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ERROR-RELATED BRAIN ACTIVITY, ANXIETY AND COGNITIVE PERFORMANCE

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ABSTRACT

Research strongly suggests that the negative thoughts and ruminations brought on by anxiety, i.e. worry, occupy working memory (WM) resources that would otherwise be applied to cognitive performance. Although worry decreased cognitive performance for individuals overall, the effects seem to particularly target those higher in trait levels of WM, as they rely on their expanded WM for more advanced problem solving strategies. Furthermore, heightened amplitudes of ACC-generated error monitoring known as error-related negativity (ERN) have been repeatedly shown to relate to higher cognitive performance. A recent hypothesis argues that as worry depletes cognitive resources, this ERN signaling represents a compensatory response in order to prevent cognitive deficits. Across three experiments, we replicate and expand these findings, while further being the first group to analyze cognitive performance in terms of WM, attentional control, anxiety and ERN within one study. In Experiment 1, we showed that the executive function of attentional control prevented worry-induced cognitive deficits in those higher in WM when levels of attentional control were high. In Experiment 2, we supported the claim that the ERN is a response to worry's depletion of cognitive resources by showing that the relationship of worry and ERN is altered by levels of both WM and attentional control. In Experiment 3, we married these two findings by predicting real-world cognitive performance in the future (GPA) using worry, WM, attentional control and ERN as predictors. Although we replicated Experiment 1 by predicting GPA, ERN failed to interact with worry to account for GPA scores. However, we did replicate findings that ERN generally relates to GPA scores, and that this relationship was altered by individuals' levels of WM and attentional control. These findings strengthen support for attentional control theory, and produce a number of questions regarding the relationship of ERN to cognitive performance.

INTRODUCTION

Anxiety

Anxiety is a common experience of worrisome thoughts and physiological arousal (Barlow, 2002). Arguably, the experience of Anxiety serves an adaptive benefit – from Darwin's 1872 description of anxiety as a communicative device (Darwin, 2013) to Walter Canon's (1929) influential look at anxiety as a motivational response, anxiety clearly plays a role in our collective fitness. However, regardless of anxiety's place in an evolutionary context, the current work will address the negative consequences of anxiety, particularly with respect to anxiety's impact on cognitive performance.

When anxiety is discussed, it is imperative to make clear that anxiety is not a unitary construct (see Reiss, 1997). Anxiety is a multidimensional construct that can refer to both the experience of anxious arousal (somatic, physiological tension in response to clear threats) and anxious apprehension (persistent psychological worries and verbal ruminations relating to future threats; Barlow, 2002). Additionally, these experiences can vary on both trait and state levels. Persistent anxieties can be relatively higher or lower between individuals (i.e. Trait Anxiety), and anxiety can also be induced from the environments we find ourselves in (i.e. State Anxiety; Spielberger & Gorsuch, 1983).

Anxiety & Performance

The first connection between anxiety and inefficient cognitive performance was largely reasoned by Processing Efficiency Theory (PET; Eysenck & Calvo, 1992), noting that since high anxious individuals showed increased reaction times without corresponding declines in task accuracy across numerous tasks, some additional effort must be used in order to maintain task performance. A later extension of PET known as Attentional Control Theory (Eysenck, Derakshan, Santos & Calvo, 2007) supports a specific relation between anxiety and cognitive performance. ACT argues that the negative thoughts and ruminations caused by anxiety (i.e. worry) produce reductions in central executive resources that could otherwise be used towards maintaining an individual's task performance. Essentially, Worry acts as a distraction which diverts cognitive resources away from task relevant information and towards internal ruminations. In particular, ACT proposes that the negative thoughts and ruminations (i.e. worry) that come from anxiety appear to strongly impact a cognitive resource known as working memory.

Working Memory

Working Memory (WM) is a limited-capacity executive resource used for immediate storage, integration and manipulation of information (Miyake & Shah, 1999). Relatively higher levels of WM are associated with a number of desirable outcomes, including greater mathematics performance (Raghubar, Barnes & Hecht, 2010) and even higher levels of general academic achievement (Alloway & Alloway, 2010). In essence, WM is a core executive resource used for performing universal operations such as mathematical calculations or comparing meanings of different sentences. This WM system is largely subserved by a distributed neural network throughout the prefrontal cortex, and in particular the dorsolateral prefrontal cortex (dlPFC; Conway, Kane & Engle, 2003). Often analyzed along with the dlPFC's maintenance of information is activity of the anterior cingulate cortex (ACC), which shares strong connections with the dlPFC. However, the ACC is less involved in the facilitation and maintenance of information and more involved in monitoring interference or conflict between pieces of information which can then signal other regions such as the dlPFC of this conflict (Liu, Banich, Jacobson & Tanabe, 2004; Osaka, Komori, Morishita & Osaka, 2007; Osaka et al., 2003).

