WORKING MEMORY CAPACITY AND TASK GOALS MODULATE ERROR-SPECIFIC EVENT-RELATED POTENTIALS

by

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A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Psychology

The University of Utah

August 2014

The University of Utah Graduate School

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ABSTRACT

The present study investigates individual differences in information processing following an error. Participants with high working memory capacity (WMC) and with low WMC performed a high congruency version of the flanker task under both speed- and accuracy-stress. We recorded event-related potentials and behavioral measures of accuracy and response time (RT) in the flanker task with a primary focus on processing following an error. We compared WMC groups on the error related negativity (ERN) and the positivity following an error (Pe) associated with both task goal and working memory capacity. Those with a high WMC had a larger ERN compared to those with lower WMC. In addition, accuracy stress reflected a larger ERN than speed-based trials. The data suggest the error related negativity was modulated by task goals and working memory capacity. The Pe was modulated by task goals, but not by WMC. However, a significant interaction demonstrates an increased awareness of erroneous responses for high WMC subjects under accuracy-stress. Additionally, both groups exhibited greater posterror slowing under accuracy-stress as compared to speed-stress. This indicates that both WMC groups were able to adjust their behaviors according to the constraints of the task goals following an erroneous response.

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INTRODUCTION

Previous research has demonstrated that individual differences in working memory capacity (WMC) modulate executive attention and cognitive control (Kane, Conway, Hambrick, & Engle, 2007). WMC reflects an individual's capacity to hold and manipulate domain-specific short-term information. An individual's WMC can be ascertained by using the operation span task (OSPAN; Unsworth, Heitz, Schrock, & Engle, 2005). Previous research has shown that the OSPAN task is reliable and valid predictor of WMC. Behavioral and physiological differences have been observed between those with high and low WMC (Kane & Engle, 2003). Specifically, researchers have found that WMC predicts the amplitude and latency of certain event-related potential (ERP) components such as the error related negativity, or ERN, which is a component of the ERP elicited after an error (Miller, Watson, & Strayer, 2012).

OSPAN performance can predict behavioral performance on conflict-type cognitive tasks. Researchers have also provided evidence that higher-order cognitive processes vary significantly between individuals, and have shown that high WMC correlates with superior performance on executive function tasks (Engle, 2010). WMC is also highly correlated with general fluid intelligence, which has implications for skill acquisition, information processing, and reasoning abilities (Ackerman, 1988; Lohman, 1989). The aim of the proposed study is to identify the behavioral and electrophysiological markers of individual differences in WMC and to understand how erroneous behaviors, when they emerge, are arrested by mechanisms responsible for behavioral self-regulation.

The ERN is the primary electrophysiological marker of interest in the current research. The ERN is a response-locked ERP component associated with an erroneous response (Gehring, Coles, Meyer, & Donchin, 1990; Gehring & Fencsik, 2001; Herrmann, Römmler, Ehlis, Heidrich, & Fallgatter, 2004). This signal occurs before conscious processing of the error response. Miller, Watson, and Strayer (2012) demonstrated that different WMC groups also have notably differing electrophysiological responses to error trials, namely, differences in the ERN. These authors conducted a study comparing individuals in upper and lower quartiles of the OSPAN distribution on their performance on the Simon task. They concluded high WMC individuals have a more robust error detection network, marked by greater ERN amplitude. Although this was not observed in behavioral data, the differing electrophysiological signature between WMC groups suggests a closer and perhaps more efficient error-monitoring network in the high WMC group.

Gehring, Goss, Coles, Meyer, and Donchin (1993) manipulated speed and accuracy stress during a flanker task and found that accuracy stress produced larger amplitude ERNs, while speed stress muted the effects of errors on the ERN. The authors posit that this occurred because it was less important to make correct responses in the speed stress condition than it was during the accuracy stress condition. When participants emphasized accuracy, erroneous responses were more salient and were more important to avoid. In this case, the data suggest the goal of being more accurate augmented the amplitude of the ERN.

Researchers have used neuroimaging methodologies to identify the error detection network's neural substrates. Evidence suggests the ERN originates within the anterior cingulate cortex (ACC) (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Hajcak, McDonald, & Simons, 2003; Herrmann et al., 2004; Kerns et al., 2004). The Pe, or positivity following an error, originates within the posterior cingulate cortex (PCC) (Falkenstein et al., 2000; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). Together, the ACC and the PCC create an error-monitoring network associated with detecting and correcting goal-inconsistent behavior, which acts to update behavioral goals under the supervision of the dorsolateral prefrontal cortex (DLPFC) (Botvinick, Cohen, & Carter, 2004).

While the ERN indicates error *detection*, the Pe denotes error *recognition* and occurs anywhere from 200-500 msec after the erroneous response (Falkenstein et al., 2000). The Pe is an ERP component believed to be a manifestation of conscious awareness of an error, and is the second electrophysiological marker of interest in the proposed study. Overbeek et al. (2005) suggest three theories as to the function of the Pe: the *affective-processing hypothesis*, the *behavior-adaptation hypothesis*, and the *error-awareness hypothesis*. The affective-processing hypothesis suggests that the function of the Pe is to provide an emotional impact of making an erroneous response, or in other words, the participant is upset by their error. The error-awareness hypothesis suggests that the Pe reflects the participants' subjective awareness of the error they have committed.

Posterror slowing is a behavioral indicator for goal maintenance that occurs when a subject slows their subsequent response following an error (Dutilh et al., 2012;

Notebaert et al., 2009; Kerns et al., 2004; Hajcak et al., 2003; Rabbit, 1981). When a subject makes an error response, especially under accuracy stress, the response on the following trial is slowed. After an error, participants require additional processing time to reassess the task goal after going off task. Under speed stress, posterror slowing should be minimal, as their goal is to maintain rapid responses. Similar effects are found in reaction time studies where either speed or accuracy is stressed. When speed is emphasized, participants tend to respond faster overall, and tend to respond slower and more deliberately when accuracy is stressed (Plamondon & Alimi, 1997; Wickelgren, 1977). This posterror processing is assumed to originate in the error-monitoring network (the ACC and PFC) and the DLPFC (MacDonald, Cohen, Stenger, & Carter, 2000).

