK

Cognitive control is typically studied through the so-called conflict adaptation effect. This effect is demonstrated through performance improvements that appear after experiencing conflict. The modulation of conflict between trials is generally considered to result from adjustments in cognitive control. The predominant theory of cognitive control and the conflict adaptation effect is the conflict monitoring theory (Botvinick et al., 2001), which explains this effect through a feedback system regulated by a conflict monitor. A carryover account adapted from Gilbert and Shallice's (2002) PDP model, which was originally intended to explain task-switch costs, is a possible alternative to the conflict monitoring theory and may better explain conflict adaptation effects. One key difference between the two explanations is in the timing of events that trigger control adjustments. The present study explored if analysis of eye movements can help to shed light on the time course of conflict-driven regulation with the goal to distinguish between the two competing accounts.

The primary characteristic of the conflict monitoring theory is the feedback loop that is regulated through a conflict monitor, which detects conflict and triggers subsequent updates in control (Botvinick et al., 2001). Thus, experiencing conflict is the source of engagement for control and antecedent to control adjustments. The theory also specifies the contents of the conflict monitoring module are read out at the end of each trial. It is this signal that subsequently triggers the adjustments in control on the following trial (Botvinick et al., 2001; Kerns, 2006; Kerns et al., 2004; Verguts &

Notebaert, 2008). Without the processing of conflict, the conflict monitor would not read-out the adjustment signal to the appropriate areas that manage attentional control and, thus, no adjustment would be made. In this respect the detection and resolution of conflict are separate stages in the adaption process (Kerns et al., 2004; Verguts & Notebaert, 2008). In behavioral studies, the trialwise conflict adaptation effect is interpreted as an indicator of the up-regulation of control. A few neuroimaging studies have shown direct evidence of regulation increases through increased prefrontal activity following conflict trials (Kerns, 2006; Kerns et al., 2004). However, behavioral evidence of regulation is largely missing. To address this issue, we will explore in the current study the degree to which eye fixations to task cues can be used as an indicator of updating processes.

An alternative account of the conflict adaptation effect is that it comes from a passive carryover of control from the previous trial. Under a carryover account, the detection and resolution of conflict unfold as a more tightly coupled process (Kuhns et al., 2011). Previous work looking at dynamic regulation of attention has shown dynamic adjustments to conflict within a trial (Braver, Gray, & Burgess, 2007; Goschke & Dreisbach, 2008; Kuhns et al., 2011; Scherbaum et al., 2011). But, these within-trial measures have yet to be related to between-trial adjustments. When a good control state is established in the previous trial by avoiding conflict processing in the face of conflict, this good control state could also then lead to reduced conflict on the current trial if that same, good control state passively carried over. A carryover interpretation is also supported through evidence that reveals an interaction between high conflict trials and

task-switch costs. Switch costs are larger on switch trials that are preceded by high conflict trials relative to a low conflict trial (Brown et al., 2007; Goschke, 2000).

These two accounts have diverging predictions regarding the performance adjustments following episodes of conflict. The conflict monitoring theory assumes that experiencing conflict is the trigger of the between-trial improvements following conflict (Botvinick et al., 2001; Kerns, 2006; Kerns et al., 2004). The greater the degree of experienced conflict during the previous-trial, the larger the adjustment should be. Conflict is also an important factor in a carryover account. However, the between-trial improvements following conflict result from high levels of control that are revealed through reduced conflict processing on the previous trial. The most common paradigms of studying cognitive control currently do not have a clear way to measure conflict processing on a trial-by-trial basis. To address this issue, we will explore here, to what degree fixations to a distractor stimulus can be used as an indicator of conflict processing.

Eye movements are one possible way to categorize to what degree conflicting information might have been processed. This assumes that looking at a stimulus means the stimulus is being processed, which is generally true (Awh, Armstrong, & Moore, 2006). In terms of eye-movements, the conflict monitoring theory would predict that in the presence of conflict, eye fixations on distracting information might be associated with improved control on the following trial. If anything, the opposite would be true for a carryover account, which predicts in the presence of conflict, an absence of eye fixations to a distractor would be consistent with a carryover of good control on the next trial.

Eye movements might also help to distinguish between the different models of conflict adaptation in another way. The conflict-monitoring model predicts a process of

updating the current task rules following the experience of high levels of conflict (Botvinick et al., 2001; Kerns, 2006; Kerns et al., 2004). However, currently no valid behavioral indicators of such updating events exist. Therefore, we explored here the degree to which fixations on task cues might serve as such an indicator of updating. In this case, the conflict-monitoring theory would predict that on trials following conflict, the probability of cue fixations should increase, and this in turn should lead to increased conflict-adaptation effects.

The Present Study

To examine both the role of experienced conflict and of cue fixations on the conflict-modulation effect we needed a situation (a) that allows assessment of conflict processing via eye movements and (b) where cue fixations might reasonably be interpreted as task-set updating events. To this end, we utilized a modified attentional capture paradigm recently introduced by Mayr, Kuhns, and Hubbard (2014).