A great deal of research supports that WM is closely related to attentional control, an executive function defined as the ability to select for goal-relevant information (Engle, 2002). In addition to past studies evidencing WM's relation to attentional control (see Kane & Engle, 2000; Redick & Engle, 2006), a large 2014 meta-analysis found that commonly used complex span working memory tasks (e.g. an Operation Span task) relate to common measures of attentional control (e.g. an arrow-based flanker task), as attentional control likely acts as a way to maintain information that has transitioned from primary to secondary memory (Shipstead, Lindsey, Marshall & Engle, 2014). Thus, it is important to understand that although WM and attentional control are distinct executive resources, they do share a relationship in the selection for and maintenance of information.

Working Memory, Anxiety & Performance

The assertion that anxiety derails WM resources and disrupts cognitive performance (i.e. Attentional Control Theory) is supported by a large amount of evidence. For example, Ashcraft & Kirk (2001) designed a series of experiments showing that anxiety specific to mathematics negatively impacts cognitive performance specifically for mathematics problems requiring greater WM resources. After first establishing that increased math anxiety is generally related to decreased measures of WM, Ashcraft & Kirk (2001) tested math performance of individuals high and low in math anxiety in a dual-task scenario. In effect, participants were required to perform math that varied in how much it taxed WM resources (i.e. problems requiring carrying numbers vs. not carrying numbers) while also performing a secondary task in which they actively remembered either a low or a high number of items. The logic was that the maintenance of items in a secondary task requires use of WM resources, and this requires even greater WM resources when the secondary task requires remembering a relatively larger number of items. Thus, if anxiety creates active depletions of WM resources, then individuals higher in anxiety should show poorer performance when WM is highly tasked (i.e. while performing carry operations and maintaining many items on secondary task). This is exactly what the researchers found – although individuals with relatively higher levels of anxiety related to math exhibited generally lower performance, they displayed the largest error rate when the dual task scenario was highly demanding (i.e. remember a high number of items) and the math task required a carrying operation.

When worry produced from high-pressure environments (i.e. anxiety at a state level) depletes WM resources, individuals are not equally susceptible to decreases in cognitive performance. A 2005 study by Beilock & Carr tested the cognitive performance of high WM and low WM individuals twice – once before and once after experimenters induced pressure in order to increase anxiety in participants. Results showed that while those high in WM performed initially better than those low in WM, the presence of pressure lowered high WMs performance to the same level of those low in WM. Additionally, this effect can be seen in some of the youngest of students. A 2013 school study tested the WM, math anxiety and math achievement of young (mean age = 7yrs) elementary school students from five different Chicago institutions (Ramirez, Gunderson, Levine & Beilock, 2013). Comparable to Beilock & Carr's (2005) finding, high math anxiety decreased mathematics achievement in students, but only for students who were also high in WM. A similar experiment (Vukovic, Kieffer, Bailey & Harari, 2013) measured elementary school students' math anxiety, WM, as well as a longitudinal measure of how students' improved in applying mathematics throughout the next school year. Mirroring previous research, Vukovic and colleagues (2013) found that an increased math anxiety predicted lower improvement in mathematics over the next school year, but only for students high in WM. Therefore, the effects of anxiety, especially in relation to differences in WM, emerge and impact real-world performance early in cognitive development.