The present study combines the Gehring et al. (1993) within-subjects manipulation of speed- and accuracy-stress with the Miller et al. (2012) between-subjects comparison of WMC groups using an Eriksen flanker task (Eriksen and Eriksen., 1974). We predicted that the WMC groups will be more similar during the speed stress and will vary the most during the accuracy stress condition. Specifically, we hypothesize an interaction between WMC group (high vs. low) and condition (speed-stress vs. accuracy-stress) for ERN area under the curve, Pe area under the curve, and posterror slowing. These error-related waveforms will be suggestive of how WMC and task instructions interact. We also hypothesize that the high WMC group will outperform the low WMC group in terms of accuracy and RT to the flanker stimuli.

The current study will provide evidence that WMC and error saliency biases processing utilized in both error detection and recognition. By utilizing an individual differences design, we will be able to differentiate the efficacy of neural mechanisms used by individuals who differ in WMC, much like the Miller et al. 2012 study. In addition, we expect to see behavioral differences between the WMC groups. With respect to posterror slowing, our prediction is that both high and low WMC subjects will demonstrate more posterror slowing in the accuracy-stress condition, and that high WMC subjects will demonstrate more posterror slowing overall. Additionally, we predict an interaction between WMC group and condition, whereas the high WMC group will show the most posterror slowing in the accuracy condition. By making errors more salient in the accuracy-stress condition and less salient in the speed-stress condition, we aim to replicate the Gerhing et al. 1993 study that emphasizes the importance of error saliency on ERN magnitude. By combining these two manipulations, we will test the factors that influence ERN magnitude and how high and low WMC individuals can bias processing strategies.

METHODS

Participants

We collected data from participants in two sessions. In the first session, approximately 250 University of Utah undergraduates performed the OSPAN task (see below for details) to assess their working memory capacity (WMC). In the second session, we invited back 25 participants in the lowest quartile of WMC scores (20 female, $\bar{x}$=24.2 years old) and 25 participants in the highest quartile of WMC scores (16 female, $\bar{x}$=23.3 years old). Participants with any neurological diagnosis, head trauma, who were left-handed, or above the age of 40 were excluded from analysis. All participants provided informed consent before starting the experiment and received course credit for participation.

Materials and Procedures

Session One: In the first session, participants were given an automated version of the OSPAN task (Unsworth, Heitz, Schrock, & Engle, 2005) to provide an estimate of their WMC. The OSPAN task consists of a series of math problems and letters. Participants were presented with simple math problems and the participant reported the veracity of the statement as either “true” or “false” (e.g., (8/2)+2=12…“False”). Following each math problem, a letter was presented for later recall. After sets of 3 to 7 math/letter pairs, the participants were prompted to recall the letters in the order in which they were presented. All OSPAN stimuli were presented on a computer screen and responses were made with a computer mouse. The total number of letters accurately recalled in the presented order determined their absolute OSPAN score out of 75. Those individuals who obtained an absolute OSPAN score at or below 25 were classified as individuals with low WMC and those who obtained an absolute OSPAN score at or above 50 were classified as high WMC individuals. Following Unsworth et al. (2005), we excluded all individuals from the experiment who correctly answered fewer than 85% of the math problems, as the math problems were designed to distract the participant from recalling the correct letters.

Session Two: In session two, 50 participants were tested individually on a version of the Eriksen and Eriksen (1974) flanker task created in E-prime 2.0. We instructed participants to respond based on the centrally presented letter in a series of five-letter strings. There were two types of stimuli: congruent and incongruent. A congruent stimulus consisted of all identical letters (e.g. SSSSS or HHHHH) and an incongruent stimulus consisted of "flanking" letters that were associated with the opposite response (e.g. SSHSS or HHSHH). Each stimulus was preceded by a fixation cross, presented for 500 msec in the center of the display followed by a blank screen for 100 msec. Stimuli were presented until the participant responded or 2000 msec had elapsed. The five-letter horizontal array subtended 2.57 degrees of visual angle.

Participants were asked to respond to the target letter with the "Z" and "/" keys on a keyboard with their left and right index fingers, respectively. The mapping of response keys and condition order was counterbalanced across subjects. At the beginning of the second session, participants completed a practice block of 50 trials. The practice was used to familiarize the participant with the task and also to collect baseline accuracy and response time data for the speed-stress and accuracy-stress conditions. Before the speed condition, participants were instructed to perform the task as quickly as possible. Similarly, before the accuracy condition, participants were instructed to perform the task as accurately as possible.

We gave feedback and bonuses to the participants with relation to their baseline performance obtained during their practice sessions. For each block of 100 trials in the speed stress condition, participants who responded 15% faster than their baseline reaction time and were at least 75% accurate received 25 cents. For each block of 100 trials in the accuracy stress condition, participants who were at least as fast as their baseline response time and at least 95% accurate received 25 cents. Participants earned up to an additional 3 dollars based on their average reaction time for the speed stress condition and their accuracy during the accuracy stress condition. We utilized monetary incentive to encourage the participants to adhere to the task instructions (i.e., responding quickly during the speed condition and responding accurately during the accuracy condition). Speed and accuracy conditions were blocked and, participants were provided with a 5-minute break between blocks.

Design

The present study utilized a 2 (high vs. low WMC group) by 2 (speed vs. accuracy stress) split-plot factorial design. All participants completed six blocks of the accuracy-based flanker task and six blocks of the speed-based flanker task, resulting in 12 blocks of trials per participant. Each block consisted of 100 randomized trials, resulting in 1200 trials per participant. The congruent stimuli (e.g., HHHHH) comprised 75% of the trials, while the incongruent stimuli (e.g., SSHSS) comprised 25% of the trials, thereby creating a high-congruency variant of the paradigm. After every block of 100 trials, the program presented the participants with feedback on their average accuracy and response time for that block.

ERP Recording

During the second session, which will took place anywhere from one day to a few months after the first session, participants had electrodes applied to their scalp and face to record electroencephalographic (EEG) and electroocculargraphic (EOG) signals. For EEG/ERP data collection, we utilized a 36-channel SynAmps cap manufactured by Compumedics Neuroscan and placed the cap according to the International 10-20 placement guidelines (Jasper, 1958). We used a Compumedics Neuroscan NuAmps amplifier to digitize the signal for computer-based recording and processing. The amplifier sampled EOG and EEG signals at a rate of 250 Hz with a notch filter at 60 Hz. Research assistants cleaned participants' skin using a light exfoliating gel on the sites where they applied 10-mm diameter Ag/AgCl biopotential electrodes external eye and mastoid electrodes. Mastoid and facial electrodes were applied using adhesive electrode collars and filled with saline-based gel. All impedances were below 10 kOhms. HEOG and VEOG artifacts were corrected offline using Neuroscan's Scan 4.5 software. In addition, trials with artifacts in the EEG signals were not included in the subsequent analysis (this excluded less than four percent of the data). Error response events were epoched from -200 milliseconds before the event to 1200 milliseconds postevent. A band pass zero phase shift filter from 0.1 Hz to 12 Hz was applied before rejecting artifacts that exceeded above 70 and below -70 microvolts. We created a final waveform by averaging the remaining accepted trials.

