

DISSOCIATING COMPONENTS OF COGNITIVE CONTROL USING HIGH-
DENSITY EVENT-RELATED POTENTIALS: IMPLEMENTATION OF CONTROL,
CONFLICT PROCESSING, AND ERROR MONITORING

By

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Abstract of Thesis Presented to the Graduate School
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Recent theories suggest that cognitive control is a dynamic process instantiated within a fronto-cortical network that implements regulative or strategic control over top-down processes, monitors and detects processing conflicts, and signals for adjustments in performance when necessary. We examined this complement of cognitive control processes behaviorally and neurally. To do this, we acquired high-density brain event-related potentials (ERPs) while 24 neurologically-normal participants performed a cued, single-trial Stroop task that temporally dissociated instruction-related regulative processes (i.e., representing and maintaining the attentional demands of the task), from evaluative processes (i.e., conflict processing, error monitoring). Implementation of control was reflected in a right frontal instruction-related slow-wave associated with the more attentionally demanding color-naming task. A mid-to-lateral frontal stimulus-related conflict N450 was elicited by the incongruent color-naming task condition.

Response-locked ERPs to incorrect responses, collapsed across task conditions, revealed a mid-fronto-central error-related negativity (ERN). Behaviorally, response times and error rates were greatest in the incongruent color-naming task condition, indicating Stroop response time and error-rate interference. Overall, ERPs are determined to be an effective methodology for examining component processes of cognitive control. Furthermore, findings are consistent with previous research indicating two distinct neural systems in cognitive control, one for regulative processes involved in the implementation of control and one involved in the evaluative processes of conflict detection and error monitoring.

CHAPTER 1 INTRODUCTION

Cognitive Control

Cognitive control refers to the ability to guide thought and action in accord with internal intentions (Botvinick, Carter, Braver, Barch, & Cohen, 2001; Cohen, Botvinick, & Carter, 2000; Miller, 2000; Miller & Cohen, 2001) and encompasses those processes necessary for controlled information processing and coordinated actions. Current cognitive neuroscience theories distinguish between at least two important components of cognitive control: a regulative or strategic component responsible for activation and implementation of control processes, and an evaluative component responsible for monitoring the need for control and signaling when adjustments in control are necessary (Botvinick et al., 2001; Kerns et al., 2004).

Regulative/Strategic Processes

Regulative processes are those involved in the top-down control of cognition and include functions such as representing and maintaining task context and goals (e.g., working memory), the allocation of limited attentional resources, as well as preparing to execute cognitive tasks and override prepotent response tendencies (Cohen, Barch, Carter, & Servan-Schreiber, 1999). Perhaps a prototypical cognitive task that requires the implementation of cognitive control is the Stroop color-word task (MacLeod, 1991; Stroop, 1935). Although there are many different versions of the original Stroop task (MacLeod, 1991), the basic paradigm requires participants to either read words or name the color in which the words are written. To perform this task successfully, participants

must selectively attend to one stimulus attribute (i.e., word or printed color). This is particularly true when naming the color of an incongruent or conflict stimulus (e.g., the word GREEN printed in blue) because there is a strong automatic tendency to read the word (GREEN), which competes with the less automatic instruction to name the color (blue). Typically, participants show robust Stroop interference effects, wherein there is increased reaction times (RT) or error rates when participants are required to name the color of the word when the word name and word color are incongruent (conflict condition). The ability to successfully complete this task and overcome the “conflict” illustrates selective allocation of attentional resources and the ability to select a weaker, task-relevant response in the face of competition from an otherwise more automatic, but task-irrelevant option (Miller & Cohen, 2001); a fundamental aspect of cognitive control.

Regulative processes of cognitive control also require the maintenance of task-relevant context and goals. Cohen and colleagues (1999) suggest that maintenance of context representations is critical to adequate performance on the Stroop task. For example, in order to respond to the appropriate dimension of the stimulus, participants must hold in mind the instruction for the trial, providing the necessary context for interpreting the stimulus and generating the correct response. In the card or Golden version of the Stroop task (Golden, 1978) frequently used in neuropsychological testing, task conditions are blocked, wherein all stimuli for each condition are presented as lists on their respective cards. This arrangement consistently reinforces the proper context (i.e., task instruction) and, therefore, places minimal demands on the representation and maintenance of context. In contrast, a single-trial computerized cued version of the Stroop task devised by Cohen et al. (1999) presents trials individually and randomly varies task instruction (color-naming, CN, word-reading, WR). To complete this task,

participants must maintain the context of the task instruction (CN or WR) prior to stimulus presentation and employ these context representations to provide the correct response.

Evaluative Processes

A second set of processes essential for cognitive control are those involved in the evaluation of performance and include functions such as detection of processing conflicts and performance monitoring. These evaluative processes are believed to play a crucial role in signaling for adjustments of top-down control needed to adapt to constantly changing task demands (Kerns et al., 2004). For example, in the card version of the Stroop task described above, participants show greater interference on the initial one or two trials in each block than on subsequent trials in a series (Botvinick et al., 2001). Additionally, participants completing a modified Stroop task show less interference on incongruent trials if the incongruent trials are frequent relative to congruent trials than if they are rare (Lindsay & Jacoby, 1994). The results of these studies indicate detection of conflict and subsequent adjustment in control processes to more efficiently perform the task as well as increased conflict when there is decreased expectancy of a conflict stimulus. Thus, cognitive control is a dynamic process that is most reliably invoked during tasks involving conflicts in information processing where modification of performance is required to successfully complete the task (Botvinick et al., 2001; Norman & Shallice, 1986).

Neural Correlates of Stroop Performance

As noted in the examples above, one experimental paradigm that consistently evokes response conflict conditions where cognitive control is necessary is the Stroop task. The Stroop task has been utilized by numerous cognitive scientists to examine a

myriad of cognitive functions, including: automatic and controlled cognitive processes (Posner & Snyder, 1975), selective attention (Rebai, Bernard, & Lannou, 1997), and disturbances in these processes due to psychiatric disorders (Cohen et al., 1999; Perlstein, Carter, Barch, & Baird, 1998). In addition, recent technological advances in hemodynamic- and electrophysiologically-based neuroimaging methods have led to increased insight into the neural correlates of the Stroop task, as well as the functional neural bases of cognitive control more generally. Traditionally, the Stroop task has been employed as an instrument used to measure pre-potent response inhibition (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), a function often attributed to the frontal lobes (Kiefer, Marzinzik, Weisbrod, Scherg, & Spitzer, 1998). Hemodynamic-based neuroimaging research has described many frontal sites as critical to the ability to overcome pre-potent tendencies, including: left inferior lateral cortex (Taylor, Kornblum, Lauber, Minoshima, & Koeppe, 1997), left superomedial cortex (Pardo, Pardo, Janer, & Raichle, 1990), right frontal polar cortex (Bench et al., 1993), and bilateral anterior cingulate cortex (Bench et al., 1993). More recently, the Stroop task has been used to examine not only the neural correlates of the ability to overcome pre-potent response tendencies, but also the neural correlates of the regulative and evaluative components of cognitive control.

Dissociation of Cognitive Control Processes

To distinguish among component processes of cognitive control, a modified version of the Stroop paradigm (Figure 1-1) has been introduced that allows one to dissociate the regulative and evaluative processes required to successfully complete the Stroop task (Cohen et al., 1999). In this modified Stroop task, participants are given an instruction before each trial indicating whether to read the word (a more automatic

response) or name the color (a condition requiring an increased amount of control due to the need to override the more automatic tendency to read the word). Following a brief delay, the Stroop color-word stimulus is presented and the participant responds. Thus, the task temporally separates the instruction-related regulative processes (representing the context/goal of the task in the CN or WR trials) from the response-related evaluative processes (the detection of incongruencies and errors and signaling for adjustments in control processes). This modified version of the Stroop task can be contrasted with the traditional Golden Stroop task, where participants respond in blocks to trials of the same type, thus temporally confounding regulative and evaluative processes.

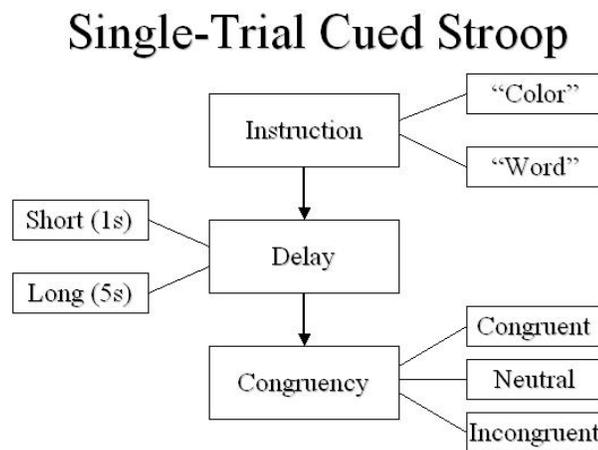


Figure 1-1. Schema of the single-trial Stroop task. Participants are first presented with an instructional cue (“Color” or “Word”), followed by a delay (1 or 5 seconds) and Stroop stimulus (congruent, neutral, incongruent).