The paradigm uses two tasks that differentially rely on top-down and bottom-up control, which are referred to as the endogenous and exogenous tasks (see Figure 12). In the endogenous task, the central symbolic cue needs to be used to locate the outside circle where the response-relevant stimulus (L or R) was located, while ignoring the sudden-onset stimulus that appears on 50% of the trials (i.e., high-conflict trials). In the exogenous task, participants needed to attend to the sudden-onset circle as the location of the response-relevant stimulus, while ignoring the central cue that again is present on 50% of the trials (i.e., high-conflict trials). The endogenous task is more difficult and shows much larger conflict effects than the exogenous task, where participants can rely

largely on bottom-up attention capture. Therefore, our main focus in analyzing conflict-adaptation effects will be on the endogenous task.

Conflict in this paradigm comes from both tasks being presented simultaneously (see Figure 12d and 12c). Mayr et al. (2014) demonstrated the endogenous task is significantly more difficult than the exogenous task because it requires a greater degree of top-down endogenous control to identify the target. The exogenous task can rely on bottom-up attention capture to pull attention to the target with relatively less control. This also means the endogenous distractor in the exogenous task is marginally effective at creating conflict. Due to the fact that conflict processing is the main focus of the current study and combined with the fact that the endogenous distractor provides minimal conflict, the results will focus on the endogenous task. Further, by monitoring eye movements we were able to distinguish between those endogenous-task, conflict trials where the irrelevant sudden-onset circle was fixated on (i.e., high experienced conflict) from those where it was not fixated on (i.e., low experienced conflict).

In order to generate a situation in which fixations to task cues might be used to indicate updating events, participants switched between the two tasks relatively infrequently. Specifically, a low probability beep sounded, which indicated that there is 50% chance that the current task will change. The first trial of each block was always a beep trial.   On beep trials, participants had to inspect the small task cues in the upper right and left corners of the screen to identify the currently relevant task (see Figure 12). Moreover, the cues were sufficiently small so that without fixations it was very hard to identify the currently relevant task. The beep trials were not of direct interest; in fact they were excluded from primary analyses. Rather, we were interested in the degree to

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which participants might revisit the task cues on non-beep trials to update their current task-set representations. In past work with a similar setup, Spieler, Mayr, & LaGrone (2007) had in fact found that participants occasionally revisited task cues even when there was no ambiguity which task was currently relevant.

To examine whether cue inspections can in fact serve as indicators of task-set updating, it is important to characterize the antecedents and consequences of such updating events. For example, we should find the cue fixations should occur more often when it is difficult to maintain the current task representation. At first sight one might think that this is the case for the endogenous task. However, Mayr et al. (2014) have shown that the increased effort needed to perform the endogenous task, relative to the exogenous task, may produce particularly large memory interference for the exogenous task. If that is the case, then the endogenous task should be more robust against the need for control updates and therefore be associated with fewer cue inspections than the exogenous task. Also, more local trial characteristics should affect cue checking. In particular, we might expect cue inspections in particular on trials with high conflict or on trials following high levels of conflict.

A final goal of the current study was to produce a situation where trialwise conflict adaptation effects could be unambiguously interpreted. Due to trial-to-trial stimulus repetitions, in many of the typical conflict paradigms repetition priming is an alternative explanation for the trialwise conflict adaptation effect (see Mayr et al., 2003). In the current paradigm, participants made a binary decision using a left or right key press in response to the letter "L" or "R" that was displayed within one of the six stimulus frames in a large circular array (i.e., the target circle) (see Figure 12). The exact location