Why is it the case that individuals high in WM are disproportionately at risk for anxiety-related decreases in performance? One possible explanation for increased susceptibility for those high in WM is in the strategies individuals use to solve cognitive tasks. Research by Beilock & DeCaro (2007) measured the math-based cognitive performance of high and low WM individuals, with half of participants performing under no pressure and half of participants performing under induced pressure. This study largely differed from previous research (i.e. Beilock & Carr, 2005) in that after certain problems, participants were directly asked to describe what strategies they used in order to solve them. Results showed that under no pressure, high WM individuals showed increased cognitive performance compared to those low in WM, and high WM individuals also reported more frequent use of advanced algorithms in order to solve cognitive problems. However, those high in WM experiencing pressure exhibited cognitive performance on par with those low in WM, and they also reported significantly lower use of advanced strategies. It appears that anxiety's effect on WM made those high in WM unable to use their more advanced problem solving strategies, and in turn their performance suffered. It is important to note that the cognitive performance of high WM individuals does not decline to the same extent across all high WM individuals, suggesting that important individual differences exist in constructs closely related to WM. It may be the case that differences in the related construct of attentional control could alter whether or not interfering information is allowed into working memory storage, and in turn change the degree to which working memory resources are compromised during a high-pressure task.

Error-related Negativity (ERN)

Research into the neural instantiations of both WM and anxiety have independently revealed distinct connections between these constructs and error-related negativity (ERN), a reliable and stable scalp-recorded neurophysiological signal generated from the anterior cingulate (ACC) within 50-100ms of committing an error within task (see Gehring, Liu, Orr & Carp, 2012 for a review). The ERN is obtained by collecting continuous electroencephalogram (EEG) data, a non-invasive measure of voltage fluctuations across an individual's scalp. This EEG data is then time-locked to a specific event (i.e. a participant's response) in order to obtain each participants' averaged event-related brain potential (ERP), or specific to the present discussion ERN amplitude. In the case of WM, increased (i.e. more negative) ERN signaling is associated with higher levels of WM and executive function (Coleman, Watson & Strayer, 2017; Larson & Clayson, 2011; Miller, Watson & Strayer, 2012). In terms of anxiety, increased ERN amplitudes are related to obsessive-compulsive disorder symptoms (OCD; Carrasco et al., 2013), subclinical obsessive-compulsive symptoms (Kaczkurkin, 2013), general anxiety disorder (GAD; Weinberg, Olvet & Hajcak, 2010), and worry (Moran, Taylor & Moser, 2012).

Function of the ERN.

What does this ERN signaling represent? Although the specific mechanism of the ERN is contested, it is largely agreed that the general function of the ERN is for cognitive control and the adaptive regulation of behavior. As converging evidence implicates the ACC as the generator of the ERN (Yeung, Botvinick & Cohen, 2004), this strongly suggests that the ERN is indicative of an evaluative process which monitors the environment for inconsistencies in information. For instance, the ACC shows a unique, reliable response to incongruent information (MacDonald, Cohen, Stenger & Carter, 2000), interfering information (Osaka et al., 2007) and especially errors (see Gehring et al., 2012 for a review). Given that errors are abundantly more likely to occur in the presence of incongruences and interferences, the ACC activity that the ERN likely represents is thought to serve as a mechanism underlying the detection of differences in order to alter future performance (Carter et al., 1998). This process is therefore not a mechanism of attentional control, but rather a process that determines future engagement of neural areas responsible for executive functioning and control (i.e. dlPFC; Banich, 2009; Crocker et al., 2014).

In regards to specific theories of the ERN, one prominent model proposes that the ERN represents reinforcement learning (Holroyd & Coles, 2002). Reinforcement learning theory posits that experiencing outcomes worse than expected results in phasic midbrain dopamine release which impacts the ACC, in turn acting as a mechanism for the ACC to bolster performance to the task at hand. Others have hypothesized that the ERN directly indexes reactive control stemming from the conflicting experience between an intended response and the actual incorrect response committed (conflict monitoring theory; Yeung et al., 2004; Yeung & Cohen, 2006). A recent union of these two hypotheses suggests that that the ERN reflects a general engagement of the ACC in the selection and maintenance of a given task rather than a responsibility for responding to specific experiences within the task itself (Hierarchal Reinforcement learning; see Holroyd & Yeung, 2012).

ERN & Cognitive Performance.