Using the modified Stroop paradigm described above and event-related functional magnetic resonance imaging (fMRI) techniques, MacDonald et al. (2000) demonstrated a double dissociation of the roles of the dorsolateral pre-frontal cortex (dlPFC) and anterior cingulate cortex (ACC) in the regulative and evaluative component processes of cognitive control. Specifically, they found that during maintenance of the task context

(CN, WR), the left dlPFC was more active following instructions to perform the CN task than the WR task, consistent with a role of the dlPFC in preparation to execute the more demanding color-naming task. In contrast, ACC activity was increased upon presentation of incongruent color-word stimuli as compared to congruent color-word stimuli, consistent with a role in detection of response conflict. Based on these data, the authors suggested that the network necessary for cognitive control is dissociable into either the regulative or evaluative processes necessary for completion of separate task aspects. This study, however, did not allow for the specific examination of conflict processing and error detecting aspects of the evaluative component of cognitive control as the stimulus-related activity did not differentiate error trials from correct trials. Thus, the evaluative processes of conflict processing and error detection are potentially confounded. Despite the limitation, this study is of great importance to the cognitive control literature as it demonstrates a functional dissociation of not only the behavioral aspects of cognitive control, but also the neuroanatomical bases of cognitive control; elucidating the dlPFC mediated regulative control processes and the ACC mediated evaluative processes. This study also emphasizes the reality that conventional behavioral methodologies do not permit cognitive psychological processes and representations to be assessed directly. Furthermore, different neuroimaging methods have different strengths in the examination of cognitive and neural processes. For example, fMRI results represent blood flow-based hemodynamic response mechanisms to specific stimuli that are not particularly sensitive to the temporal course of neural activity. In the MacDonald study, the hemodynamic-response signal was examined over five 2.5-second increments per trial, while verbal responses to Stroop stimuli tend to occur in less than one second. Thus, results of this fMRI study reflect a spatially sensitive common neural output, rather than a direct

reflection of neural processes.

In contrast to hemodynamic-based measures of brain activity, event-related potentials (ERPs) provide direct measurement of neuronal electrical activity with sub-millisecond resolution. Moreover, under some circumstances, ERPs may be able to detect neural activity that is unaccompanied by secondary phenomena such as changes in regional blood flow or local metabolic activity (Gaetz & Bernstein, 2001). However, ERPs have limited spatial resolution, potentially leading to ambiguous spatial localization. Therefore, a convergence of information based on multiple neuroimaging methods, including scalp-recorded brain ERPs, can provide additional clarity into the nature of the cognitive and neuronal processes of cognitive control.

Event-related Potentials

In order to have a thorough understanding of the contributions of ERPs to theories of cognitive control, one must understand the assumptions behind ERP neuroimaging methods. Briefly, two major assumptions of ERP neuroimaging research are, first, that the distribution of electrical activity across the scalp indicates the activities of underlying neural structures, and, second, that this neural activity corresponds with specific cognitive states and processes. To the extent these assumptions are valid, electrical potentials then represent information regarding cognitive states and processes (Kutas & Dale, 1995). The electrical activity of the brain can be measured non-invasively across the scalp using electrodes. The electroencephalogram (EEG) is the record of the volume-conducted electrical activity of the brain. This overall background, or ongoing electrical activity, however, is not the interest of the present study; rather, the time- (event-) locked averaged electrical activity associated with the presentation of specific events is of

interest. Initially, the event-related signal associated with the presentation of a stimulus is embedded in the noise of the background EEG activity. Extracting the signal associated with a specific cognitive activity from the “noise” (background activity and measurement error) is accomplished by averaging multiple samples of the EEG that are time-locked to repeated occurrences of the event (i.e., stimulus or response) of interest. The logic of averaging is that the signal does not change from trial to trial, while the noise is random, thus, the signal is enhanced by a factor proportional to the square-root of the number of trials, while the noise is reduced essentially to zero (Fabiani, Gratton, & Coles, 2000). Due to the direct measure of electrical brain activity associated with specific cognitive events, ERPs are currently considered the “gold standard” in terms of temporal resolution among noninvasive imaging methods (Fabiani et al., 2000).

ERP waveforms typically consist of a series of discrete deflections (i.e., peaks and troughs), often followed by so-called slow-wave potentials¹. Characteristics of ERP waveforms usually include descriptors of polarity (positive or negative) and latency (in milliseconds). For example, “P300” refers to an ERP with a positive peak that has an approximate latency of 300 milliseconds. Another similar labeling system involves a descriptor of polarity followed by a number representing the ordinal latency of the component. Using these labeling criteria, “P3” refers to the third positive peak in the ERP waveform. Other descriptors, such as scalp location at which the component is maximal (e.g., frontal P3) are also used.

Cortically, the activity of neurons associated with ERP activity is attributed primarily to post-synaptic potentials (Williamson & Kaufman, 1990). As an example,

¹ A slow-wave potential is a temporally extended change in the ERP waveform, rather than a distinct or punctate deflection.

consider the case of an excitatory post-synaptic potential (although similar activities occur for inhibitory post-synaptic potentials). While at rest, neurons contain a lesser concentration of sodium ions (Na^+) and a greater concentration of potassium ions (K^+) inside the cell. When the dendrites of a neuron receive an excitatory signal from an adjacent neuron, the resulting change in the cell membrane allows Na^+ to flow into the cell. This results in a reduction of positive ions in the extracellular space—making the space more negative. This negativity in the extracellular space is known as the *current sink*. The positive Na^+ ions that entered the cell repel like-charged ions, and create a current that sends the K^+ ions toward the cell body. This buildup of positive charge near the cell body is known as the *current source*. The current source repels like-charged ions in the extracellular space, which are then attracted back to the sink, producing a dipolar extracellular current. It is this extracellular current that produces the electrical potentials. ERPs, then, represent the net activities of a large population of neurons that must be synchronously active and configured in such a way they produce dipolar electromagnetic fields that can be measured at the scalp. Such a synchronously activated configuration of neurons is known as an “open field,” and usually involves the alignment of neurons in an orientation parallel to the scalp (Coles & Rugg, 1995)².

ERPs and Cognitive Control

Electrophysiological Correlates of Evaluative Processes

In cognitive control research, ERPs can serve an important purpose because they are particularly sensitive to the temporal course of neural activity and, by extension, the concomitant underlying sensory, motor, and cognitive processes. Of particular interest to

² Information on the physiological bases of ERPs taken from Coles & Rugg, 1995; Fabiani et al., 2000; Simmons, 1998. Please see these sources for additional information.

the current study is the idea that ERPs can be used to temporally dissociate the component processes of cognitive control by facilitating inferences regarding the timing, level of processing, and, roughly, the anatomical location of neural mechanisms supporting these processes. The preponderance of research on component processes of cognitive control using ERPs has focused on the evaluative components of conflict detection and error monitoring. For example, using tasks that reliably invoke processing conflicts between simultaneously active task-relevant representations (e.g., Stroop or Eriksen flanker tasks³), investigators have found a reliably evoked late fronto-central ERP signature referred to as the N450 or N2 component (van Veen & Carter, 2002a, 2002b; West, 2003). These components both reflect conflict detection processes and differ only based on the stimulus paradigm presented (e.g., Stroop vs. Eriksen flanker tasks). Conflict detection in the Stroop paradigm has been associated with the negative deflection between 400ms and 500ms known as the N450 (Liotti, Woldorff, Perez, & Mayberg, 2000; West & Alain, 1999), while conflict associated with the incongruent condition of the Eriksen flanker has been associated with a slight negative deflection in the ERP waveform known as the N2 (van Veen & Carter, 2002b). These ERP components are largest under conditions in which response conflict is high, such as the incongruent condition of the Stroop color-naming task (Grapperon, Vidal, & Leni, 1988; Liotti et al., 2000; Rebai et al., 1997). Increased amplitude of the N450 has been observed following unexpected or rare incongruent trial presentation (West & Alain, 2000b), consistent with the hemodynamic-based neuroimaging results presented

³ The Eriksen Flanker task (Eriksen & Eriksen, 1974) consists of a target central stimulus “flanked” by either congruent or incongruent stimuli. For example, participants may be instructed to press a button with their left hand if a central target arrow points left (e.g., <) or a button with their right hand if a central target arrow points right (e.g., >). For congruent trials the flankers are the same as the specified target (e.g., <<<<<), while incongruent trials have flankers that are opposite the target (e.g., <<<<<).

previously of MacDonald et al. (2000) implicating the role of the ACC in conflict detection. In support of this hypothesis, source localization algorithms have also localized regions of the ACC as the neural generators of the N450 and N2 components (van Veen & Carter, 2002a, 2002b; West, 2003). These results implicate the N450 and N2 components as neurobiological indices of conflict detection, and support the role of ACC as a conflict detection mechanism.

Detection of errors is another component of the evaluative processes in cognitive control that, due to the exquisite temporal sensitivity of electrophysiological-based neuroimaging methods, has been widely investigated using ERPs. The detection of errors has been associated with a midline fronto-central negative deflection in response-locked ERPs that occurs within 100ms of committing an error. This negative deflection is known as the error-related negativity (ERN), and is the first identified neurobiological index of performance monitoring (Dahaene, Posner, & Tucker, 1994; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Gehring, Goss, Coles, Meyer, & Donchin, 1993; Luu, Flaisch, & Tucker, 2000). The precise function responsible for the ERN continues to be debated (Cohen et al., 2000b; Gehring & Knight, 2000); however, the ERN has typically been referred to as a representation of an error/conflict monitoring system that operates across various stimulus and response modalities. Specifically, the ERN has been found with visual, auditory, and movement responses (Bernstein, Scheffers, & Coles, 1995; Holroyd, Dien, & Coles, 1998), is present following errors of omission as well as errors of commission (Falkenstein et al., 2000), and is greatest in amplitude when participants are aware that an error has been made (Luu, Collins, & Tucker, 2000; Scheffers & Coles, 2000)--consistent with the action of an error detector/performance monitor in cognitive control. Furthermore, the ERN is observed when participants make

“partial” errors (begin to make an error but spontaneously correct themselves), and is greater in amplitude on the trials with “partial” errors than errors where the conflict is not produced in time to spontaneously correct the response (Gehring et al., 1993). These results implicate the ERN as an on-line index of error detection or performance monitoring. Such an index is critical because an important function of the human brain is to monitor behavior and prevent undesirable actions. Like the N450 and N2 components, dipole-modeling techniques have localized the neural activity associated with the ERN to the ACC (Holroyd et al., 1998; van Veen & Carter, 2002b). In fact, van Veen and Carter (2002a) reviewed multiple studies of the N2 and ERN components and concluded that both components are representations of similar conflict detection processes. Specifically, they concluded that the N2 reflects pre-response detection of conflict between competing response tendencies, while the ERN reflects post-response detection of incompatible responses following error trials. The similarities between the N2/N450 and the ERN provide additional support for a model of cognitive control with ACC mediated evaluative processes detecting incongruities and possibly signaling for changes in the top-down control of cognition.