of a given stimulus was never allowed to repeat from one trial to the next, thus, eliminating any exact stimulus repetitions. Therefore, the conflict adaptation effects can be interpreted here as resulting from the experienced conflict, rather than from low-level priming from stimulus repetitions.
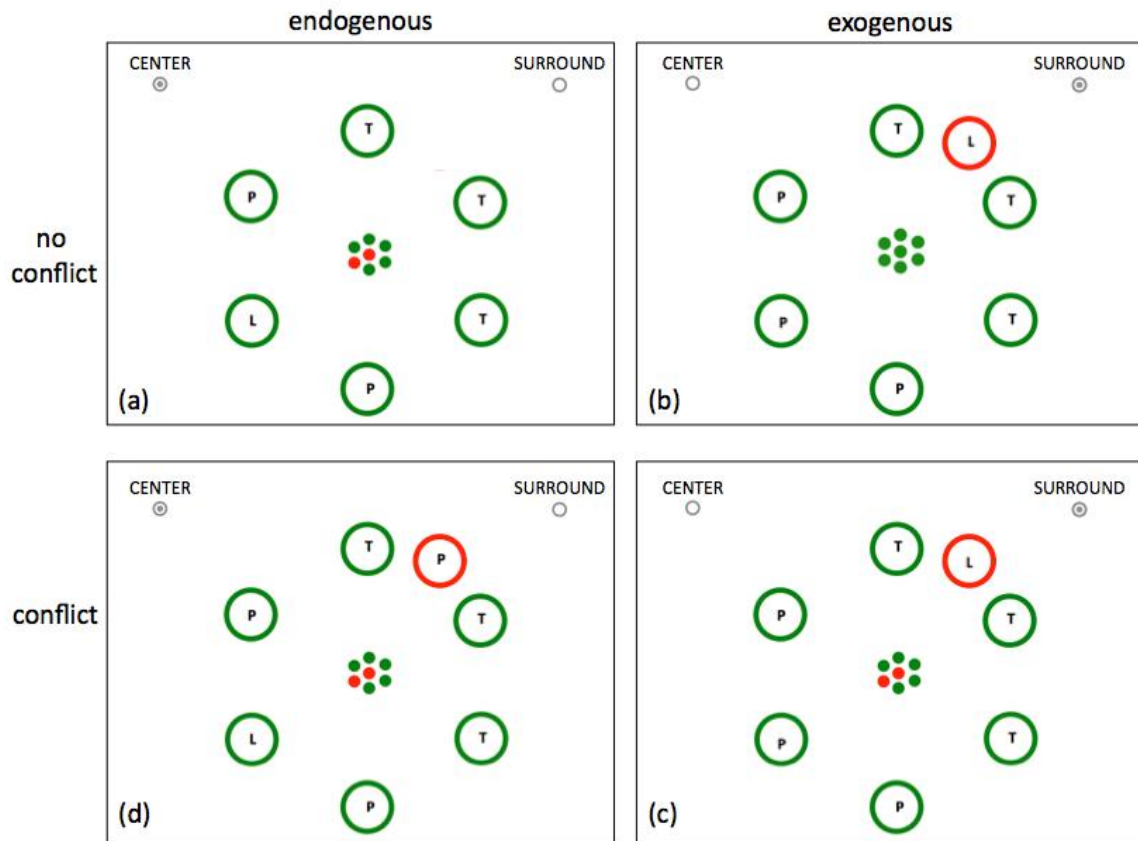
Figure 12. All possible combinations of no-conflict shown in figures (a) and (b), conflict shown in figures (c) and (d) with the endogenous task shown in figures (a) and (d) or exogenous task shown in figures (b) and (c). Experimental stimuli were shown in white on a black background, stimuli shown in red here were also displayed in red in the experiment.

Methods

Participants.

Thirty-one students from the University of Oregon participated in exchange for partial course credits in introductory psychology courses. One of the participants was excluded from the final analyses due to unusable eye-movement data.

Apparatus and stimuli.

Stimuli were presented on a 17-in. Dell CRT monitor set to 1024 x 768 resolution. A desk-mounted SR Research Eyelink 1000 recorded eye movements, controlled with Matlab and the third-party Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002). Participants sat with their eyes approximately 50 cm from the monitor with their heads supported by an adjustable chin rest.

Six circular stimulus frames (diameter of each circle = 13 mm = 1.5 degrees) were presented around a virtual circle (diameter = 14 cm = 16 degrees), centered around the screen's center (see Figure 12). These circles were always presented in white on a black background. Within each circle the "&" symbol or the letters L, R, P, or T appeared in white, size 12 Times font. An additional, sudden-onset circle of the same size could appear between two of the six, regular circle positions. This sudden onset circle was always presented in red and could also contain the letters L, R, P, or T, also in white, size 12 Times font. At the center of the screen there were six smaller "center cue circles", (diameter of each circle= 4 mm = .5 degrees). These were arranged in a way that copied the configuration of the larger, outer set of stimulus circles (diameter of the central cue circle= 14 mm = 1.6 degrees). For each position in the larger stimulus circle, there was a corresponding, smaller circle. The smaller cue circles could be presented either in white

or red, with red pointing toward the position of a distractor or target circle in the outer circle.

Finally, the display also contained two task cues made up of the text "CENTER" and "SURROUND", located 5% of the distance from the top and outer edges of the screen on the left and right for the left and right cues, respectively. The left/right placement of the two tasks cues was counter balanced between participants. In addition to the text, the cues also contained a circle, which was centered and immediately below the text cues (see Figure 12). These circles were empty during the inter-trial periods, but synchronized with the onset of the stimuli, the circle below the currently relevant task cue became filled. However, the task cues were only required on task-switch trials, which were indicated by the auditory tone.

In the mixed blocks a 50% valid, auditory a tone indicated the current trial would possibly switch tasks. The switch cue (i.e., tone) sounded on average with either 12.5% or 8.33% probability, counterbalanced across participants. Thus, the actual task-switch rate was either 6% or 4%, for the 12.5% and 8.33% conditions, respectively.

Tasks and procedure.