In short, the ERN is a rapid process generated by the ACC that in part determines future engagement of neural areas responsible for executive functioning and control (i.e. dlPFC). However, the connections of the ACC to the PFC are likely not unidirectional in controlling for attention. In fact, it appears that maintenance of information served by PFC activity can bias

ACC activity, as well (Faraco et al., 2011; MacDonald et al., 2000). For instance, Faraco and colleagues (2011) used fMRI to compare neural responses when participants needed to perform mathematic verification versus when participants needed perform mathematic verification while maintaining secondary information (i.e. a working memory OSPAN task). Relative to solely verifying mathematic statements, the maintenance of information in WM resulted in recruitment from both the dlPFC and ACC, despite the fact that a dissociated role is repeatedly found between these two closely linked regions. Given this findings, one would expect higher ACC-generated ERN signaling to relate to higher levels of executive functions such as WM and attentional control. This is, in fact, the case. Work by Miller and colleagues (2012) found a relationship between WM and scalp-generated ERN signaling, such that higher levels of WM corresponded to significantly higher ERN signaling. This finding was replicated in later work of theirs, as well (see Coleman et al., 2017). Additionally, ERN amplitudes have been to significantly relate to measures of attention, such that as the ERN grows larger, scores on attentional control tasks increase, as well (Larson & Clayson, 2011).

Given that the ERN is posited to play a role in the adaptive regulation of behavior and it holds a relationship to the maintenance of information in WM, it follows that increased ERN signaling should provide a relative benefit to cognitive performance. As mentioned above, it is often difficult to spot performance differences during the simple, force-choice tasks usually used to collect trait ERN signaling (Hajcak, McDonald & Simons, 2003; Schroder & Moser, 2014). However, the ERN is evidenced to provide a benefit to cognitive performance when analyzed on a larger scale. In one the first ERP studies on the subject, Fisher, Marshall & Nanayakkara (2009) analyzed the ERN amplitudes and GPAs of seventeen third-to-fifth grade students. Despite the low sample size, they found that increased ERN amplitudes did marginally relate to increases in students' GPA scores. Hirsh & Inzlicht (2010) followed this study by similarly analyzing the relationship of ERN and GPA within a larger population of undergraduate students. Their results showed a significant relationship between ERN and GPA, such that a relatively higher ERN was related to increased GPA scores.

Functional Connection of the ERN & Worry.

If the general function of the ERN is in the adaptive regulation of behavior – and it shares such a close tie to executive functions such as working memory - why does the ERN share such a close relationship with anxiety? As it turns out, an abundance of evidence shows that the amplitude of the ERN is specifically modulated by the worry dimension of anxiety, and not with the anxious arousal dimension of anxiety or anxiety in general (Lin, Moran, Schroder & Moser, 2015; Moran et al., 2012; see Moser, Moran, Schroder, Donnellan & Yeung, 2013 for a meta-analysis and review). Recently, a framework was proposed in order to explain the functional connection of worry to the ERN. The Compensatory Error Monitoring Hypothesis (CEMH; Moser et al., 2013; 2014) argues that as worry reduces active goal maintenance, compensatory post-error processing occurs and is reflected in an enlarged ERN. This hypothesis relies heavily upon the work we previously outlined in regards to Attentional Control Theory – specifically that worry produces reductions in central executive resources such as WM that could otherwise be used towards maintaining task performance (Eysenck et al., 2007; Moran, 2016). As these resources are diverted away from task-processing and to internal threat (i.e. worry), maintaining performance requires anxious individuals to compensate by increasing cognitive effort. Thus, the enlarged ERN seen yoked with worry is a reflection of compensatory effort underlying the maintenance of performance.

A great amount of research supports that the ERN is specifically modulated by the demand worry places on WM resources. Behaviorally speaking, anxiety-induced cognitive deficits have been shown to impact tasks requiring WM resources specifically in the same domain as worry. In one example of this, see DeCaro, Rotar, Kendra and Beilock (2010) used an anxiety-invoking pressure induction to test the cognitive performance of individuals. They manipulated the types of questions they used to test participants, with half of the questions relying on spatial WM (i.e. vertically presented problems) and half relying on verbal WM (i.e. horizontally presented problems; Trbovich & LeFevre, 2003). Results demonstrated that pressure-induced deficits were seen only on verbally demanding cognitive problems, providing support that it is specifically the negative verbal ruminations of worry that are occupying WM resources and disrupting cognitive performance. This is directly reflected within ERN literature, as a 2012 study found that increasing general cognitive load during an affectively-neutral task resulted in an enlarged ERN (Schroder, Moran, Moser and Altmann, 2012), and follow-up studies that explicitly manipulated verbal and spatial WM load (Lin et al., 2015; Moran & Moser, 2012) showed that the ERN was modulated specifically by verbal WM load within an affectively-neutral task. This strongly evidences that the relationship of worry to ERN is not driven by some somatic or affective response to worry, but the demand that worry places on WM resources.