RESULTS

Behavioral Data

We calculated cumulative accuracy functions (CAFs) as a way of visualizing the data and verifying that participants complied with the speed-accuracy instructions. In addition, the CAFs are useful in examining individual differences of the temporal limits of visual attention (Heitz & Engle, 2007). CAFs were created for the accuracy-stress condition (see Figure 1.1) and the speed-stress condition (see Figure 1.2) by creating Vincentized deciles for participants in each of the experimental condition. The CAFs reflect the average accuracy at each decile as a function of the average RT associated with that group (high vs. low WMC), condition (speed vs. accuracy), and trial type (congruent vs. incongruent). Perusal of Figures 1.1 and 1.2 indicates that both groups complied with speed-accuracy instructions and that the high WMC group exhibited a faster rate of evidence accumulation.

The behavioral data from the flanker task were analyzed using a 2 (WMC group) by 2 (speed-stress vs. accuracy-stress) by 2 (congruent vs. incongruent trial type) split-plot ANOVA. Response time (RT) and accuracy means are displayed in Figures 1.3 and 1.4, respectively. We considered trials outside the range of 200 to 2000 milliseconds as outlier trials, and they were excluded from analysis. Additionally, trials where participants responded three standard deviations above or below their mean RT for that condition were also excluded from further analysis (less than 2% of trials).

There was a main effect of WMC group on RT $F(1, 48)=4.27$, $p<0.05$, $\eta^2=0.08$. Participants in the high WMC group responded significantly faster in both conditions and trial types. Under accuracy stress, RT was significantly slower than in the speed stress condition $F(1,48)= 131.27$, $p<0.05$, $\eta^2= 0.73$. There was also a main effect of trial type on RT. Participants had significantly slower responses for incongruent trials than for congruent trials $F(1,48)=373.09$, $p<0.05$, $\eta^2=0.89$. In addition, there was a significant condition by trial type interaction for RT $F(1,48)= 36.48$, $p<0.05$, $\eta^2=0.43$, indicating that participants were substantially slower on incongruent trials during the accuracy stress condition. None of the interactions involving WMC were significant.

Accuracy was significantly higher in the accuracy stress condition than in the speed stress condition $F(1,48)= 142.84$, $p<0.05$, $\eta^2= 0.75$. Participants were also less accurate on incongruent trials than congruent trials $F(1,48)=146.06$, $p<0.05$, $\eta2=0.75$. There was also a significant condition X trial type interaction for accuracy at $F(1,48)=130.96$, $p<0.05$, $\eta^2=0.73$. Participants were the least accurate on incongruent trials under speed stress and the most accurate on congruent trials under accuracy stress. There were no group effects on accuracy.

Error-Related Event Potentials

Figure 1.5 presents the average response-locked ERPs for trials in which the participant made an error recorded at Cz, plotting time as a function of amplitude. Additionally, average response-locked ERPs for trials in which the participant made a correct response recorded at Cz are displayed in Figure 1.6. For trials with an error, there is an initial negative component in the ERP that peaks at 75 msec, followed by a positive component that peaks at 325 msec. By convention, this earlier ERP component has been referred to as the ERN, and the positivity following the ERN is referred to as the Pe.

Error-related Negativity

To analyze the ERN, we first calculated response-locked averages for each condition and baseline corrected at the moment that participants made their response, referred to as 0 milliseconds. Three participants in each group were excluded (6 participants total) due to fewer than five errors in one or more conditions. Next, we quantified the ERN by integrating the area under the curve between 0 and 80 milliseconds. Inferential statistics were generated using a 2 (WMC group) by 2 (speed-stress vs. accuracy-stress) split-plot ANOVA. There was a significant main effect of condition $F(1,34)=4.37$, $p<0.05$, $\eta^2=0.11$. In addition, there was a significant effect of WMC group on ERN area $F(1,34)=4.29$, $p<0.05$, $\eta^2=0.11$ (see Figure 1.7). Notably, there was no interaction between WMC group and condition.

Positivity Following an Error

The Pe waveforms were baseline corrected at 150 msec postresponse. A window of 150 to 450 msec was selected based on visual inspection of the grand averaged waveforms and Pe was quantified by integrating the area under the curve between 150 and 450 milliseconds. A 2 (WMC group) by 2 (speed-stress vs. accuracy-stress) split-plot ANOVA revealed a main effect of condition $F(1,150)=62.87$, $p<0.05$, $\eta^2=0.29$, and a significant WMC group X condition interaction $F(1,150)=217.65$, $p<0.05$, $\eta^2=0.59$ (see

Figure 1.8). The Pe was larger under accuracy stress than under speed for the high WMC group, but did not differ as a function of condition for the low WMC group.

Posterror Slowing

Posterror slowing was calculated on a participant-by-participant basis by subtracting the average response time of correct trials following a correct response from the average response time of correct trials following an error response (see Table 1.1). We analyzed posterror slowing using a 2 (WMC group) X 2 (speed-stress vs. accuracy-stress) split-plot ANOVA. The analysis revealed that responses following an error were slower under accuracy stress were slower than those under speed stress $F(1,38)=12.81$, $p<0.05$, $\eta^2=0.25$. Additionally, the effect size statistics for the high WMC group were far more robust than the low WMC group. For the high WMC group, we calculated a Cohen's *d* of 0.78, indicating a large effect size. For the low WMC group we calculated a Cohen's *d* of 0.47, indicating a small to medium effect size. The difference in effect sizes for each group suggest that high WMC subjects posterror slowing behaviors are more substantial than low WMC subjects. These data also indicate that participants were more likely to adjust the speed of their response following an error when it was consistent with task instructions (e.g., "be accurate").