Participants performed both the "endogenous" and "exogenous" tasks, one at a time. For both tasks the participants had to search for a target location, identify the letter at the target location, and press the left-arrow key if the letter was an "L" or the right-arrow key if the letter was an "R".

The task cues at the top of the screen indicated to the participants to perform either the endogenous, "center", task, or the exogenous, "surround" task. The endogenous task required participants to use the location of the red circle within the

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center array to identify the target location in the surround display. The exogenous task required participants to use an abrupt onset stimulus in the surrounding circle array to identify the target location.

Each session began with a 40-trial mixed, practice block, with the first task in this block counterbalanced between participants. Participants then completed two, single task blocks, one of each task, with the order of the tasks counterbalanced between participants. The main experimental blocks were the following eight mixed blocks, with the first task in each block alternating between blocks. In the main, mixed experimental blocks, the participants switched between both the endogenous and exogenous tasks. The auditory tone at the beginning of a trial indicated a possible task switch.

Half of all trials for both tasks were conflict trials. For the no-conflict exogenous trials, the white inner cue circles remained white throughout the entire trial. For the conflict exogenous trials, when the exogenous stimulus would appear, one of the inner circles for the endogenous task would switch to red in the same way it would on endogenous task trials. For no-conflict endogenous trials the inner cue circles switched to red, with no exogenous stimulus in the outer circles. On the conflict trials, when one of the inner cue circles switched to red to indicate the location of the target, a circle in the surrounding display would also appear. For both no-conflict and conflict trials the stimuli remained on the screen until the participant made a manual response.

In all block types, each trial began with a 1000 ms period in which the large peripheral circles all contained the "&" symbol and all central cue circles were red. Next the relevant cue circle was filled and the response-relevant stimulus was presented in form of a sudden-onset circle, containing either the letter "L" or "R". Participants had to

press the left-arrow key for the letter "L" and the right-arrow key for the letter "R". The large stimulus circles contained either the letters "P" or "T", to which no response was assigned. Depending on condition, non-conflict or conflict trials were presented.

Analysis of eye movements.

Eye positions were sampled from the right eye only at 1000 Hz. Fixations were defined as the absence of either a blink or a saccade, where a saccade was identified for each pair of successive samples for which the eye's velocity surpassed 30°/s or the acceleration surpassed $8,000°/s^2$. Fixations before or after blinks were not excluded from the data— doing so would not affect the results. For the purpose of categorizing eye-fixations, areas of interest (AOI) outlined each object center, 1.7° (i.e., half the distance between a given object and any other object) to create non-overlapping circles around each object in the stimulus array. Any fixations the eye-tracker recorded within these circles were categorized as a fixation on that object. In the present analyses, we limited the analysis interval to the stimulus-response interval beginning at 600 ms following the beginning of each trial until the manual response at the end of the trial.

Results and Discussion

The primary aim of the current study was to test whether a carryover account of conflict monitoring theory best explains the conflict adaptation effect. The most important test between the two is whether or not conflict processing on the previous trial predicted improved performance on the current trial. In the current experiment eye-movements to the distractor are considered as evidence for greater experienced conflict. Therefore, faster RTs and a reduced probability of eye-movements to distractors on the current trial that followed trials with eye-movements to distractors would be consistent

with conflict monitoring and the opposite would be consistent with a carryover account. Additionally, the inclusion of the task cues was intended to provide an indicator of control attempts. The conflict monitoring predicts updating following conflict. In a carryover account a control attempt might suggest a weak control state that would be more susceptible to conflict.

Before the analysis began we filtered the data to remove the practice bocks, the first trial from each remaining block, all error trials, all trials following errors, and all trials that began with the auditory switch cue. Moreover, the analyses were restricted to only the eight mixed blocks, excluding the four pure, single task blocks that came in the beginning and end of each experiment session. Within the mixed blocks and after the exclusion criteria has been applied, a total of 15,711 trials remained for analysis ($N=30$).

Antecedents of cue inspections.

We first examined to what degree task-cue inspections can be used to indicate updating events. A series of linear regression model probed 15,711 trials to see what factors predicted cue inspection events. The first model tested main effects and two-way interactions of both global and trial-specific factors. The probability of a cue inspection was predicted from (1) task type (endogenous vs. exogenous), (2) switch cue frequency (8% vs. 12%) and also from the trial-specific factors of (3) current trial conflict, (4) previous trial conflict (N-1 conflict), (5) previous trial cue inspection (N-1 cue inspection), (6) previous trial distractor fixation (N-1 distractor fixation), and (7) the number of trials since last switch cue (mean centered). The between-participant switch cue frequency was not significant nor did it interact with any other factors; therefore, it was removed from the following analyses. Moreover, removing the switch cue frequency

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did not change the overall pattern of results. The subsequent model revealed an overall

mean probability of a cue inspection of 8.18% *(sd* = 1.88%, *t* = 4.35). The model also

revealed an increase in the probability of cue inspections for the exogenous task and

following previous cue inspections (see Table 2). In contrast to what was expected, the

probability of cue inspections decreased slightly when the number of trials since the

switch cue exceeded the average number of trials between switch cues (β = -.11%, *sd*

= .033%, *t* = -3.52). See Table 2 for all main effects and significant two-way interactions.