Electrophysiological Correlates of Regulative Processes

Regulation of cognitive control has also been examined using ERPs. The allocation of attentional resources under challenging task conditions and the active maintenance of goal/task-representations have been shown to be reflected in differential ERP slow-wave activity between tasks requiring differing levels of attentional demands (Curtin & Fairchild, 2003). Under the appropriate task conditions, investigators have observed a slow-wave in the ERP that appears to be associated with the implementation of cognitive control, perhaps reflecting an active biasing of processing in favor of the

more attentionally-demanding aspect of the task (Curtin & Fairchild, 2003; West, 2003). This slow-wave has also been used to distinguish between subsequent correct and incorrect responses on a version of the cued-Stroop task, with greater slow-wave activity preceding correct than incorrect responses (West, 2003). The slow-wave activity that differentiates trials where there is a “dysregulation” of control processes (incorrect trials) and trials where control is adequately implemented (correct trials) also supports the contention that slow-wave activity reflects the implementation of control processes.

Dissociation of Cognitive Control Component Processes using ERPs

Cognitive control component processes have also been dissociated temporally using ERPs. Using a variation of the modified Stroop described above (Cohen et al., 1999; MacDonald, Cohen, Stenger, & Carter, 2000), West (2003) reported a temporal dissociation between the regulative and evaluative component processes of cognitive control. Following presentation of task instruction, implementation of regulative processes was exhibited by an occipital-parietal slow-wave that differentiated correct (“goal-compatible”) and incorrect (“goal incompatible”) response trials. In addition, implementation of control was associated with frontal slow-wave ERP modulation that differentiated CN trials, more attentionally demanding trials where participants prepare to override the more automatic WR response, from less demanding WR trials. These findings are consistent with the allocation of increased attentional resources during tasks requiring increased cognitive processes, as well as increased implementation of control on correct trials. Conflict detection was associated with a fronto-central N450 with greater amplitude for incongruent than congruent trials. Consistent with a role in conflict monitoring, the N450 amplitude was reflected equally for incongruent trials in both CN and WR conditions. In addition, West reported a frontal slow-wave component 500ms to

600ms following incongruent stimulus presentation. This component, known as the conflict slow-wave potential (conflict SP), was interpreted to reflect the allocation of increased attentional resources in preparation for future incongruent trials during the incongruent condition of both CN and WR trials. These findings taken together indicate that the different neural processes reflecting the regulative and evaluative of cognitive control can be dissociated in time using ERPs.

Predictions

Given the sensitivity of ERPs in examining the temporal course of neural activity, the goal of the present study was to use the modified Stroop task developed by Cohen and colleagues to give added support to the temporal dissociation of the regulative and evaluative components of cognitive control using high-density event-related potentials. Based on previous research the following predictions are offered:

Behavioral Data

It is predicted that standard Stroop effects for both RT and error-rates will be manifest by increased RTs and error rates to incongruent CN and WR conditions. In addition, it is predicted that interference effects will be disproportionately greater in the CN as compared to the WR task. It is also predicted that facilitation effects (faster RTs to congruent than neutral conditions) for both the CN and WR tasks will be manifest. For delay conditions, it is hypothesized that greater time between instruction and stimulus presentation will allow for increased implementation of regulative processes; therefore, fewer errors and faster RTs are predicted for trials following the 5s delay, as compared to trials following the 1s delay.

ERP Data

Since the behavioral data alone cannot address the potential mechanism(s) underlying task performance and allocation/implementation of cognitive control resources, ERPs are necessary to further examine the electrophysiological signatures of the following possibilities (Figure 1-2)⁴:

Regulative Processes

- Regulative processes associated with the preparation to override more automatic response tendencies and the maintenance of task-relevant representations are predicted to be manifest in frontal slow-wave activity locked to the task instructional cue that will differentiate preparation to engage in the more attentionally demanding CN task as compared to the more automatic WR task.
- In addition, it is hypothesized that lapses in regulation of cognitive control processes leads to increased errors. This will be examined in instruction-locked slow-wave ERP activity collapsed across conditions for error and correct trials. It is predicted that task instruction-related slow-wave activity will differentiate subsequent correct and incorrect trials.

Evaluative Processes

- Evaluative processes associated with conflict detection are predicted to be reflected in an N450 ERP deflection that has increased amplitude to stimulus-locked incongruent vs. congruent CN stimuli.
- Evaluative processes associated with error processing will be reflected in response-locked ERPs that exhibit an increased ERN following incorrect trials that is less pronounced during correct trials--indicative of the detection of incompatibilities (conflicts) between the response given and the accurate response.

⁴ Examination of the effect of delay on stimulus-locked ERP reflections of task (CN, WR) effects is currently underway. These analyses, however, are incomplete and will not be discussed. Additionally, delay x congruency effects for each task will not be examined since the number of trials per condition is low (< 28, see Methods section below) resulting in inadequate signal-to-noise ratio for examining these effects.

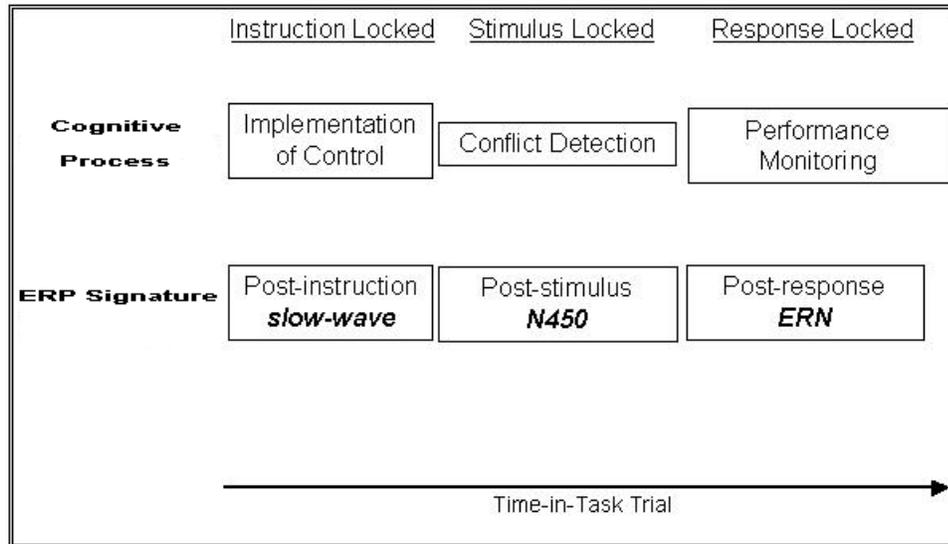


Figure 1-2. Schemata of cognitive control functions and subsequent ERP manifestations predicted in the current study.

CHAPTER 2 METHOD

Participants

Twenty-four right-handed individuals (14 female) between the ages of 18 and 24 participated in the study in exchange for course credit. All participants provided written informed consent according to procedures established by the University of Florida Health Science Center Institutional Review Board. Participants were screened for depressive or anxious symptoms that may influence results using the Beck Depression Inventory (Beck & Steer, 1987; Beck, Steer, & Garbing, 1988) and Beck Anxiety Inventory (Beck & Steer, 1990), respectively. Descriptive information regarding participants' age, education, and depression and anxiety levels is reported in Table 1. Participants were excluded if they reported previous neurological insults, traumatic brain injury (TBI), psychiatric diagnosis, current psychotropic medication use, or color-blindness (color-blindness was assessed using the Ishihara pseudo-isochromatic color plates, Clark, 1924). All participants reported normal or corrected-to-normal vision.

Table 2-1. Demographic information

	Mean	Standard Deviation	Range
Age (years)	19	1.4	18 - 24
Education (years)	13.4	1.0	12 - 16
Beck Depression Inventory score	5.5	5.2	0 - 25
Beck Anxiety Inventory score	5.2	4.8	0 - 19

Materials and Procedure

Participants performed a computerized single-trial, cued version of the Stroop task (see Figure 1-1), originally developed by Cohen et al. (1999). In this task, each trial began with the computer presentation of an auditory instructional cue (the word "color")

or “word”), followed, after a short delay, by a visual stimulus, which remained on the screen until participant’s response. Stimuli comprised the same three colors and color-words (red, green, and blue) used in the card Stroop (Golden, 1978), and commonly employed in clinical neuropsychological settings. Participants were instructed to respond verbally to the stimulus as quickly and accurately as possible. RTs were determined by a voice-activated relay connected to the computer, and the examiner manually coded response accuracy. Participants performed the color-naming and word-reading tasks, each comprising three congruency conditions. Congruent stimuli were words printed in the same color (e.g., “RED” printed in red), incongruent stimuli were words printed in a different color (e.g., “RED” printed in blue), and neutral stimuli were animal names printed in red, green, or blue (e.g., “BEAR” printed in red) for the color-naming trials and words displayed in white for word-reading trials. The context provided by the task instruction (e.g., color) must be used to override the influence of the stronger dimension (i.e., word) when the task is to respond to the less prepotent or automatic dimension (i.e., color). Additionally, reliance on context was increased by (a) varying the task to be performed on each trial and (b) introducing a delay between the task instruction for each trial and the stimulus to be responded to. For the current task, we used two delays (stimulus onset asynchrony, SOA, of 1s and 5s). Visual stimuli were presented in the center of a visual display, and delivered using an Apple Macintosh computer using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993). A total of 336 experimental trials were distributed equally across task and congruency, resulting in 28 trials of each type.

Prior to acquisition of electrophysiological data, participants completed a practice block consisting of random presentation of 12 trials, one of each stimulus type. On these

trials, if the participants RT was over 1000ms, an auditory beep was presented, indicating to the participant a need to respond more quickly.