Individuals' mean posterror response times are plotted as a function of their Pe areas in Figures 1.9 and 1.10. This provides a direct comparison between the Pe waveform and posterror slowing. For the accuracy-stress condition, the model explains 9% of the variance for the high WMC group, but only 2% of the variance for the low WMC group. For the speed-stress condition, the model explains less than 1% of the variation for both groups. When speed is stressed, participants do not slow their responses following an error, which is reflected in the behavioral statistics for posterror slowing and the electrophysiological signatures of the Pe.

A subsequent hierarchical linear model analysis was conducted to determine the predictability of Pe area on posterror slowing. When collapsing across conditions, the analysis revealed a significant Pe area by WMC interaction on posterror slowing ($p>$ 0.01). Those with high WMC who have a larger Pe area are more likely to exhibit more posterror slowing as compared to those with low WMC.

Table 1.1– Mean posterror RTs and the standard error for high and low WMC groups

	Accuracy Stress	Speed Stress
High WMC	38 msec, Se=8.28	21 msec, Se=5.36
Low WMC	35 msec, Se=5.85	19 msec, Se=3.79

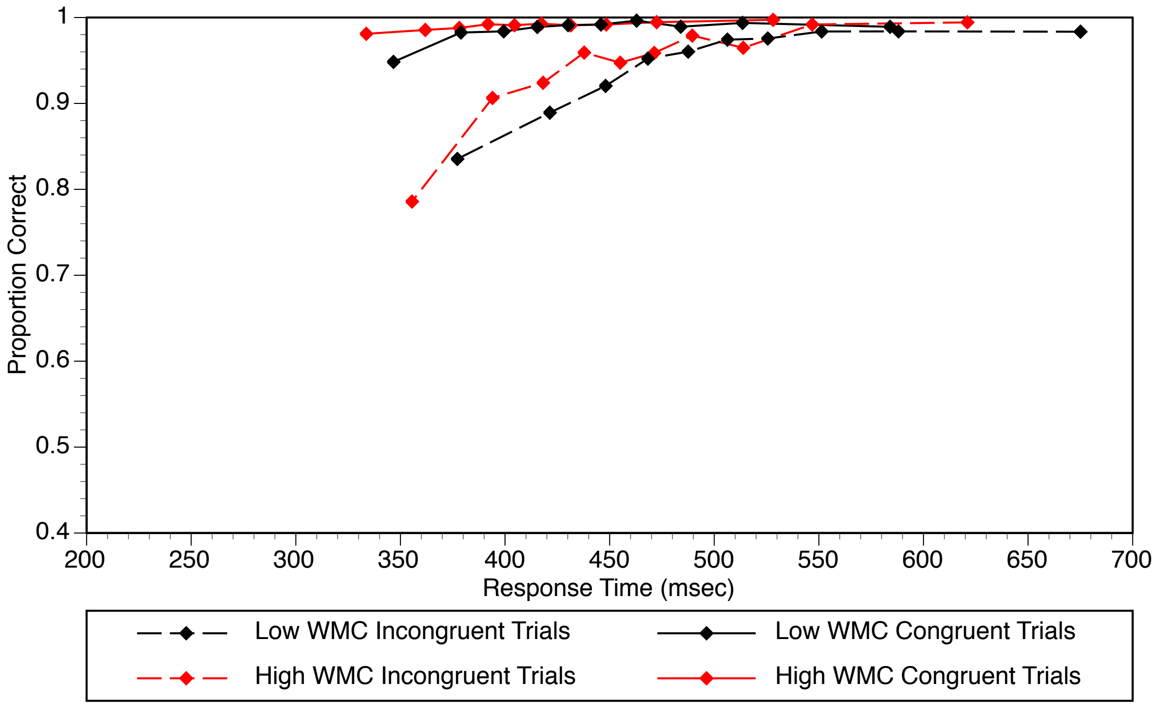