Table 2. Summary of the regression model predicting the probability of a cue inspection from task (endogenous vs. exogenous), conflict (non-conflict vs. conflict), N-1 conflict (non-conflict vs. conflict), N-1 cue inspection, N-1 distractor fixation, and mean centered number of trial since last switch cue with participant as a random factor.

Variable	B	SE(B)	*t*	*p*
Intercept	7.93	1.98	4.00	*
Task	2.92	0.52	5.59	*
Conflict	0.94	0.52	1.82	
N-1 conflict	0.12	0.52	0.22	
N-1 cue inspection	23.27	0.70	33.08	*
Trials since last switch cue	0.12	0.03	-3.52	*
Task x N-1 cue inspection	5.78	1.20	4.80	*
Task x trials since last switch cue	-0.13	0.06	-2.21	*
N-1 conflict x N-1 cue inspection	3.15	1.19	2.64	*
N-1 cue inspection x trials since last cue	0.61	0.08	6.74	*

* *p* < .05 significance

The largest increase in the probability of a cue inspection resulted following a previous trial cue inspection (i.e., N-1 cue inspection). A follow-up analysis looked at the effects on cue inspection probability without previous cue inspections to probe current trial cue inspections that are separate from previous-trial cue inspections. The same pattern of results remained even when restricted to trials where no cue inspections occurred on the previous trials.

Overall, it is clear that participants looked at the cues and there is some indication that participants used the cues to update their task-set representation. For example, the rate of cue fixations was higher on exogenous task than endogenous task trials, where task representations may be more difficult to maintain, and it increased on conflict trials. However, we failed to find a significant increase in the probability of cue fixations following trials with high conflict. Furthermore, the strongest effect was the increase in the probability cue fixations following previous trial cue fixations. Such a pattern suggests a high degree of trial-to-trial carryover in terms of how eye-movements are allocated. Thus, based on these results it is not clear to what degree cue fixations can serve as valid indicators of updating.

Conflict adaptation.

A linear regression model tested for a reliable trialwise conflict adaptation effect on RT. The first model predicted RTs from current trial conflict (no-conflict vs. conflict), N-1 conflict (no-conflict vs. conflict), switch cue probability (8% vs. 12%), and task type (endogenous vs. exogenous) with participants as a random effect. Cue inspection trials significantly increased RT simply by looking at the cues (286.08 ms, $sd = 7.60$, $t = 37.63$). Because of the relatively few (8%) cue inspections trials and the large increase in RTs

from looking at the cue, we removed all current trial cue inspection trials from further

analyses of RT's to prevent the cue inspection from masking other effects. Additionally,

switch cue probability was also removed because it did not significantly predict RTs nor

did it interact with any other factors. Removing both variables from the final model did

not change the overall conclusions.

The revised model with cue fixations removed retained 13,906 trials and revealed

significant main effects for all variables (see Table 3). The model also revealed

significant interactions between task and current trial conflict and, most importantly,

between current trial conflict and N-1 conflict (see Table 3). The interaction between

current trial conflict and N-1 conflict confirms a statistically reliable trialwise conflict

adaptation in RTs.

Table 3. *Summary of the regression model of RT (ms) predicted from current trial conflict (no conflict vs. conflict), N-1 conflict (no conflict vs. conflict), and task type (endogenous vs. exogenous) with participant as a random factor.*

Variable	B	SE(B)	t	p
Intercept	776.83	22.68	34.25	*
Conflict	52.48	3.33	15.75	*
N-1 Conflict	-9.14	3.33	-2.74	*
Task	-212.71	3.63	-63.26	*
Conflict x N-1 Conflict	-18.57	6.67	-2.80	*
N-1 Conflict x Task	13.16	6.66	1.96	
Conflict x Task	-88.21	6.66	-13.23	*
N-1 Conflict x Conflict x Task	16.30	12.34	1.22	

* $p < .05$ significance

Between-trial adaptation effects.

With the confirmed presence of an overall RT conflict adaptation effect, the critical test was to determine if conflict processing or the carryover of control better explains the adaptation effects for the endogenous task. The results from the RT analysis replicate the findings of Mayr, Hubbard, and Kuhns (2014), showing very little conflict effect for the exogenous task with the endogenous distractor. In light of this and further supported by the significant difference between the endogenous and exogenous task and the significant interaction between the task type and conflict (see Table 3), the between-trial effects focused only on the endogenous task.