We previously discussed the role that the ERN plays in the adaptive regulation of behavior, its strong relationship to two executive resources (i.e. WM and attentional control) and the fact that this increased signaling thus correlates to real-world cognitive performance (i.e. Hirsh & Inzlicht, 2010). However, if the CEMH is correct in stating that the ERN acts in part as a response to the demand that worry places on executive resources, one would expect that the benefit a higher ERN provides real-world cognitive performance such as GPA would be altered by levels of worry. Cursory evidence does suggest this, as Moser and colleagues' review (2013) took a subset of participant data from a previous study (*N*=59; Moran et al., 2012) who had GPA data available. After dichotomizing participants into high and low-worry groups based on PSWQ scores, they found that the relationship of ERN existed GPA existed for those high in worry, but not those low in worry. However, the difference between slopes was not significant within this subset of participants (z=1.05, p=.15) likely given sample size, and thus further research is needed regarding the possible role of worry in moderating the connection between ERN and real-world cognitive performance.

Summary & Project Motivation

A story is starting to emerge that outlines the impact of anxiety on cognitive - and ultimately real-world - performance. Higher executive resources (i.e. WM and attentional control) are typically related to higher levels of cognitive performance. However, the negative thoughts and ruminations caused by anxiety (i.e. worry) can act as a drain on these resources which disrupts and impedes performance. This is especially so for those higher in WM who rely on advanced WM resources for problem solving. Along with WM and attentional control, a neurophysiological signal which in part determines engagement of neural areas responsible for attentional control (i.e. ERN) also strongly relates to cognitive performance. Individuals who exhibit relatively higher ERNs generally see a benefit to cognitive and academic performance, while also exhibiting higher levels of WM and attentional control. However, some research argues that the benefit of a higher ERN to cognitive performance may not exist for all individuals, as it may be the case the ERN is actually acting as a compensatory mechanism to maintain the cognitive performance of individuals who may be having their resources drained by worry at a given point in time.

This story has many moving parts and unanswered questions. The goal of the current work is to outline a comprehensive path that worry takes in impacting cognitive performance through a series of three experiments. In Experiment 1, we test if there are differences in how people control their attention that would explain why anxieties disrupt WM-based performance for some and not for others. We expand on this in Experiment 2 and provide a direct test of the CEMH's claims that worry leads to a heightened ERN through worry's depletion of executive resources. Evidence from Experiments 1 and 2 provide the basis for using ERN, worry and trait cognitive measures (i.e. working memory and attentional control) to predict real-world cognitive performance (i.e. GPA) within Experiment 3.

EXPERIMENT 1

The goal of Experiment 1 was to provide a replication of Beilock & Carr (2005) while including two additions to their procedure. We wanted to replicate their finding that state-induced anxieties deplete WM resources and decrease cognitive performance specifically for those high in WM, and we wanted to extend this by testing if there were any additional factors that prevented (or accounted for) this depletion of WM resources.

In addition to testing the cognitive performance of low and high WM individuals both before and after experiencing an anxiety-inducing situation, we added a pre- and post-pressure report of anxiety. This allowed us to test if those higher in WM perhaps experience anxiety to a greater extent, thus leading to greater cognitive deficits under high-pressure situations. Furthermore, we collected a measure of attentional control. We hypothesized that variability in attentional control may alter the amount of interfering information allowed into working memory storage, thus affecting the degree to which working memory resources are compromised during a high-pressure task.

We first looked to test if higher working memory scores related to higher attentional control as indexed by either of our flanker RT measures (Kane & Engle, 2000; Redick & Engle, 2006). More importantly, however, we hypothesized that the relationship between working memory and cognitive performance under pressure would be altered by levels of attentional control, as indexed by either of our flanker RT measures. Overall, the decrease in cognitive performance due to pressure should grow larger as working memory increases, replicating the research of Beilock and Carr (2005). However, attentional control may alter this relationship. When attentional control is lower, higher working memory should predict decreases in performance due to pressure. Task-irrelevant information stemming from our pressure manipulation is likely to be allowed into working memory, in turn decreasing cognitive performance those higher in working memory. When attentional control is higher, the relation between working memory and performance under pressure may not be as robust, as higher attentional control should prevent pressure-induced worries from co-opting working memory resources.