EEG Acquisition and Reduction

EEG Acquisition

EEG was recorded from 64 scalp sites using a 64-channel geodesic sensor net (Figure 2-1) and amplified at 20K using an Electrical Geodesics Incorporated (EGI) amplifier system (nominal bandpass .10 – 100Hz). Electrode placements enabled recording vertical and horizontal eye movements reflected in electro-oculographic (EOG) activity: one placed above and below each eye and centered around the pupil to record vertical eye movements; the others placed at the outer canthus of each eye for recording horizontal eye movements. EEG was referenced to Cz and was digitized continuously at 250Hz with a 16-bit analog-to-digital converter. A right posterior electrode served as common ground. The impedance of all electrodes was kept below 50 k Ω , consistent with procedures suggested by the manufacturer.

EEG Data Reduction

Due to the volume conducting nature of the brain, no one site on the head can be considered an “inactive” reference site (Tucker, Liotti, Potts, Russell, & Posner, 1994); therefore, data was mathematically rereferenced against an average reference (Bertrand, Perrin, & Pernier, 1985). In this procedure, the activity of each electrode site is reflected as the difference between itself and the average of all the other recording sites. Editing of the EEG for movement, electromyographic muscle artifact, electro-ocular eye movement, and blink artifacts was performed by computer algorithm in Brain Electrical Source Analysis software (BESA; (Scherg, 1990).

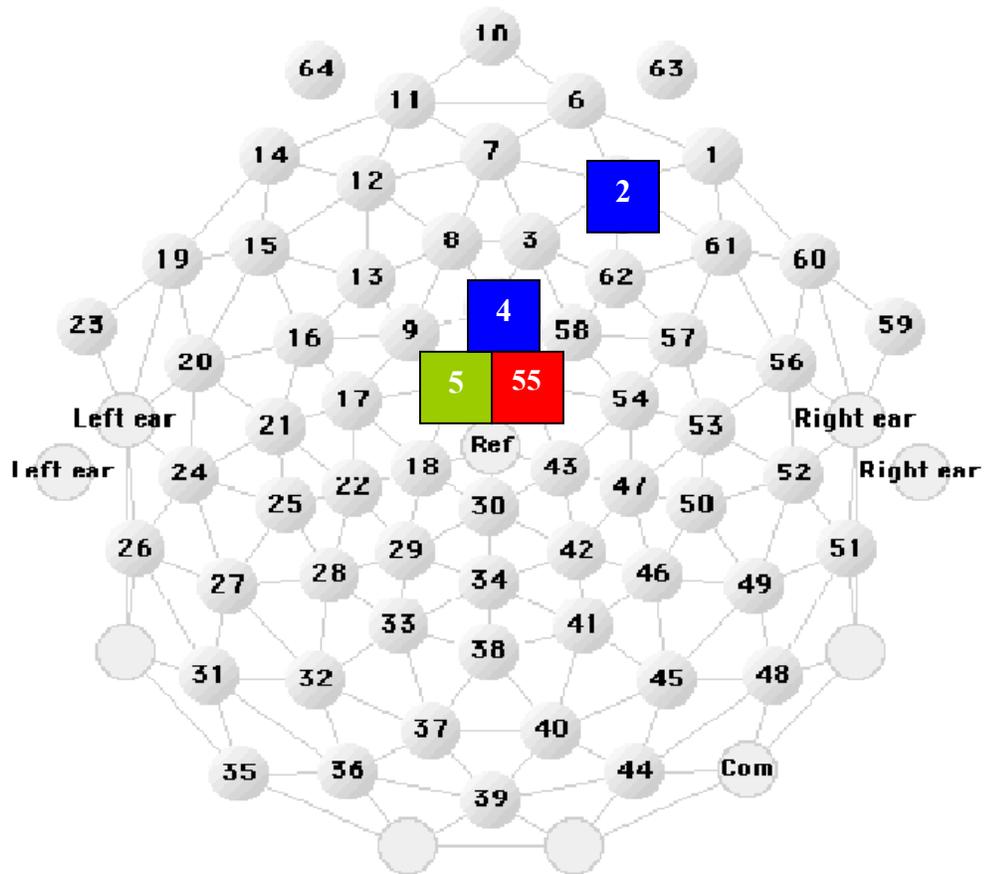


Figure 2-1. Sensor layout of 64-channel geodesic sensor net. Slow-wave activity was quantified at scalp sites #2 and #4 (blue); N450 activity at scalp site #55 (red); and, ERN activity at scalp site #5 (green). See ‘ERP Data Analyses’ in text for details.

Individual-subject ERP averages were divided into three categories and included a pre-stimulus baseline period: auditory task instruction-related activity, visual stimulus-presentation activity, and response-related activity (see Figure 1-2). Instruction-locked epochs, associated with the implementation of control, were extracted from 100ms prior to instruction presentation to 1000ms post instruction presentation. Instruction-locked epochs were calculated for correct trials of both the presentation of the color-naming and word-reading tasks. Similarly, instruction-locked epochs were extracted separately for correct and incorrect responses from 100ms prior to instruction presentation to 1000ms post instruction presentation, collapsed across color-naming and word-reading tasks.

Stimulus-locked epochs, associated with the detection of conflict, were extracted with a duration of 100ms prior to stimulus presentation and 750ms post-stimulus presentation. Individual subject averages were calculated for the correct-trial congruent, neutral, and incongruent stimulus-locked conditions. Response-locked averages were created separately for correct and incorrect responses, collapsed across color-naming and word-reading tasks, as well as congruencies. Collapsing across conditions was necessary because of insufficient numbers of incorrect responses to conduct specific error x congruency analyses. In addition, two-participants did not make any errors, their data, therefore, were not included in the analyses of response-related activity. Response-locked activity was extracted with a duration of 400ms pre-stimulus presentation and 400ms post-stimulus presentation. All averaged ERP epochs were baseline corrected using a 100ms window prior to stimulus or response onset and digitally filtered using a 30 Hz low-pass filter and a .5 Hz high-pass filter.

Statistical Analyses

Behavioral Data Analyses

For analysis of behavioral data, correct-trial RTs and overall error rates were analyzed separately. For each trial type and participant, we calculated the median RT for correct responses as well as proportion of errors by subjecting them to 2-Task x 2-Delay x 3-Congruency repeated-measures analysis of variance analyses (ANOVA). Tests of simple effects were used to decompose interaction effects. For error rates, due to the high probability of no errors in several conditions (e.g., congruent word-reading condition), raw data were normalized prior to analysis using the arcsine transformation (Neter, Wasserman, & Kutner, 1985).

ERP Data Analyses

Analysis of ERP waveforms focused on instruction-related, stimulus-related, and response-related activity as indicated in Figure 1-2. Statistical analyses of ERP waveforms were performed on mean voltages over specified temporal windows extracted from individual electrode sites. Scoring windows and electrode positions for each condition of interest were determined by examination of grand-average ERP waveforms and spline-interpolated scalp voltage distribution plots (Perrin, Pernier, Bertrand, & Echallier, 1989). Instruction-related activity was quantified at electrode site #2 (see Figure 2-1) and was examined over the period of 800ms to 1000ms post-stimulus presentation. Paired t-tests were conducted between the CN and WR instruction-related slow-wave activity. Additionally, instruction-related activity for subsequent correct and incorrect trials, collapsed across conditions, was quantified at electrode site #4 (see Figure 2-1) and was examined for the period of 700 to 1,000ms post-instruction presentation. Stimulus-related activity was examined over the period of 440ms to 500ms post-stimulus presentation, and was quantified at electrode site #55 (see Figure 2-1). Paired t-tests examined conflict detection through comparison of congruent and incongruent CN stimulus presentation. Response-related activity was examined over the period of 32ms to 72ms post-response, and quantified at electrode site #5 (see Figure 2-1). Paired t-tests were used to compare mean amplitudes of correct and incorrect responses. Previous research has shown the ERN and the N450 to be phasic components of the ERP waveform (i.e., brief deflections, Rebai et al., 1997; West & Alain, 1999), and durations for examination were chosen to reflect their short-term nature. Slow-wave activity is tonic in nature, therefore, a broader window for averaging was chosen.

CHAPTER 3 RESULTS

Behavioral Analyses

Initial analyses examined the possibility of a speed/accuracy trade-off by correlating RT and error-rates. Analyses revealed that RT and error-rate data were negatively correlated ($r = -.30$); however, the correlation was not significant ($p > .10$), indicating a slight, but non-significant speed/accuracy trade-off.

Error Rate Analyses

Mean error rates and standard errors as a function of task condition, congruency, and delay are provided in Table 3-1. Analyses revealed the standard Stroop effects: A main effect of task, $F(1,23) = 10.51, p < .01$, with WR more accurate than CN; a main effect of congruency, $F(2,46) = 53.2, p < .01$, with significantly more errors in the incongruent condition than congruent condition, $F(1,23) = 59.53, p < .01$, and the neutral condition, $F(1,23) = 55.51, p < .01$. There was also a Task x Congruency interaction, $F(2,46) = 7.02, p < .01$, with increased errors in the incongruent condition of the CN task compared to the congruent condition, $F(1,23) = 10.86, p < .01$, and the neutral condition, $F(1,23) = 6.40, p < .01$, of the CN and WR tasks (i.e., error rate interference), but no significant difference in error facilitation (neutral condition errors - congruent condition errors), $F(1,23) = .46, p > .40$ (Figure 3-1). Of note is the finding that there was not a significant main effect of delay, $F(1,23) = 1.01, p > .50$, and delay did not significantly interact with any task, $F(2,46) = 2.55, p > .10$, or congruency conditions, $F(2,46) = .62, p > .50$.