The results showed evidence consistent with a carryover effect more than conflict adaption. The conflict monitoring theory predicts that conflict processing is the critical trigger to control adjustments. Endogenous task trials that followed a trial where the participants' eyes went to the distractor were significantly slower. Moreover, the effect was particularly strong on conflict trials that followed distractor fixations. The exception was trials that followed conflict trials with cue inspections. Assuming cue inspections represent control attempts, these attempts in the presence of conflict would seem to have a beneficial effect on performance.

Between-trial contrasts.

An additional set of models tested two planned contrasts to test the predictions made by conflict monitoring and carryover accounts. The conflict monitoring theory predicts that N-1 conflict trials with N-1 distractor fixations should predict faster RTs, increased probability of task-cue inspections as indicators of control updates, and reduced probability of eye fixations to distractors. In contrast, a carryover account predicts

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previous N-1 conflict trials without N-1 distractor fixations should predict faster RTs, reduced probability of cue inspections, and reduced probability of distractor fixations

Two contrasts compared these predictions: (1) N-1 no-conflict trials relative to N-1 conflict trials and (2) N-1 no-conflict trials against N-1 conflict with fixations on the distractor. There was no contrast for N-1 no-conflict trials with eye fixations on distractors because no distractor was present on N-1 no-conflict trials.

A final set of three regression models predicted the contrasts for testing the between-trial adaptation effects for the probability of a distractor fixations, RT, and cue inspections (see Table 4 for summary).

Table 4. The model coefficients, standard errors, and t-values for hierarchal model for endogenous task distractor fixations, RTs, and cue inspections from two planned contrasts: N-1 no-conflict vs. N-1 conflict without distractor fixations and N-1 no-conflict vs. N-1 conflict with distractor fixations with each contrast and individual participants as a random factors.

Conflict effect	Variable	B	SE(B)	t	p
Distractor fixations	Intercept	27.48	2.93	9.38	*
	N-1 no-conflict vs. N-1 conflict without distractor fixations	-8.34	1.81	-4.62	*
	N-1 no-conflict vs. N-1 conflict with distractor fixations	2.08	2.54	0.82	
RT	Intercept	945.38	2.93	26.83	*
	N-1 no-conflict vs. N-1 conflict without distractor fixations	-42.52	14.40	-2.95	*
	N-1 no-conflict vs. N-1 conflict with distractor fixations	0.45	15.25	0.03	

* $p < .05$ significance

Table 4. (Continued).

Conflict effect	Variable	B	SE(B)	t	p
Cue inspections	Intercept	10.84	2.57	4.22	*
	N-1 no-conflict vs. N-1 conflict without distractor fixations	0.43	1.11	0.379	
	N-1 no-conflict vs. N-1 conflict with distractor fixations	2.19	1.31	1.67	

* *p* < .05 significance

Overall, the three sets of planned contrasts revealed evidence consistent with a carryover account for RTs and distractor fixations, but not for cue inspections. Between the two contrasts for distractor fixations, only the first contrast (N-1 no-conflict vs. N-1 conflict) predicted faster RTs on the current, conflict trial. The conflict monitoring theory predicts the opposite of this result that conflict processing triggers control adjustments that increase control and the increase in control should then improve performance and therefore reduce RTs. In the current experiment the opposite was true, the trials that followed conflict without eye fixations on the distractor showed a faster RTs. This pattern of distractor fixations is fully consistent with a carryover account.

The conflict effect for the distractor fixations also revealed evidence consistent with a carryover account. As predicted by the carryover account, N-1 conflict trials without eye fixations on the distractor showed a reduced probability of eye movements to the distractor than N-1 conflict trials also with N-2 eye fixations on distractors (see Figure 13).
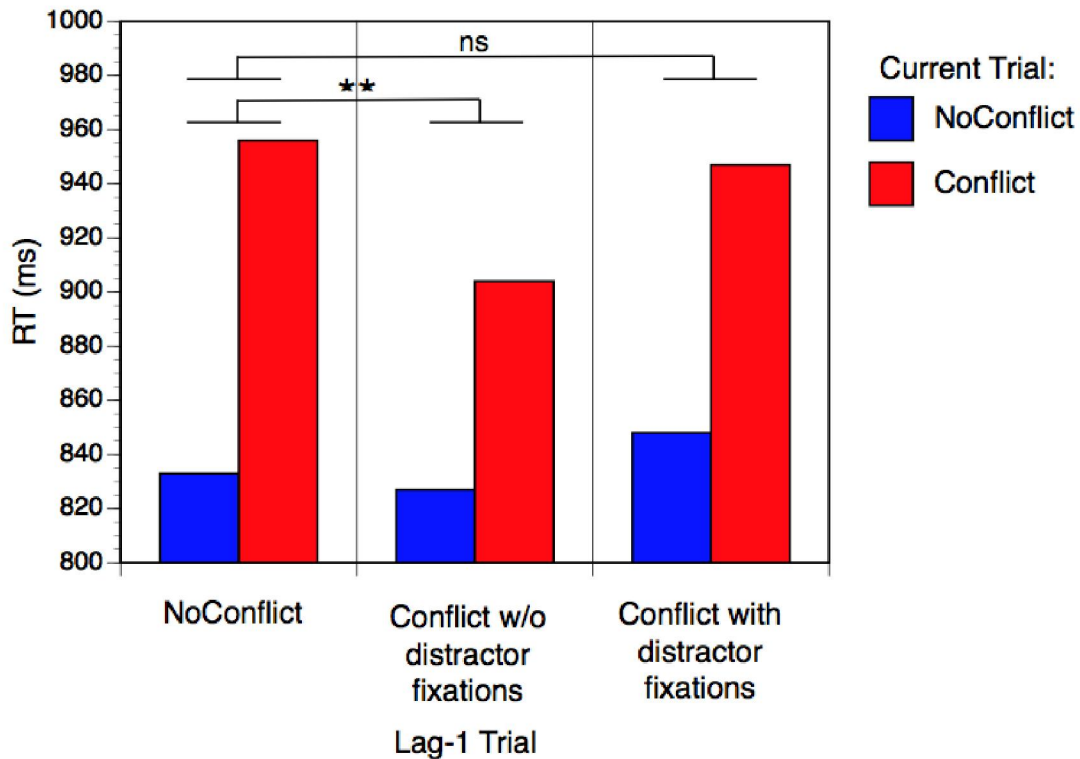
Figure 13. RT difference for N-1 no-conflict trials vs. N-1 conflict trials without distractor fixations and N-1 no-conflict trials vs N-1 conflict trials with distractor fixations.