Methods

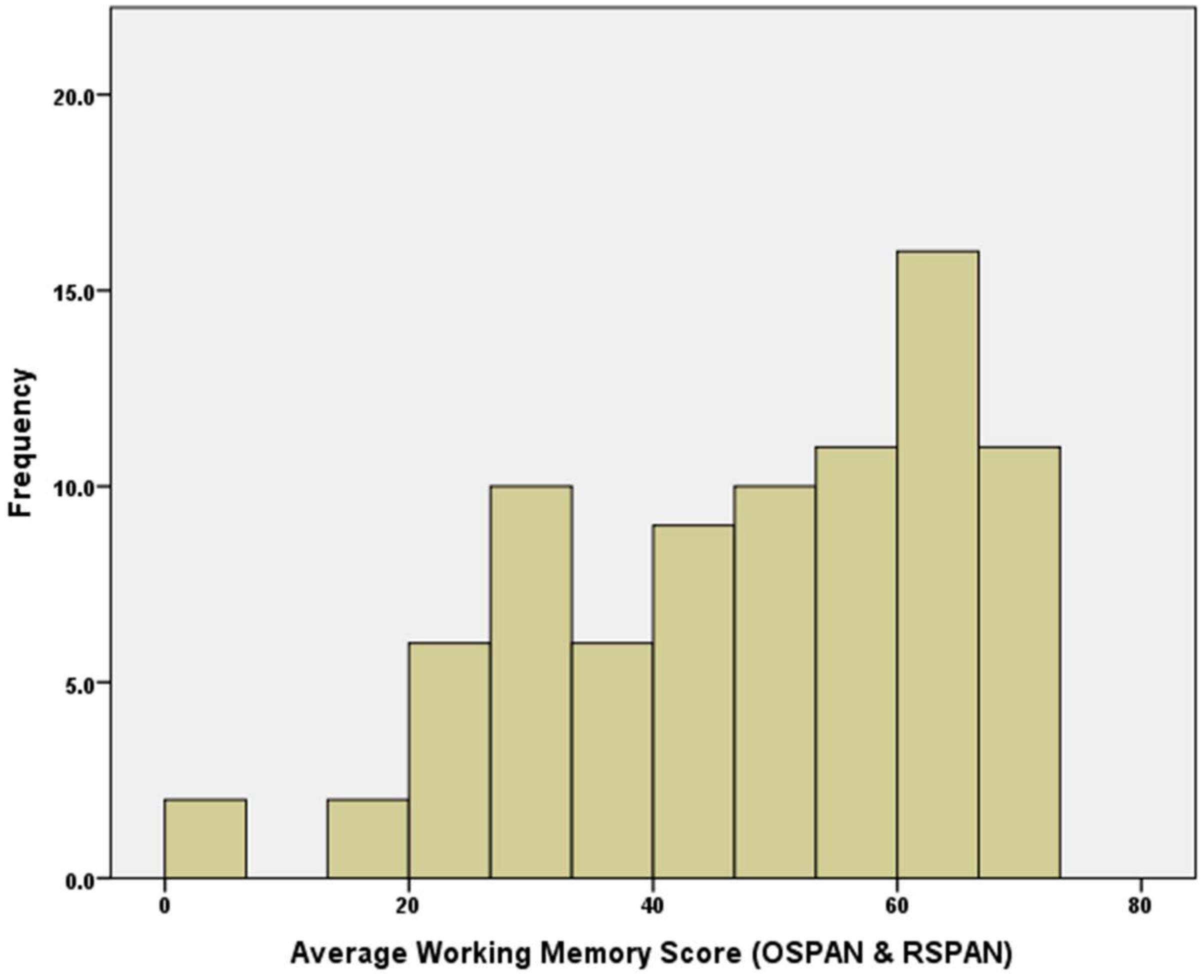
Participants

Participants were recruited from both the greater Chicago, IL (*N*=68) and Lansing, MI (*N*=15) metropolitan areas (age range 18 to 35yo; M = 23.19, SD = 4.52) surrounding the University of Chicago and Michigan State University campuses, respectively. Data was collected continuously through one complete year; at the end, a total of 95 participants had been collected. Exclusion from the data set occurred if participants had < 80% on the mathematical and sentence-comprehension portion of the working memory tasks (5 removed), exhibited flanker performance 3SDs outside the mean or below 50% for congruent trials (4 removed) or failed to complete the working memory tasks (3 participants removed). Therefore, a final count of 83 participants' (35 male) data is included in the present analysis.