Table 3-1. Means and standard errors of error rates (%) in the single-trial Stroop

	<u>M</u>	<u>SE</u>
Color-naming		
<i>Short Delay</i>		
Congruent	.31	.20
Neutral	2.01	.70
Incongruent	10.20	2.70
<i>Long Delay</i>		
Congruent	1.39	.40
Neutral	1.54	.40
Incongruent	11.90	3.10
Word-reading		
<i>Short Delay</i>		
Congruent	.31	.20
Neutral	1.08	.40
Incongruent	4.32	.90
<i>Long Delay</i>		
Congruent	.62	.30
Neutral	.93	.40
Incongruent	3.40	.70

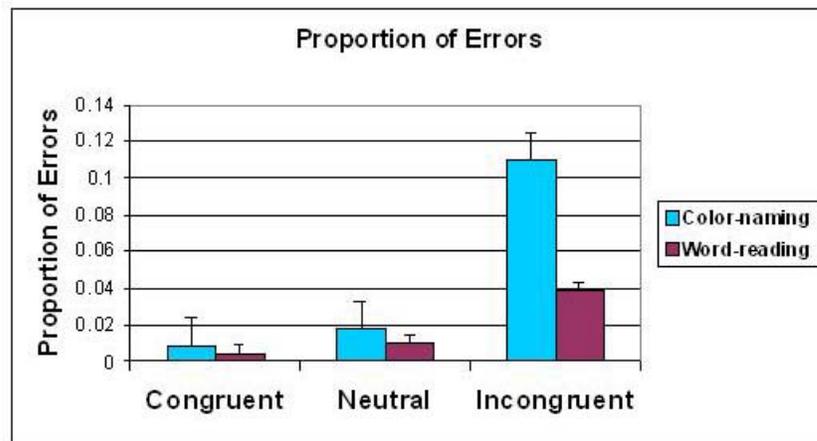


Figure 3-1. Error rates by task and congruency conditions collapsed across delay. Error bars represent standard errors.

RT Analyses

Means and standard errors of median RTs as a function of task condition, congruency, and delay are provided in Table 3-2. As with the accuracy data, analyses of

RT data revealed the standard Stroop effects: A main effect of task, $F(1,23) = 47.31$, $p < .01$, with WR faster than CN; a main effect of congruency, $F(2,46) = 53.2$, $p < .01$, with significantly slower RTs in the incongruent (i.e., interference) condition as compared to the neutral condition, $F(1,23) = 51.20$, $p < .01$, and congruent condition, $F(1,23) = 64.71$, $p < .01$, and a facilitation effect as evidenced by significantly faster RTs to congruent conditions compared to neutral conditions, $F(1,23) = 6.68$, $p < .05$. There was a significant Task x Congruency interaction, $F(2,46) = 12.6$, $p < .01$, with stronger interference effects in the CN task compared to the WR task, $F(1,23) = 17.99$, $p < .01$ (see Figure 3-2). Similar to the error rate analyses, there was not a significant main effect of delay, $F(1,23) = .13$, $p > .70$, and delay did not significantly interact with task, $F(1,23) = .16$, $p > .60$, or congruency conditions $F(2,46) = 1.25$, $p > .25$.

Table 3-2. Means and standard errors of median RT (ms) in the single-trial Stroop

	<u>M</u>	<u>SE</u>
Color-naming		
<i>Short Delay</i>		
Congruent	735.88	25.73
Neutral	799.67	23.19
Incongruent	895.65	32.79
<i>Long Delay</i>		
Congruent	743.65	23.59
Neutral	777.46	22.71
Incongruent	896.58	29.67
Word-reading		
<i>Short Delay</i>		
Congruent	724.50	25.72
Neutral	721.90	23.88
Incongruent	800.73	33.07
<i>Long Delay</i>		
Congruent	723.42	27.58
Neutral	717.83	27.42
Incongruent	805.65	34.96

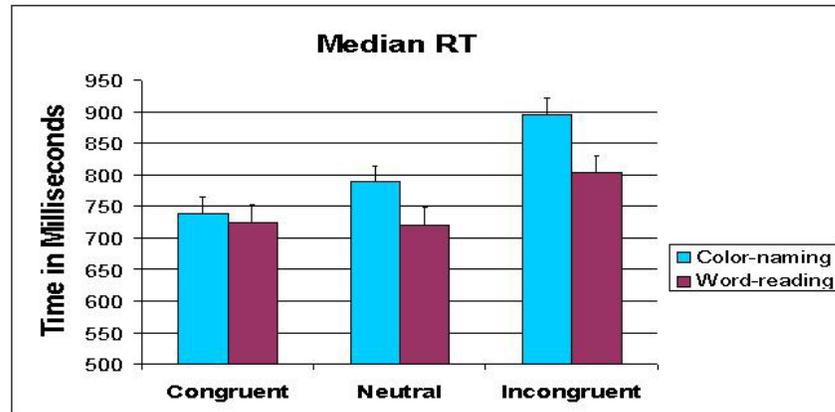


Figure 3-2. Median RTs by task and congruency conditions collapsed across delay. Error bars represent standard errors.

ERP Analyses

Instruction-related Activity

Spline-interpolated scalp voltage maps for instruction-related ERP activity showed a right inferior frontal difference between the CN and WR instruction presentation (Figure 3-3). ERPs to the task instructional cues (CN or WR) showed differential slow-wave activity quantified at scalp electrode site #2 following instructions to engage in the CN and WR tasks $t(23) = 1.73, p < .05$ (Figure 3-4). These findings are consistent with the deployment of regulative processes associated with the implementation of cognitive control to the more attentionally-demanding CN task (e.g., implementation of control reflected in preparation to override the prepotent WR response tendency). Additionally, inspection of spline-interpolated scalp voltage maps revealed a medial frontal difference between instruction-related activity of subsequent correct and incorrect responses (Figure 3-5). ERP slow-wave activity quantified at scalp site #4 revealed slow-wave activity that differentiated subsequent execution of correct and incorrect responses collapsed across conditions, $t(23) = 6.3, p < .01$ (Figure 3-6).

Stimulus-related Activity

The behavioral data (RTs, error rates) did not differ as a function of delay; therefore, stimulus-locked ERPs were collapsed across delay conditions. In addition, increased conflict was reflected in the significantly longer RTs to the incongruent CN condition as compared to the incongruent WR condition; therefore, ERP analyses focused on the congruent and incongruent CN conditions, collapsed across delay. Consistent with previous research (Liotti et al., 2000; West, 2003; West & Alain, 1999), spline-interpolated scalp voltage maps for stimulus-related ERP activity showed a mid to right-lateral frontal difference between the congruent and incongruent conditions of the CN task (Figure 3-7). Stimulus-locked ERPs showed significantly greater N450 deflection to the incongruent than congruent stimuli of the CN task quantified at scalp site #55 approximately 450ms post-stimulus presentation, $t(23) = 3.28, p < .01$ (Figure 3-8). Similar findings have been interpreted as the neural representation of conflict detection in the incongruent condition as compared to decreased conflict in the congruent condition (Liotti et al., 2000; West & Alain, 2000b).

Response-related Activity

Spline-interpolated scalp voltage maps for response-related ERP activity revealed a medial-frontal difference between the correct and incorrect responses, collapsed across task and congruency due to insufficient error trials (Figure 3-9). Response-locked ERPs to correct and incorrect responses exhibited a significant negative deflection (ERN) quantified at scalp site #5 occurring approximately 50ms following incorrect responses that was not present following correct responses, $t(21) = 2.11, p < .01$ (Figure 3-10). These results are consistent with previous research and have been previously interpreted

to represent the detection of conflict in task performance (Falkenstein et al., 2000; Gehring et al., 1993; van Veen & Carter, 2002a).

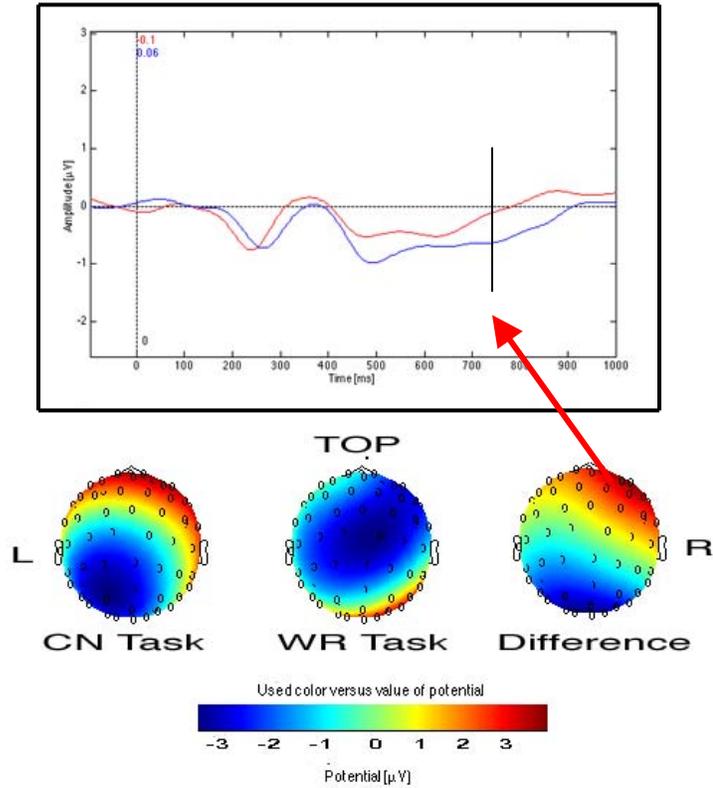


Figure 3-3. Top view of spherical-spline interpolated voltage maps representing instruction-related activity of the CN task, WR task, and the difference between the two tasks (CN – WR, bottom). ERP waveforms of the grand average differential slow-wave activity between the CN and WR tasks at scalp site #2 (top).