Figure 1.1 – Cumulative Accuracy Functions for Accuracy-Stress Condition

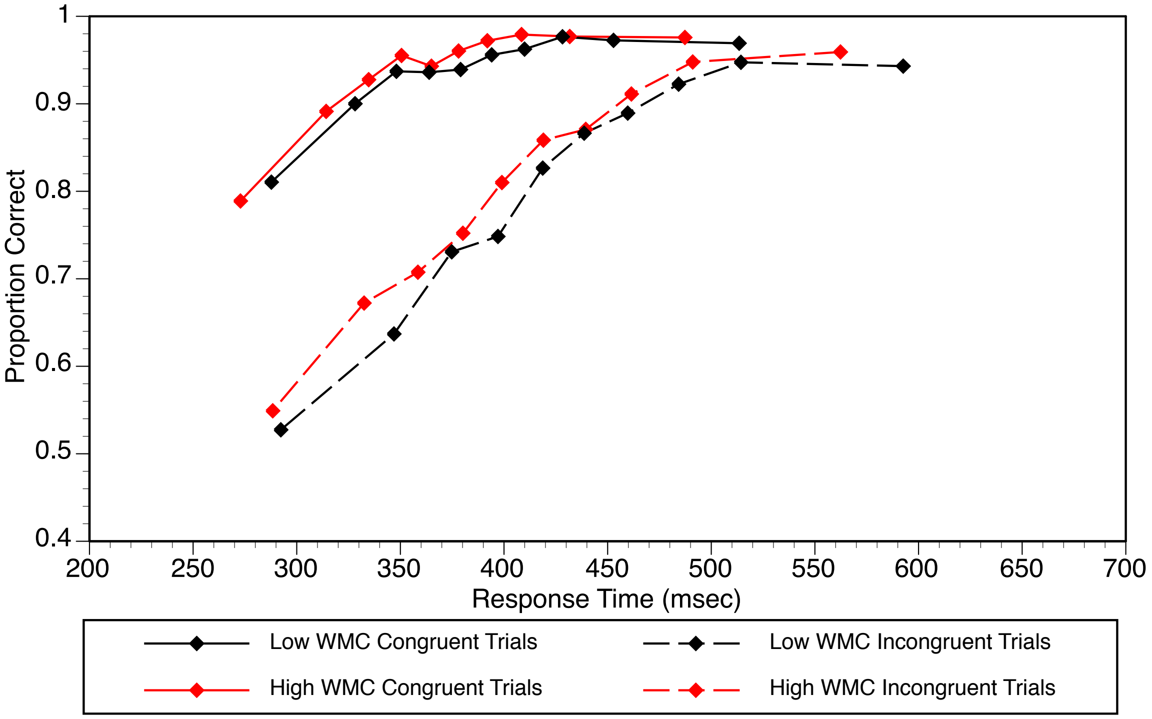

Figure 1.2 – Cumulative Accuracy Functions for Speed-Stress Condition

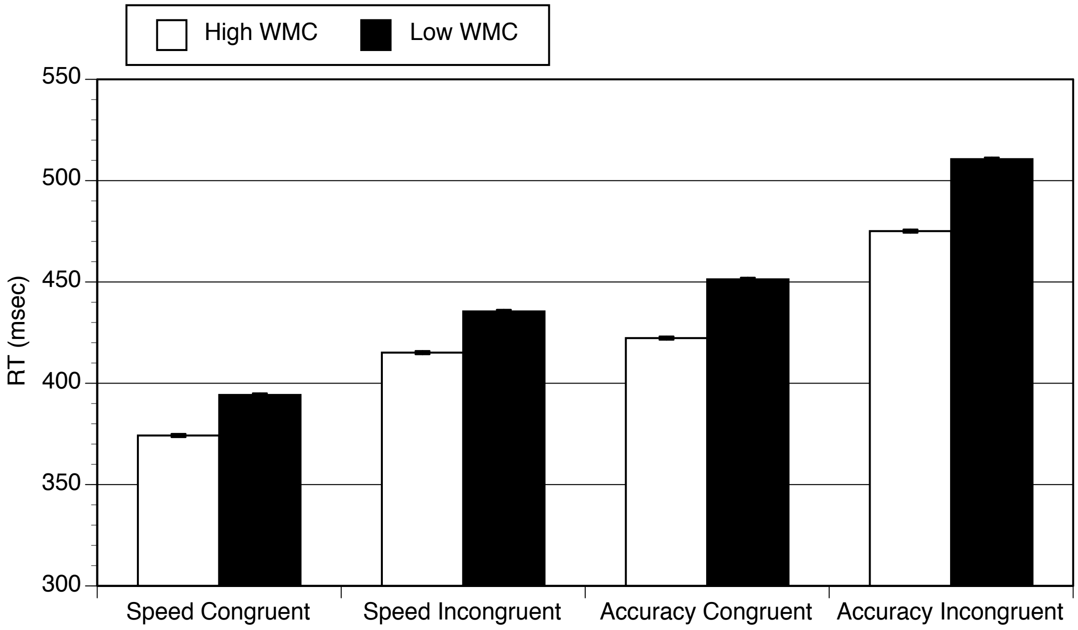

Figure 1.3 – Mean Response Times

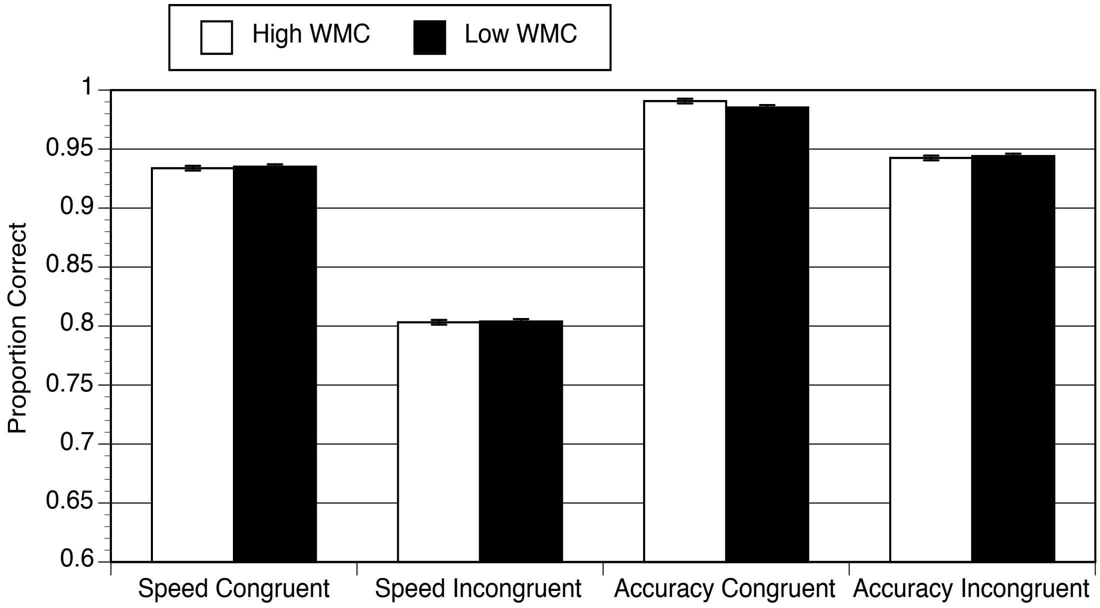

Figure 1.4 – Mean Accuracy

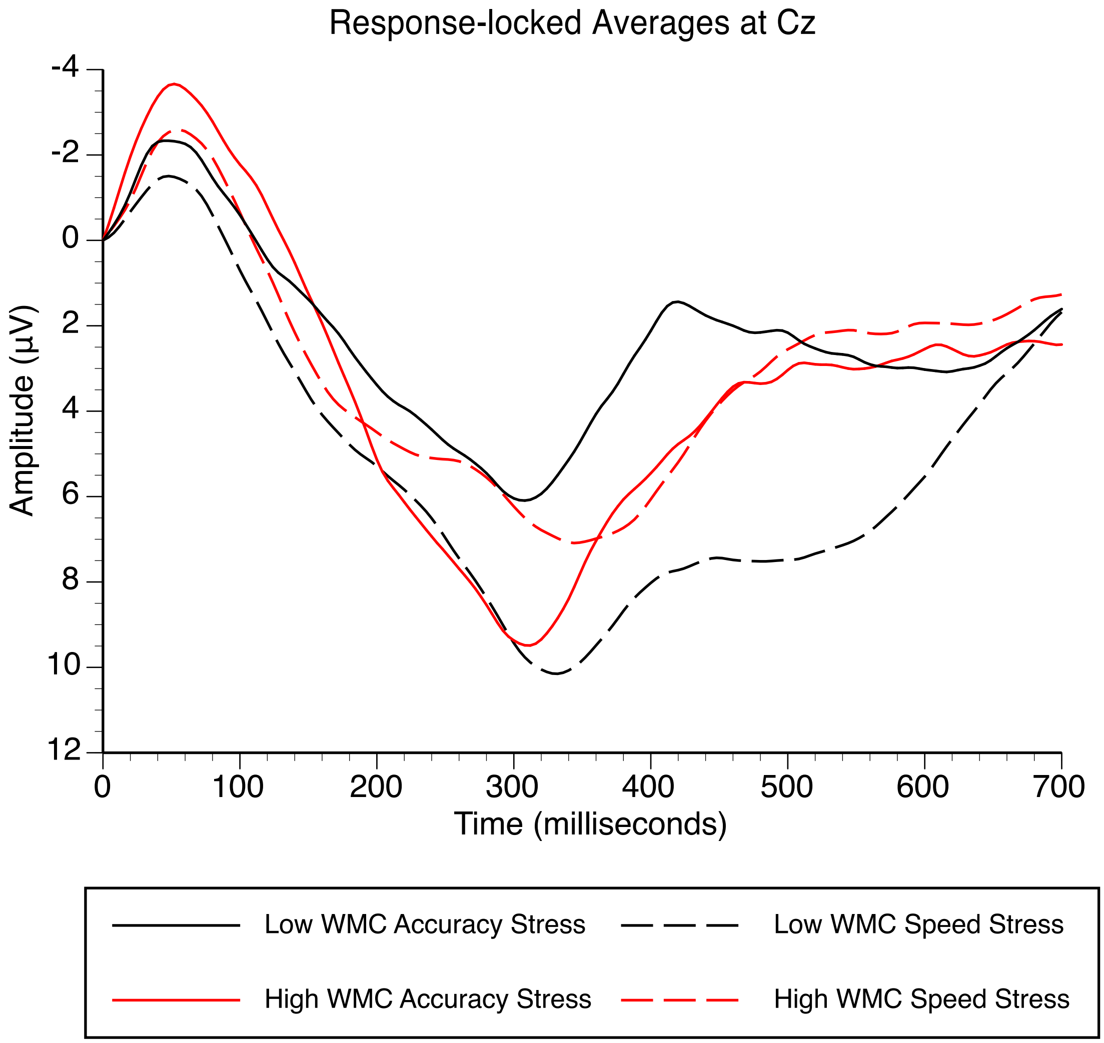

Figure 1.5 – Error ERPs

Figure 1.5 shows response-locked grand averages of error responses for both congruent and incongruent trials.

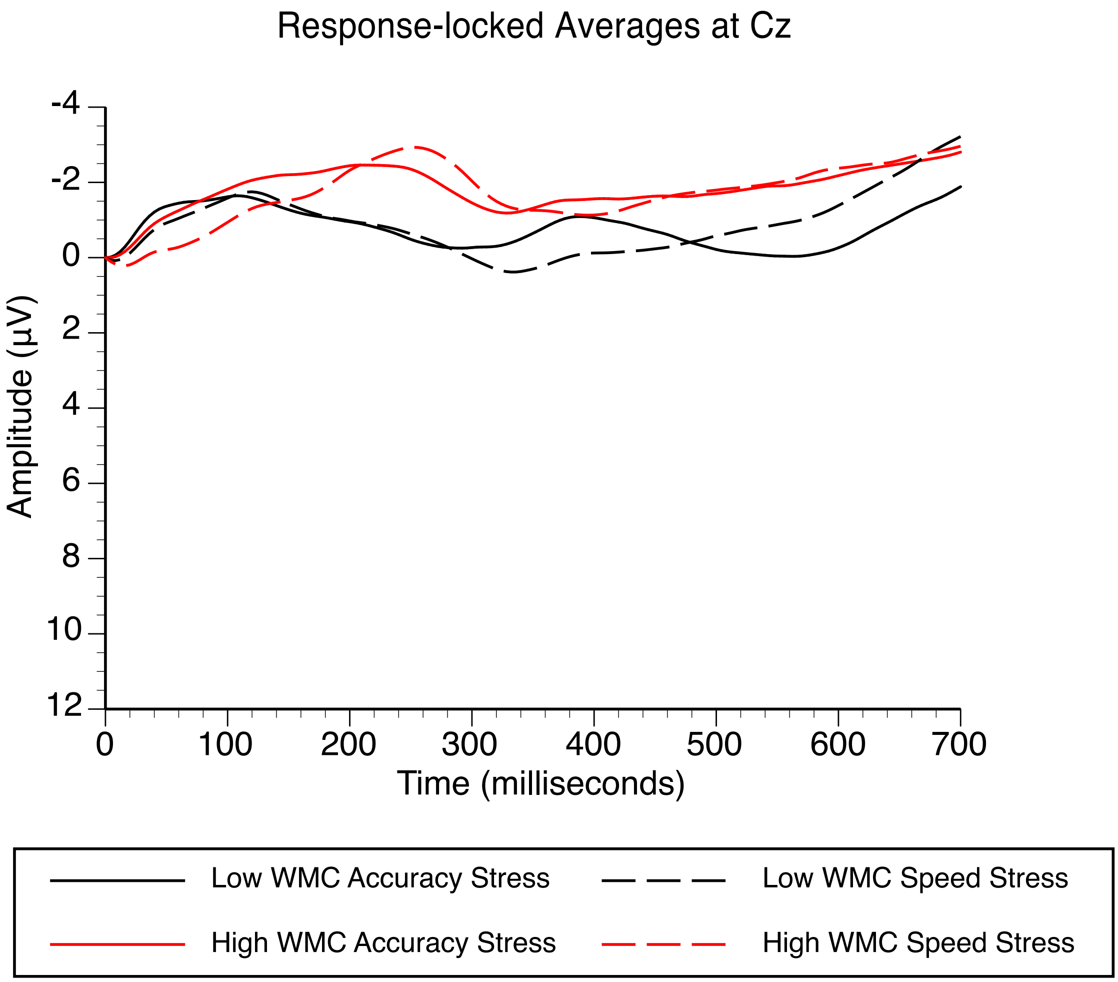

Figure 1.6 – Correct ERPs

Figure 1.6 shows response-locked grand averages of correct responses for both congruent and incongruent trials.