Variables

WM scores were calculated as an average of two working memory tasks: an automated Operation Span (OSPAN) task (Turner & Engle, 1989; Unsworth, Heitz, Schrock & Engle, 2005) and an automated version of Daneman & Carpenter's (1980) Reading Span (RSPAN) task. Both working memory tasks require participants to solve either a sequence of mathematical operations (OSPAN) or sentence-comprehension exercises (RSPAN), while in between each trial a letter is presented on the screen. At the end of a sequence of trials, participants were required to recall, in perfect order, the letters that had been presented during the previous sequence of math or reading exercises. In either span task, each sequence ranged from 3 to 7 trials, requiring participants to recall strings of 3 to 7 letters. A participant's final OSPAN and RSPAN score reflects the total number of letters which were recalled on perfectly recalled trials (i.e. absolute score; out of a possible 75). Because working memory scores were negatively skewed (see Figure 1), a square root transformation was performed on averaged span scores ($M = 6.79$, $SD = 1.45$).

Figure 1. Histogram of Average WM Scores in Experiment 1



Attentional control was measured via an arrow-based flanker task (Eriksen & Eriksen, 1974). Although previous studies have shown a relationship between working memory capacity and measures of attention recorded from flanker tasks (Heitz & Engle, 2007; Redick & Engle, 2006), flanker tasks used have varied greatly, and separating what specific functions of attention these RT measures represent is problematic. Therefore, we used two separate RT measures from our flanker task to index attentional control and test if either measure of attention altered the relationship of working memory and choking under pressure. First, we used a comparison of response times (RTs) on trials with interfering information (incongruent) to RTs on trials without interfering information (congruent; i.e. the Flanker Effect; Sanders & Lamers, 2002). Although greater differences in this "inhibition" measure have been related lower working memory in the past (see Redick & Engle, 2006), RT difference scores can be incredibly unreliable (Lord, 1963). Therefore, we also analyzed flanker RTs across all trials (congruent + incongruent). We reason that if participants are matched on flanker accuracy, then lower overall RTs indicate a relatively increased ability to sustain attention to the task at hand throughout the course of the flanker task.

Materials and Procedure

Session 1

Prior to arrival in the laboratory, participants responded to a series of online questionnaires including a report of demographic information and the trait portion of the State-Trait Anxiety inventory (STAI; Spielberger & Gorsuch, 1983). Additional questionnaires were included for the purpose of obscuring the connection between anxiety and our study, but these are not analyzed any further.

Session 1 | Flanker Task. Next, participants completed an arrow-based flanker task (Eriksen & Eriksen, 1974) presented using E-prime software (Psychology Tools, Inc.). In this task, participants judge the direction of a center arrow placed within a series of five total arrows. Arrows only pointed either leftwards or rightwards, and within the series of arrows, the center arrow was either congruent (e.g., <<<<<) or incongruent (e.g., <<><<) with the arrows flanking it on either side. Left and right responses were indicated by pressing "A" and "L" on the keyboard, respectively. Each trial began with the presentation of a fixation cross for 100ms, followed by the presentation of five congruent or incongruent arrows for 100ms. The subsequent inter-trial interval varied from 800-1200ms, during which a fixation cross was presented. After 40 trials, a break slide appeared and informed participants of a discretionary break before beginning the next set of trials. A total of 15 blocks of 40 trials were administered (600 trials altogether).

Session 1 | Modular Arithmetic & Pressure Induction. In order to examine the impact of a high-pressure scenario upon cognitive performance, we next enacted a method previously outlined in Beilock & Carr (2005). Baseline cognitive performance was first measured using 40 trials of Gauss' (1801) modular arithmetic. In modular arithmetic, participants make judgements about the truth value of mathematical statements such as, "$121 \equiv 94 \pmod 3$." Judging the problem requires subtracting the second number from the first (i.e. 121-94) and subsequently dividing the difference by the last number (i.e. $27 \div 3$). The dividend in this case is a whole number (i.e. 9), so the modular arithmetic problem is judged true. When the dividend is not a whole number, the modular arithmetic problem is judged false. A modular arithmetic problem in which the first number in the sequence is large (>20) or the first subtraction step requires a carrying operation (similar to our example above) is high in working memory demand. However, problems such as, "$5 \equiv 2 \pmod 3$," require no carrying operation and are defined as low working memory demand. Since modular arithmetic is a mathematical task novel to participants regardless of math experience, it is an excellent task for measuring cognitive performance. Our modular arithmetic task included 40 trials, 20 of which were of low working memory demand and 20 were of high working memory demand.