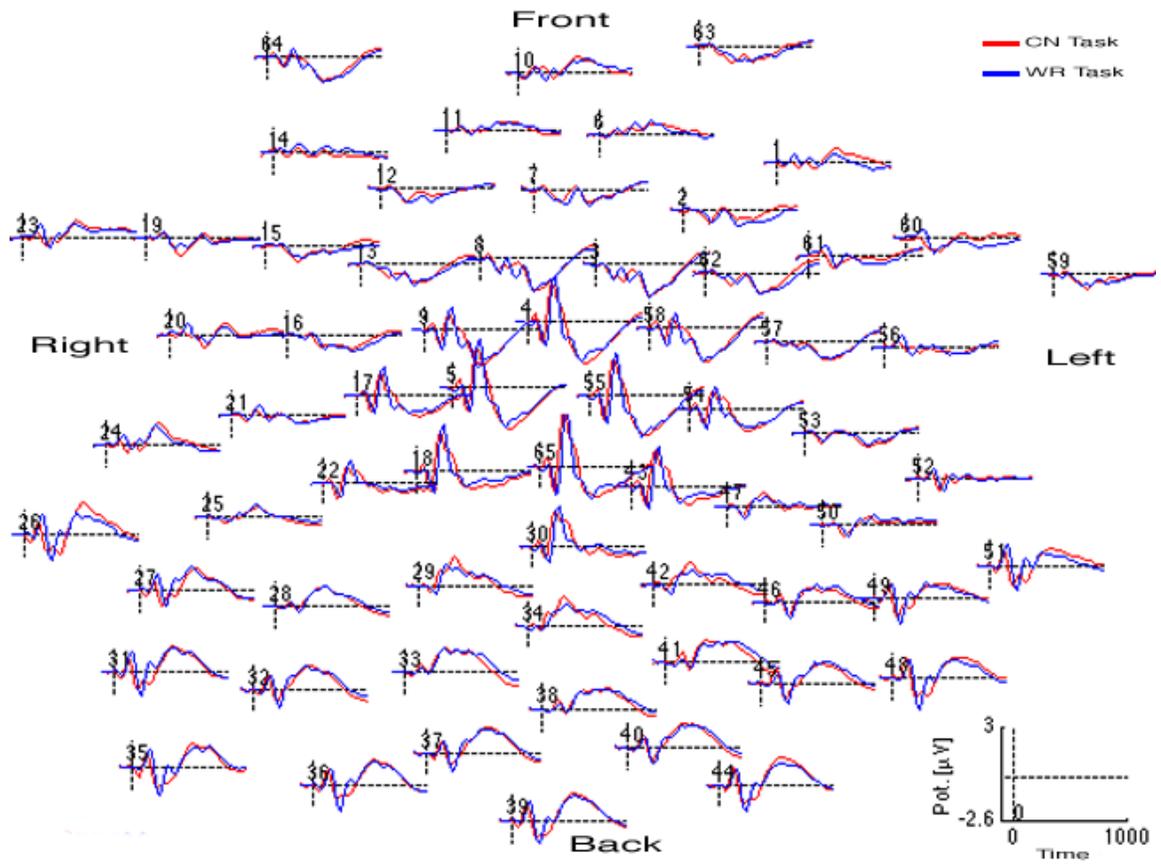


Figure 3-4. Grand average instruction-locked ERPs for all scalp sites of the CN (red) and WR (blue) task presentation.

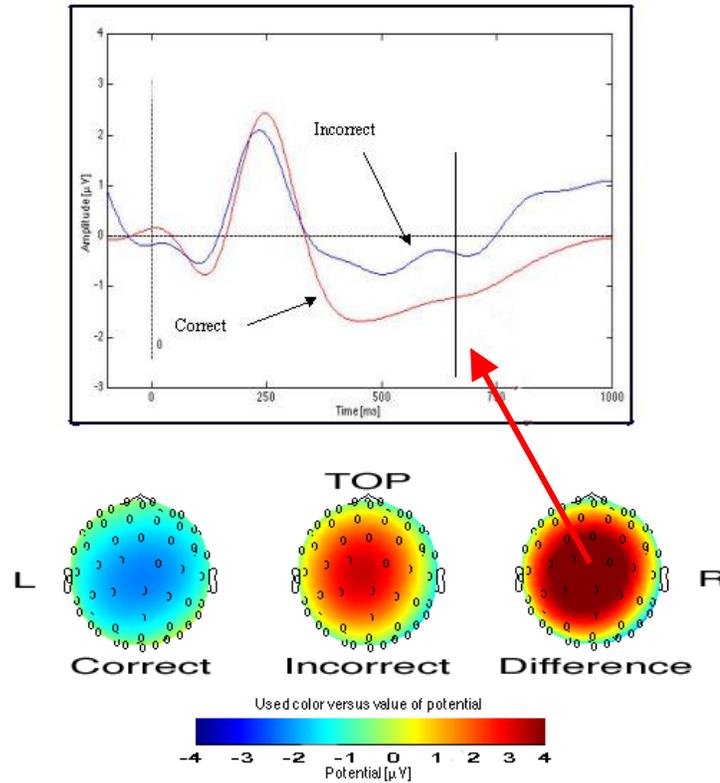


Figure 3-5. Top view of spherical-spline interpolated voltage maps representing instruction-related activity of subsequent correct and incorrect trials, and the difference (correct – incorrect, bottom). ERP waveforms of the grand average differential slow-wave activity between subsequent correct and incorrect trials collapsed across conditions at scalp site #4 (top).

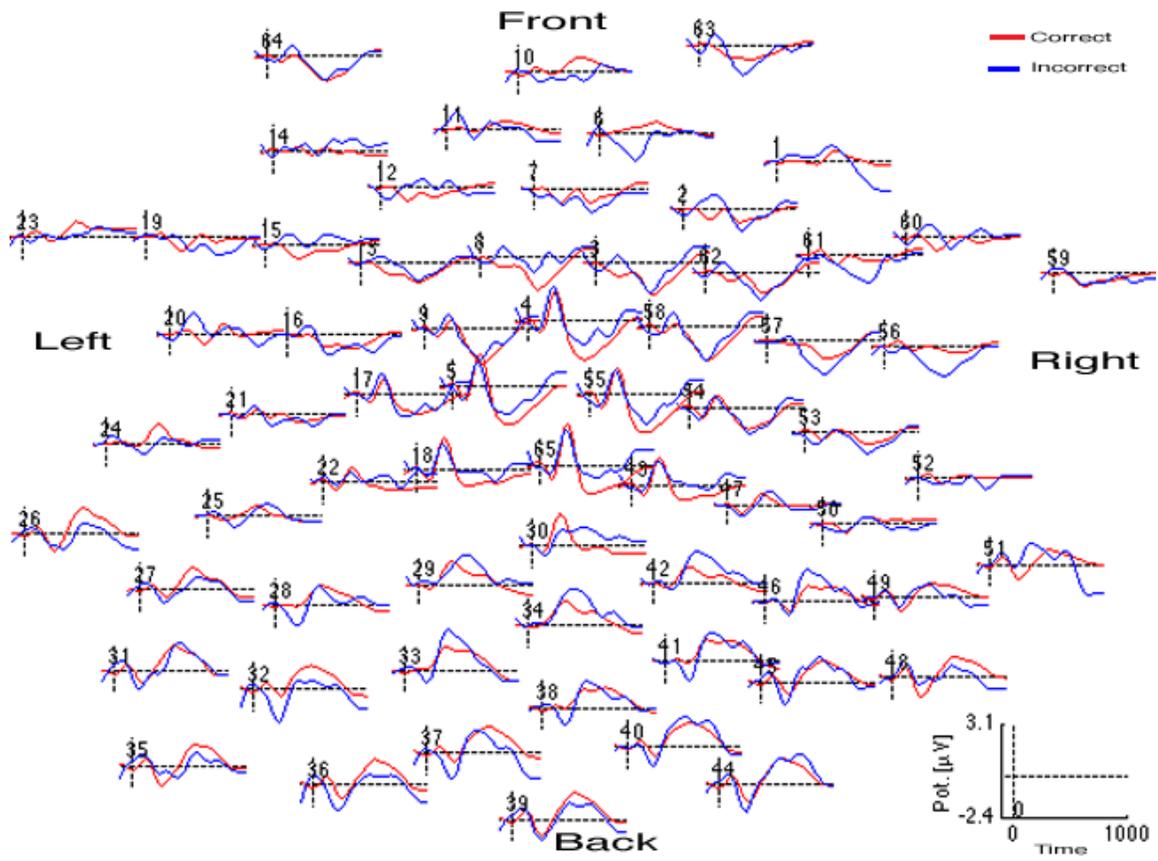


Figure 3-6. Grand average instruction-locked ERPs for all scalp sites of correct (red) and incorrect (blue) task presentation collapsed across conditions.

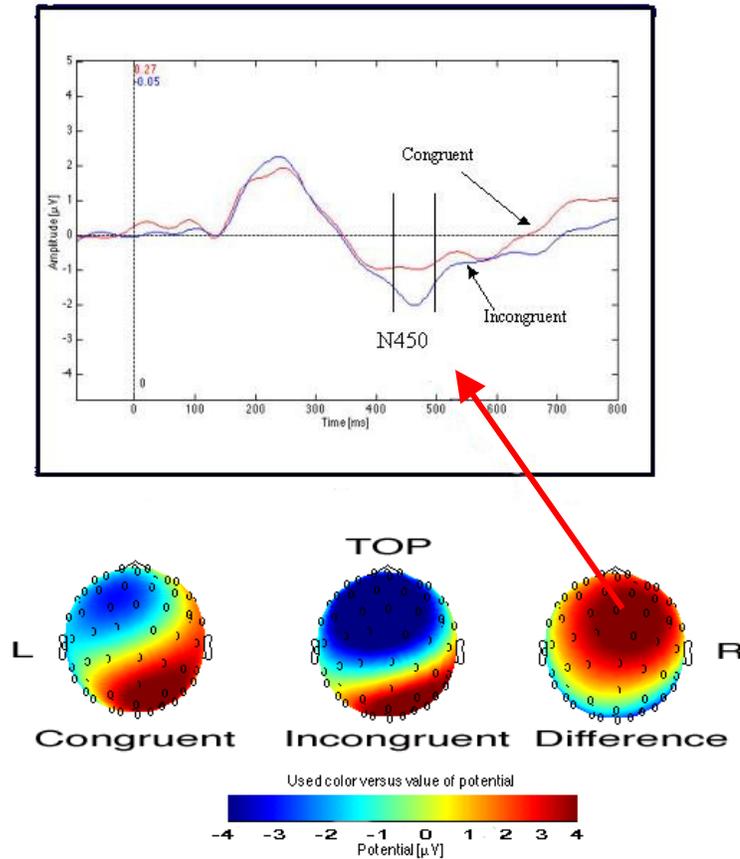


Figure 3-7. Top view of spherical-spline interpolated voltage maps representing stimulus-related activity of the congruent CN condition, the incongruent CN condition, and the difference between the conditions (congruent – incongruent, bottom). ERP waveforms reflect the grand average N450 to the incongruent CN trials at scalp site #55 (top).