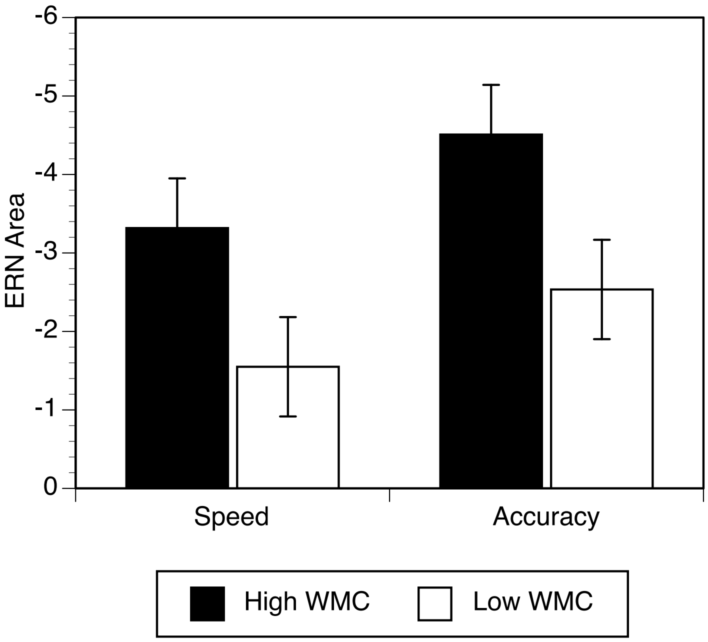

Figure 1.7 – ERN Area

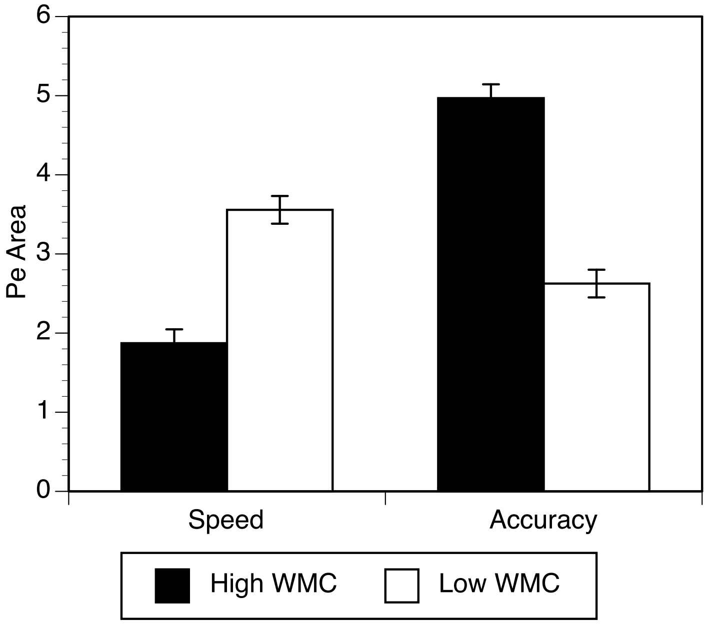

Figure 1.8 – Pe Area

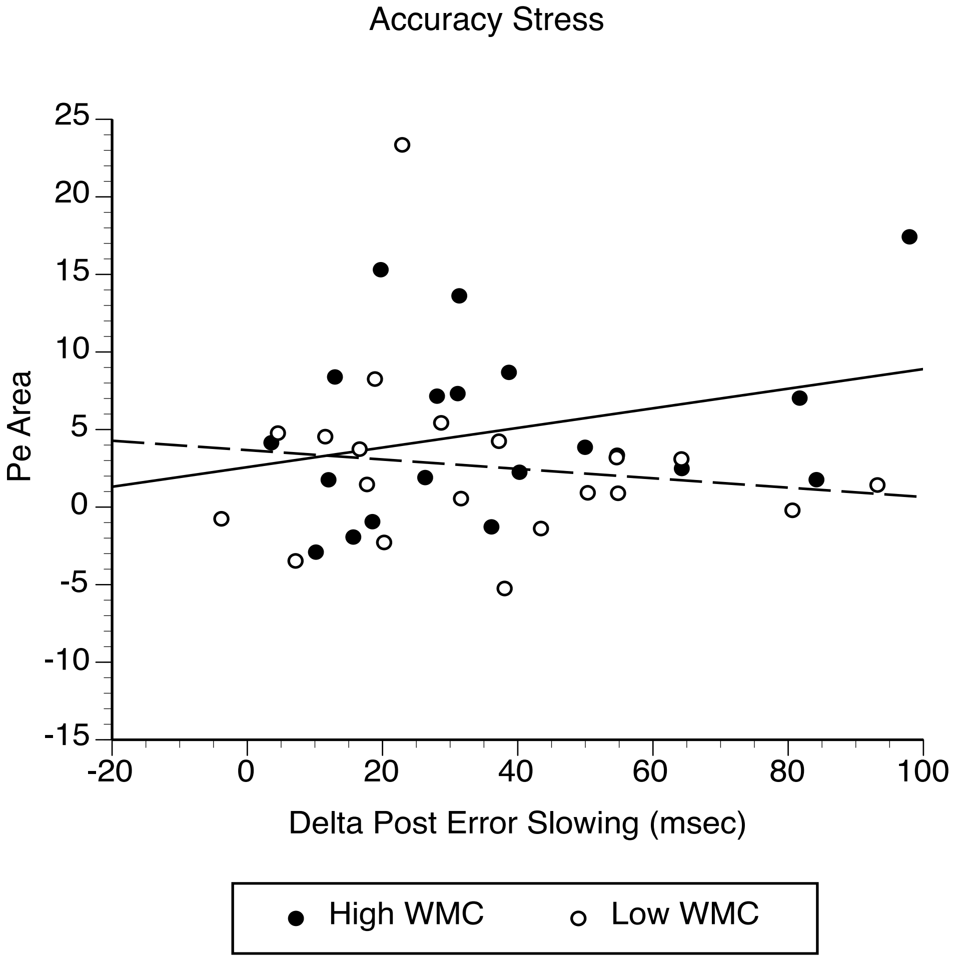

Figure 1.9 Pe Area by Posterror Slowing Scatterplot for Accuracy-Stress Condition