Summary

This experiment produced very clear results regarding the effect of experienced conflict on the conflict-adaptation effect. When trial n-1 experienced conflict was high, as indexed through fixations to the distractor, the conflict adaptation effect was relatively small and non-significant. However, when the experienced conflict was low (i.e., eyes did not fixate the distractor) a robust adaptation effect was obtained. This pattern is not consistent with the conflict-monitoring model, which clearly predicts more adaptation after more experienced conflict. Instead, the results are consistent with the view that control states carryover across trials without intervening control attempts.

The results are less clear with regard to our attempt to use cue inspections as indicators as a process of task-set updating. There were some indicators that, at least occasionally, cue inspections were used in this manner. For example, there were higher rates of cue fixations for the exogenous relative to the endogenous task. However, there was also evidence that cue inspections themselves are subject to large carryover effects, which is not consistent with updating of task-sets. If cue inspections were updating events, then a reduced probability of cue inspections would be expected following a previous trial cue inspection. Even if cue inspections could be interpreted in terms of task-set updating, they did not behave in the way that would be expected from the conflict-monitoring theory. Specifically, there was no increase in cue fixations on conflict trials, nor after conflict trials. In other words, we were not able to demonstrate a feedback loop that leads from high previous trial conflict to updating and finally to improved conflict processing on the current trial.

CHAPTER V

GENERAL DISCUSSION

The main focus of this work was to understand how cognitive control deals with conflict. To this end I reviewed the literature, conducted a meta-analysis, and two empirical experiments that tested the predictions from the primary model of cognitive control, the conflict monitoring theory, against predictions from a carryover account inspired by Gilbert and Shallice's (2002) model of task-switching. The evidence reviewed and obtained in previous chapters all share a common theme that points towards a carryover account of conflict adaptation effects.

Whether or not conflict adaptation is task-specific or generalizes to all tasks is one issue debated in conflict adaption literature. The literature is mixed, but the results from the meta-analysis suggest conflict adaptation is task-specific. Task specific adaption would be consistent with Gilbert & Shallice's (2002) carryover model where carryover is a phenomenon that is limited to a specific task because the carryover results from priming a specific task-demand unit.

It is not clear whether the task demand units in the Gilbert and Shallice model truly capture the full breadth of how past control events influence future control events. It is important to also consider the influences of information stored in long-term memory. Task-switching literature provides evidence consistent with task-relevant information being organized in task-sets that are stored in long-term memory (Mayr & Kleigl, 2000; Meiran, 1996; Rogers & Monsell, 1995). These task-sets represent task-specific stimuli, responses, and rules.

In some instances previous control events do influence future control events. Jacoby et al. (2003) noted, one explanation of their blockwise conflict adaptation could be associative learning between cues and control states. In their account, any relevant environmental cues would become associated with control states. Mayr et al., (2014) explained a greater susceptibility to conflict following an interruption in their exogenous task relative to an endogenous task as the result of weaker task representations due to reduced control demands for the endogenous task. Mayr and Bryck (2005) also observed evidence in support of a learning account in a task-switching paradigm where learning accounted for improvements in performance of a task that shared SR associations but not an abstract rule for responding. Such results point toward a parsimonious, model of long-term memory where rules are simply an additional component of memory that influences the similarity between cues and memories (Mayr & Bryck, 2005). This account may extend to not only SR associations and rules, but also control states.