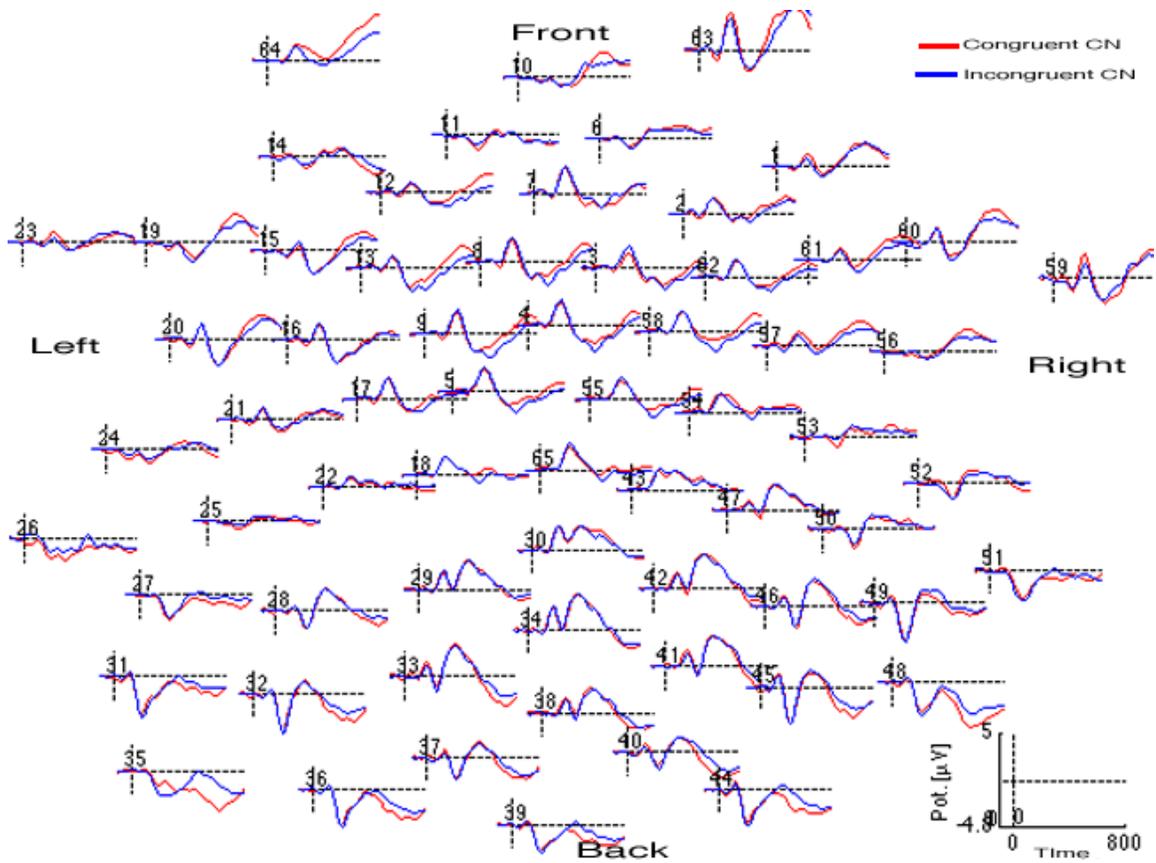


Figure 3-8. Grand average stimulus-locked ERPs for all scalp sites of the congruent (red) and incongruent (blue) CN task.

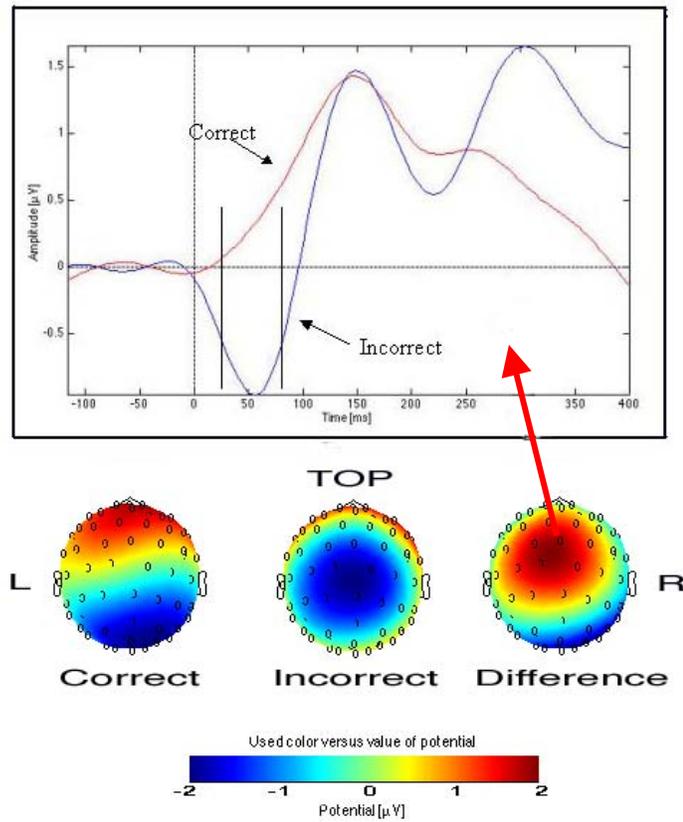


Figure 3-9. Top view of spherical-spline interpolated voltage maps representing response-related activity of correct and incorrect trials (collapsed across conditions), and the difference (correct – incorrect, bottom). ERP waveforms of the grand average ERN deflection to the incorrect trials as compared to the correct trials at scalp site #5 (top).

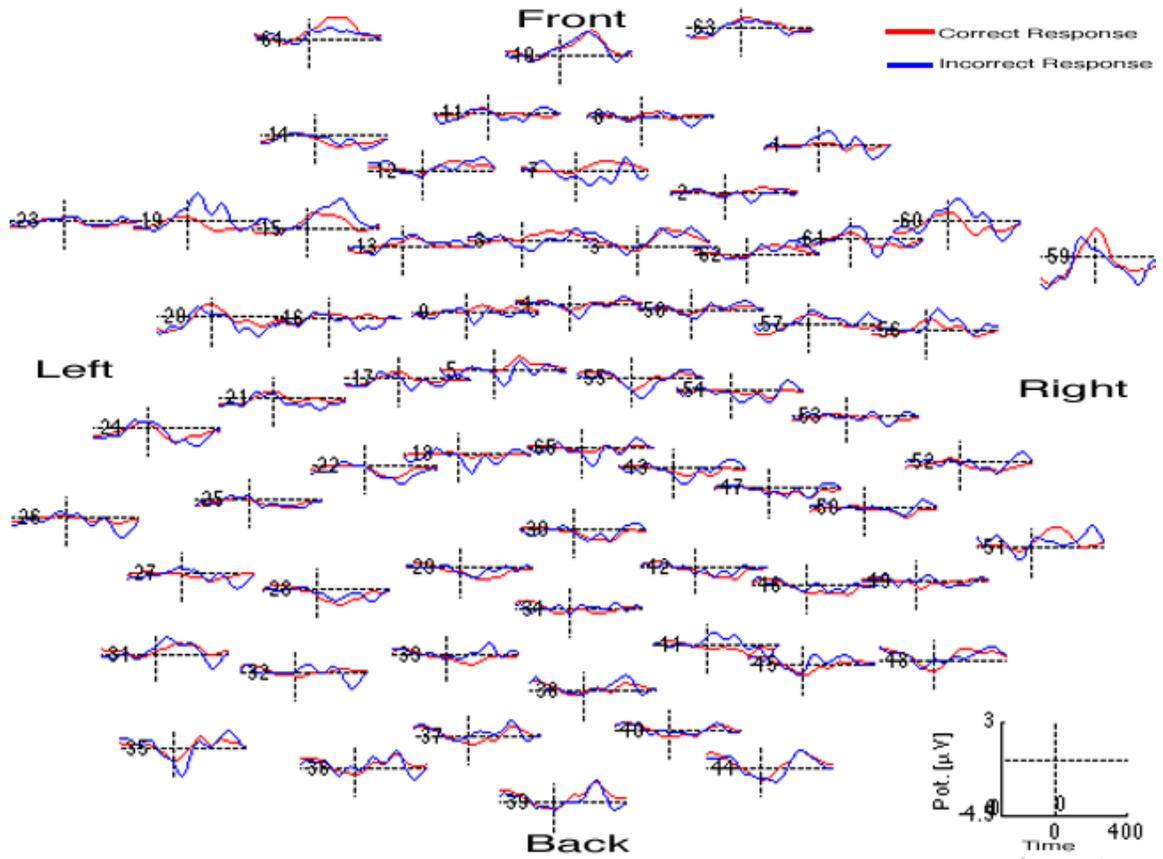


Figure 3-10. Grand average response-locked ERPs for all scalp sites of correct and incorrect responses collapsed across conditions.

CHAPTER 4 DISCUSSION

Current theories of cognitive control recognize two features as essential to negotiating everyday cognitive tasks: an evaluative component responsible for monitoring the need for internal adjustments in control and signaling when such adjustments are necessary and a regulative component responsible for activation and implementation of control processes. The current study utilized ERPs and a modified version of the Stroop task to temporally dissociate the electrophysiological signatures of the regulative and evaluative processes of cognitive control.