—— High WMC $f(x)= 0.06x + 2.57$ $R^2 = 0.09$

- - - Low WMC $f(x)= -0.03x + 3.67$ $R^2 = 0.02$

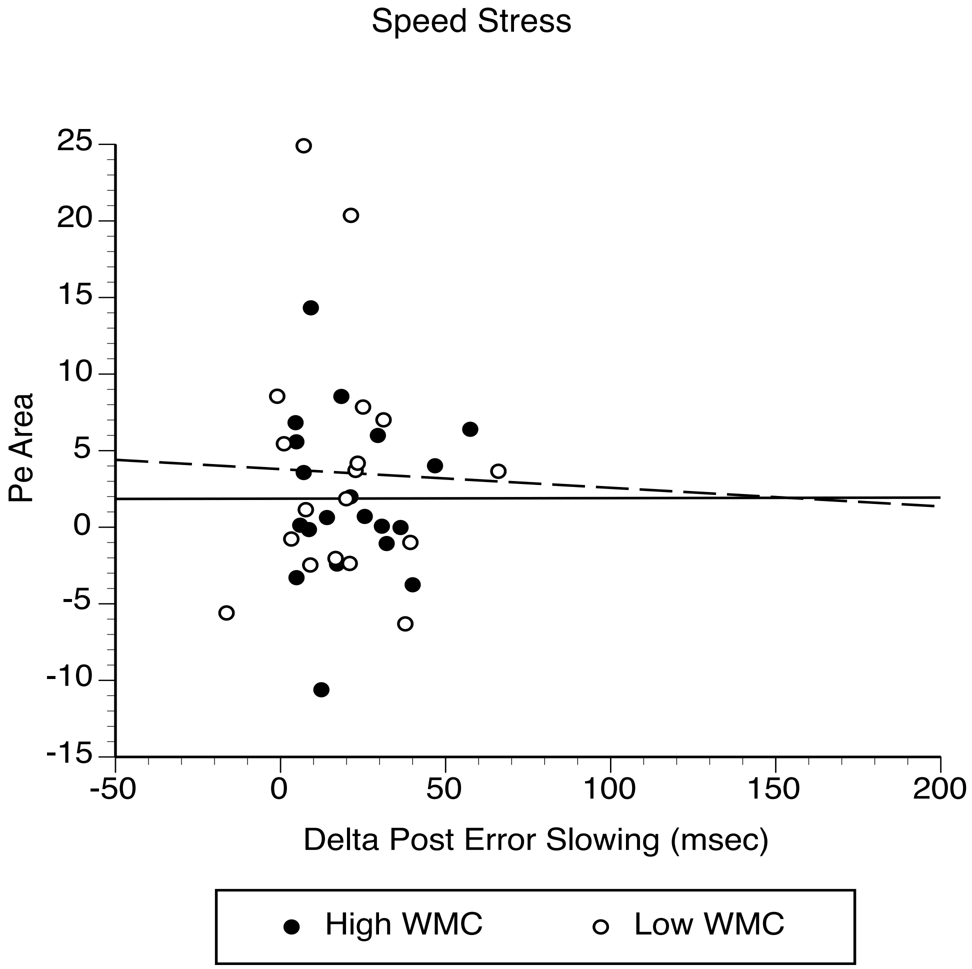

Figure 1.10 Pe Area by Posterror Slowing Scatterplot for Speed-Stress Condition

—— High WMC f(x)= 0.0004x + 1.86 $R^2 = 0$

- - - Low WMC f(x)= -0.01x + 3.79 $R^2 = 0$

DISCUSSION

The primary purpose of this experiment was to use evoked potentials to examine individual differences in attentional control, focusing in particular on situations when individuals stray off task. We contrasted high and low WMC participants under speed- and accuracy-stress. Our target measures were two ERP components that have shown to be sensitive to error monitoring, the ERN, and error regulation, the Pe. Based on prior research, we predicted enhanced ERN and Pe neural signatures for the high WMC group compared to the low WMC group (Miller et al., 2012). Moreover, Gehring's (1993) work suggests that pushing participants for speed makes the commission of an error less important to their behavioral goals and should result in a diminished ERN and Pe compared to circumstances when accuracy is stressed.

With respect to the ERN, a component that is thought to be an automatic signature of error detection (Falkenstein et al., 2000; Hajcak et al., 2003: Kerns et al., 2004), we found additive effects of WMC group status and speed-accuracy condition. High WMC participants exhibited larger ERNs than low WMC participants did, and the accuracy-stress condition elicited a larger ERNs than the speed-stress condition. This additive pattern indicates that WMC and speed/accuracy tradeoff effect different aspects of error detection. These findings replicate the Miller et al. 2012 study, demonstrating electrophysiological differences in the way WMC modulates the processing of errors.

Independent of the task goal, participants with low WMC had smaller ERNs, while those with high WMC had larger ERNs.

The current experiment also replicates the Ghering et al. 1993 study manipulating speed- and accuracy-stress task goals. Under speed stress where the accuracy of a response is less important, both WMC groups show a smaller ERN. By contrast, under accuracy stress, avoidance of errors is more salient and is reflected in a larger ERN amplitude for both WMC groups. In line with additive factors logic (Sternberg, 2004; 1998; 1969), the additivity of WMC group and speed-accuracy bias on the ERN suggests that these two factors modulate the ERN independently.

The pattern was different for the Pe, where the effects of WMC group and speed-accuracy stress interacted. For the low WMC subjects, there was no difference between the speed-stress and accuracy-stress conditions, reflecting an insensitivity to task instructions. However, the Pe was modulated by speed-accuracy instruction for the high WMC group, in a way that is much more consistent to what the task goals required. This latter pattern is consistent with the data reported by Gehring (1993) where they suggested that the magnitude of the Pe is indicative of behavioral changes that reflect strategic changes in behavior (e.g., slowing down following an error).

As expected, we observed less posterror slowing under speed stress, and greater posterror slowing under accuracy stress, suggesting that both groups complied with task instructions. Importantly, we observed differences between the WMC groups in terms of posterror slowing. We noticed that when high WMC subjects regulated their behavior (i.e., slowed down if they made an error under accuracy, but not speed-stress), it was predicted by their electrophysiology on the preceding trial with an errant response. As such, our study is in line with the Overbeek et al. (2005) behavior-adaptation hypothesis providing evidence of posterror slowing and the magnitude of the Pe. The same pattern does not appear for the low WMC group, as their Pe did not vary between conditions. The posterror slowing for the low WMC group data converge with the electrophysiological data to demonstrate changes in behavior based on task instructions.

In summary, we found support for the existence of an error-monitoring network that is sensitive to individual differences in WMC and task instructions. On the one hand the high WMC group exhibited larger ERN and Pe waveforms and show greater posterror slowing when they were instructed to be more accurate. By contrast, when pushed for speed the high WMC group exhibited muted ERN and Pe waveforms and no posterror slowing. On the other hand, the low WMC group was not as adaptable to the attentional demands of the task, which resulted in slower response times and muted error-specific ERPs.

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