The conflict-monitoring model describes an independent detection and adjustment process of cognitive control. In contrast, the results from Ch. III reveal control can be engaged within a trial to improve the efficiency of allocation of eye-movements to targets and distractors. This type of dynamic, within-trial control adjustment is at odds with the Botvinick conflict monitoring theory and suggests a single detection-adjustment control process ((Braver, et al., 2007; Goschke & Dreisbach, 2008; Scherbaum et al., 2011)

Arguably the most important aspect of the conflict monitoring theory, is the role of the conflict monitor plays in triggering control adjustments (Egner, 2007). The results from Ch. IV suggest that conflict is not the primary trigger to increasing cognitive control. The capture paradigm provided evidence that is more consistent with a carryover of

control. In general, performance declined following conflict processing, but improved in conflict situations without conflict processing. The conflict monitoring theory predicts the opposite.

The combined results from the empirical work here both point toward a carryover account. Both the within-trial evidence that attention is dynamically regulated and also from the between-trial evidence that showed the level of control on the previous trial predicts performance on the current trial. Adapting Gilbert & Shallice's (2002) carryover model of task switching to also include the ability to store control states is a more parsimonious account. It is also an account that draws on previous learning and task-switching work (e.g., Mayr & Bryck, 2005).

A carryover account is also consistent with neuropsychological evidence that is inconsistent with the conflict monitoring theory. The ACC is hypothesized to carry out the conflict monitoring function in the conflict-monitoring model (Botvinick et al., 1999; Botvinick et al., 2001; Kerns, 2004; Kerns et al., 2006). Multiple neuropsychological studies with patients who have ACC damage, however, have reported no loss in the ability to perform conflict tasks (DiPelligrino, et al., 2007; Fellows & Farah, 2005)

Limitations in Eye Tracking

Eye tracking provides a relatively simple online measure of attention allocation. However, using eye fixations is limited in revealing how the information is processed. The results from Ch. IV produced two contradictory conclusions of cue inspections. N-1 cue fixations predicted current trial cue fixations, but N-1 cue fixations predicted faster RTs, which were interpreted to be control updates. One suggests weak control, but in another context also was interrupted to indicate a control update that explained faster RTs.

The problem with cue fixations is there is no way to know how the cues are used. Inattentional blindness is a well-known phenomenon that demonstrates people can fixate on a stimulus without processing it, if the stimulus is outside the current focus of attention (Mack & Rock, 1999).

Future Work

The next step in advancing online measures of cognitive control is to better understand if information is being processed and how it is being used. Scherbaum et al.'s (2011) use of SSVEP's is a good example of using EEG to observe online processing of conflict. In this respect EEG has a significant advantage over using eye-movements. The use of the static, task cues in the paradigm used in Ch. IV holds a great deal of potential for detection control attempts. But, with eye movements alone it is unclear when the cues are actually being processed.

Combining EEG with eye-movements is a difficult challenge. The electrical signals generated from the eye-movements interfere with the recordings of the electrical signals from the brain. Although electrical signals produced by the eyes moving are a definite challenge, previous work has combined eye-movements with EEG to detect event-related potentials (ERP) (Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011; Kliegl, Dambacher, Dimigen, Jacobs, & Sommer, 2012). Dimigen et al. (2011) used the N400 ERP, an electrical component associated with semantic mismatch (Kutas & Hillyard, 1980), in a realistic reading task that required participants to scan text left-to-right.

Combining techniques that allow for simultaneous EEG and eye-movement records could yield results that enable not only online measures of dynamic attention

allocation, but also attention allocation to an object. For example, ERP work using the so-called P300 has demonstrated it is associated with attention allocation to an object (Polish, 2003). Strayer and Drews (2009) used the P300 ERP in an eye-tracking study that investigated attention allocation to visual stimuli while driving under conditions of divided attention. Their results demonstrated that during conditions of divided attention, fixations on objects in the absence of a P300 were associated with worse recognition of the objects than when similar objects were fixated upon with a P300 ERP. Moreover, in conditions of undivided attention participants were more likely to fixate upon objects and elicit a P300 ERP. Combining these types of techniques with the paradigm from Ch. IV would not only allow for observation of cue inspections, but also for determining when the cue inspections were effective updating events or failed control updating attempts.

In light of the existing work it seems unlikely that the conflict-monitoring theory can explain the full range of conflict-adaptation effects. An account based on the idea that adaptation results from the carryover of control settings from the previous trial is a more promising alternative. Behavioral measures like eye-tracking offer great potential as an online measure of the allocation of attention. Combining eye-tracking with other neuroimaging techniques offers new potential. Additionally, new neuroimaging techniques such as optical brain imaging offer novel measures of direct brain measurement in traditional laboratory environments. The opportunities from new measures and insights from the current work combine together to offer an exciting step toward studies that further reveal the nature of cognitive control.

APPENDIX

META-ANALYSIS SOURCE LIST

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