Behavioral Data

Participants displayed the typical Stroop interference effects, with increased error rates and RTs on incongruent CN trials. These results reflect the increased influence of word-reading over color-naming on the incongruent CN trials and the need to override the more automatic tendency to read the word. Delay did not significantly affect RT or error-rate performance in any task or congruency conditions. The absence of delay effects may be attributed to the demographics of the sample used in this study. The sample consisted of educated college students who had intact working memory skills and had little difficulty maintaining the representation of the CN or WR tasks; therefore, performance on the long and short delay conditions was nearly equivalent. These results can be contrasted with those of Seignourel et al. (in preparation) who found in healthy, slightly older, control participants decreased error-rates following the 5s delay condition, but no differences in RTs. Cohen et al. (1999) found increased facilitation of RTs (faster

RTs to congruent than neutral stimuli) in the 5s delay condition as compared to the 1s delay, also in slightly older controls. The RT facilitation and decreased error rates in the 5s condition were attributed to the increased time allowed to engage regulative control mechanisms and prepare to override prepotent response tendencies. Interestingly, Seignourel et al. found that moderate-to-severely traumatic brain injured participants did not display differential error rate performances by delay and Cohen et al. found no within, or between subjects error-rate differences in patients diagnosed with schizophrenia and normal controls. Based on this information, current theories hypothesizing that increased delay between instruction-cue and stimulus presentation facilitates the implementation of regulative control processes remain ambiguous. Nonetheless, computational modeling studies do suggest that, in healthy participants using a different cognitive control task (i.e., AX-CPT, (Braver, Barch, & Cohen, 1999), the biasing of control requires some time to achieve full strength. Furthermore, functional neuroimaging studies have shown that this delay-related effect is mediated, at least in part, by the dlPFC (Barch et al., 2001). More studies are necessary to determine the effects of delay between instruction-cue and stimulus presentation on the implementation of regulative processes in cognitive control.

ERP Data

Regulative Processes

As predicted, regulative processes reflecting the implementation of control were shown in frontal slow-wave activity, more specifically, instruction-related slow-wave activity that differentiated the CN from the WR tasks. These results are consistent with an increased requirement for top-down control and increased allocation of attentional resources to the CN task in preparation to override the more automatic tendency to read

the word. These results are similar to the fMRI results of MacDonald et al. (2000) who attributed increased left dlPFC activity to the CN task as compared to the WR task to the implementation of increased cognitive control processes in preparation for the more demanding CN task. Reasons for the differences in lateralization are currently unclear; however, due to the volume-conducting nature of the brain, the lack of spatial sensitivity associated with ERPs, and the failure of the current investigation to provide consistent source localization results using more advanced dipole modeling techniques, speculation about specific anatomical locations of control processes is considered tentative. The results and interpretations of the current study and those of MacDonald et al. can be contrasted with those of West (2003). Using a similar modified version of the Stroop task as that used by the current study and MacDonald et al., West also found instruction-locked slow-wave activity that differentiated the CN and WR tasks. The slow-wave activity found by West, however, was reflected primarily in a slow negativity over the occipital-parietal regions and positivity over the frontal-central region. West also described an instruction-locked slow-wave that differentiated correct and incorrect responses. This slow-wave activity reflected greater negativity for incorrect relative to correct responses and was specifically related to whether or not a correct response was made, rather than any particular aspects of the presented stimulus. Dipole-based source localization methods used by West determined that the best dipole model for the slow-wave activity occurred using mirrored dipoles in the occipital-parietal region, with a single dipole in the left dlPFC. The dipole in the left dlPFC contributed only moderately to the overall fit of the model. Based on these findings, West concluded that instruction cue-related slow-wave activity over the occipito-parietal region supported the processing

of “goal-compatible responses” (correct responses) rather than preferential processing of a more attention demanding stimulus attribute.

To examine the hypothesis that occipital-parietal slow-wave activity is associated with correct and incorrect responses, we collapsed CN and WR trials by accuracy. Our findings revealed a mid frontal-central slow-wave that differentiated subsequent correct and incorrect responses. However, in contrast to the findings of West, our slow-wave activity reflected greater negativity for correct relative to incorrect responses. Based on the assumption that errors are committed when there is a break down in the regulative processes of cognitive control, these findings could represent a possible “dysregulation” of control processes during error trials as compared to correct trials. Due to the fact, however, that trials were collapsed across conditions, no conjectures about specific stimulus attributes associated with the correct and incorrect trials are offered on the basis of the current study.

Evaluative Processes

Evaluative processes were reflected in a mid to right-lateral frontal N450 with greater negativity to the incongruent CN trials than congruent CN trials. These results are consistent with previous studies of the Stroop task (Liotti et al., 2000; West, 2003; West & Alain, 1999) that suggest the N450 is an electrophysiological reflection of conflict detection. In support of this interpretation, West (2003) showed increased negativity to the incongruent trials of both the CN and WR tasks, allowing him to conclude that the N450 is a neural representation of a cognitive process with a role in conflict detection independent of task condition. Previous dipole source localization research on the N450 has localized possible neural generation of the N450 to the ACC (West, 2003; West & Alain, 1999). These results are consistent with fMRI results found

by MacDonald et al. and several PET studies (Carter, Mintun, & Cohen, 1995; Zysset, Muller, Lohmann, & von Cramon, 2001) indicating greater activity in the ACC during the incongruent, compared to congruent, CN trials.

Evaluative processes were further explored in the current study by examining response-related ERP activity following correct and incorrect responses. The ERN, a significantly greater negativity following error trials compared to correct trials, has been suggested to reflect an error detection mechanism that plays a role in signaling for adjustments in performance following the occurrence of errors. Results of the current study replicate previous findings discussed previously of the ERN following error trials. Previous dipole source localization of the ERN has also implicated the ACC as the most likely neural generator (Falkenstein et al., 2000; Gehring et al., 1993; van Veen & Carter, 2002a, 2002b). Overall, convergence of evidence from N450 and ERN components of electrophysiological-based ERP methods, as well as results of hemodynamic-based neuroimaging studies, emphasizes an evaluative mechanism of cognitive control that is neurally distinct from the regulative components of cognitive control.

Alternative Explanations and Potential Limitations

While we propose that the observed ERP results reflect the regulative and evaluative components of cognitive control, other alternatives and potential limitations must be considered. First, the precise function responsible for the ERN has been subject to multiple interpretations (Cohen, Botvinick, & Carter, 2000a; Gehring & Knight, 2000). Research has not clarified whether the ERN is caused by the error itself, or by processing conflicts that produce uncertainty and predispose to error. Additionally, previous research has been incongruous on performance adjustments following error trials, with some research correlating post-error slowing with the ERN and some failing to document

such a slowing effect (Hajcak, McDonald, & Simons, 2003); therefore, it remains unclear how a monitoring function such as the ERN relates to mechanisms of cognitive control. In addition, there is considerable evidence that attentive and motivational factors modulate ERN magnitude. For example, when participants are motivated to make accurate rather than speedy responses, the ERN is larger (Falkenstein et al., 2000). Similarly, larger ERNs occur when participants are certain they have made an error (Gehring et al., 1993). Continued research is required to further elucidate the precise cognitive focus reflected in the ERN.

Second, the current study employed ERP methodologies to provide direct measurement of the temporal course of neurological reflections of cognitive control processes. Under some circumstances, ERPs may be able to detect neural activity that is unaccompanied by changes in regional blood flow or metabolic activity. However, ERPs have limited spatial resolution, potentially leading to ambiguous spatial localization. Nonetheless, relatively recent developments resulting in high-density spatial sampling of EEG (i.e., 64, 128, 256 channels), combined with sophisticated source localization algorithms, have been used to provide greater confidence in source localization (Pascual-Marqui, Michel, & Lehmann, 1994; Scherg, 1990). In the current study, source localization methods were not employed due to artifact introduced into the EEG recordings by concerns of contamination due to the vocal response mechanism. Vocalization-related cortical potentials (VRCs) are one potential contaminant and consist of a movement-related cortical potential preceding vocalization and an auditory-evoked negative potential that immediately follows vocalization (Masaki, Tanaka, Takasawa, & Yamazaki, 2001). Additionally, following each trial response, electromyographic activity was observed throughout the EEG that could not be

completely removed using current data-correction algorithms. Due to this variability associated with vocal response introduced into the EEG data, it was felt that source localization methods would not be reliable estimates of the potential neural generators of cognitive control processes. Nonetheless, our finding of N450 modulation over medial-frontal regions is consistent with several studies that employed manual responses (West, 2003; West & Alain, 1999, 2000b) and both manual and verbal responses (Liotti et al., 2000).

Future Directions

The present study lends continued credence to the use of a single-trial version of the Stroop task that specifically examines the component processes of cognitive control. Previous research using the Golden version of the Stroop task has not had the sensitivity of the single-trial version of the Stroop used in this study due to the temporal confound between the regulative and evaluative processes of cognitive control. This is of particular relevance in the study of functional impairments in groups who demonstrate putative cognitive control deficits on traditional measures (e.g., blocked Stroop task), as well as groups whose underlying deficits have been proposed to be related to impaired goal maintenance or conflict detection processes, for example, schizophrenia (Cohen et al., 1999; Perlstein, Dixit, Carter, Noll, & Cohen, 2003), aging (West, 1999; West & Alain, 2000a), and traumatic brain injury (Seignourel et al., in preparation) . The current study lays the foundation for examining the electrophysiological representations of cognitive control in these groups. Future studies using ERPs and hemodynamic-based neuroimaging methods will examine the specific components of goal maintenance and conflict processing deficits in these populations where dysfunctions in broader cognitive control processes have been hypothesized to account for disease-specific impairments.

Specifically, future studies are underway in aging, ADHD, and traumatic brain injury (TBI; Larson, Kelly, & Perlstein, 2003) that will further elucidate the specific nature of deficits and the underlying neural substrates of cognitive control dysfunction.

Summary

Current cognitive neuroscience theories distinguish between at least two important components of cognitive control: an evaluative component responsible for monitoring the need for control and signaling when adjustments in control are necessary, and a regulative component responsible for activation and implementation of control processes. The current study used ERPs in an effort to temporally dissociate these regulative and evaluative components of cognitive control. The findings of this research are consistent with the hypothesis that regulative and evaluative components of cognitive control are dissociable with ERP methods. This conclusion lays the foundation for future studies that will provide increased clarity into specific cognitive control deficits in clinical populations (e.g., TBI).

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