Following the first modular arithmetic task, participants were exposed to a high-pressure scenario that has been reliably demonstrated to increase feelings of pressure, anxiety, and induce performance deficits across a range of tasks. The pressure induction requires performing a second block modular arithmetic problems in the context of monetary incentive ($\geq 20\%$ improvement on modular arithmetic leads to a $10 bonus), peer pressure (failure to improve modular arithmetic accuracy by ≥ 20% causes another participant to not receive bonus) and social evaluation (performance is recorded for local teachers and professors to examine). Once these terms of the second block of modular arithmetic were explained, participants completed an additional 40 modular arithmetic problems unique from the first block. Again, 20 problems were low in working memory demand and 20 high in working memory demand. Blocks 1 and 2 of modular arithmetic were counterbalanced across all participants, and modular arithmetic stimuli were presented using E-prime software (Psychology Tools, Inc.).

A second state-anxiety measure (STAI; Spielberger & Gorsuch, 1983) immediately followed block 2 of modular arithmetic to serve as a comparison to the state anxiety measure collected prior to the pressure induction. The post-pressure anxiety questionnaire did not save for a single participant, explaining the variation in degrees of freedom within the analysis on STAI below.

Finally, scheduling for Session 2 occurred at least two days after Session 1. Participants were told that this was because of the time required to analyze modular arithmetic data in order to calculate final reimbursement for the study, when in actuality we wanted to guarantee that the pressure induction in Session 1 did not impact results in Session 2. Importantly, participants were also told that performance in Session 2 held no bearing on final reimbursement for the study.

Session 2

The purpose of Session 2 was to collect participants' working memory scores. Upon arriving to the lab, participants completed an automated version of both the OSPAN and RSPAN tasks. Once completed, a short interview was conducted by the experimenter in which participants were asked (a) to what extent they felt pressured to perform well during Session 1 and (b) what they believed was the purpose of the experiment. While this interview functioned to flag participants expressing explicit knowledge of either the experiment's purpose or previous research pertaining to this same experimental design, no participants were removed from analyses for this reason. Participants were then debriefed and paid $25 regardless of their modular arithmetic performance within Session 1.

Results

Pressure Manipulation Check: STAI

Means and standard deviation for pre- and post-pressure anxiety (STAI) ratings are located in Table 1. A repeated measures ANOVA showed that our pressure manipulation did increase participants' reported levels of anxiety ($F(1,81)=43.42$, $p<.01$, $\eta^2=.35$). Correlation analyses show no relationship of pre-anxiety, post-anxiety or an anxiety difference score (post-STAI minus pre-STAI) with working memory, any measure of flanker accuracy or any measure of flanker RT (all correlations at $p>.10$).

Modular Arithmetic Performance

Math Accuracy. Means and standard deviation for all pre- and post-pressure modular arithmetic performance are located in Table 1. Problems high in working memory demand were performed less accurately than problems low in working memory demand. In an attempt to replicate findings by Beilock & Carr (2005) showing that under pressure, working memory demanding cognitive performance is most likely to decrease for those relatively higher in working memory, we first performed a repeated measures ANCOVA (Pressure: low, high) analyzing the accuracy of high-demand math while using working memory scores as a continuous between-subjects variable. There was a significant two-way interaction of pressure and working memory ($F(1,81)=4.29$, $p<.05$, $\eta^2=.05$)[1]. To make it clear how differences in working memory related to changes in cognitive performance before and after pressure, we performed a median split in our WM scores. Using these two groupings, a comparison of pre- to post-pressure high-demand math accuracy revealed no significant change for those lower in working memory ($t(40)=-1.63$, n.s.). However, for those higher in working memory, there was a significant decrease in high-demand math accuracy ($t(41)=2.30$, $p<.030$).

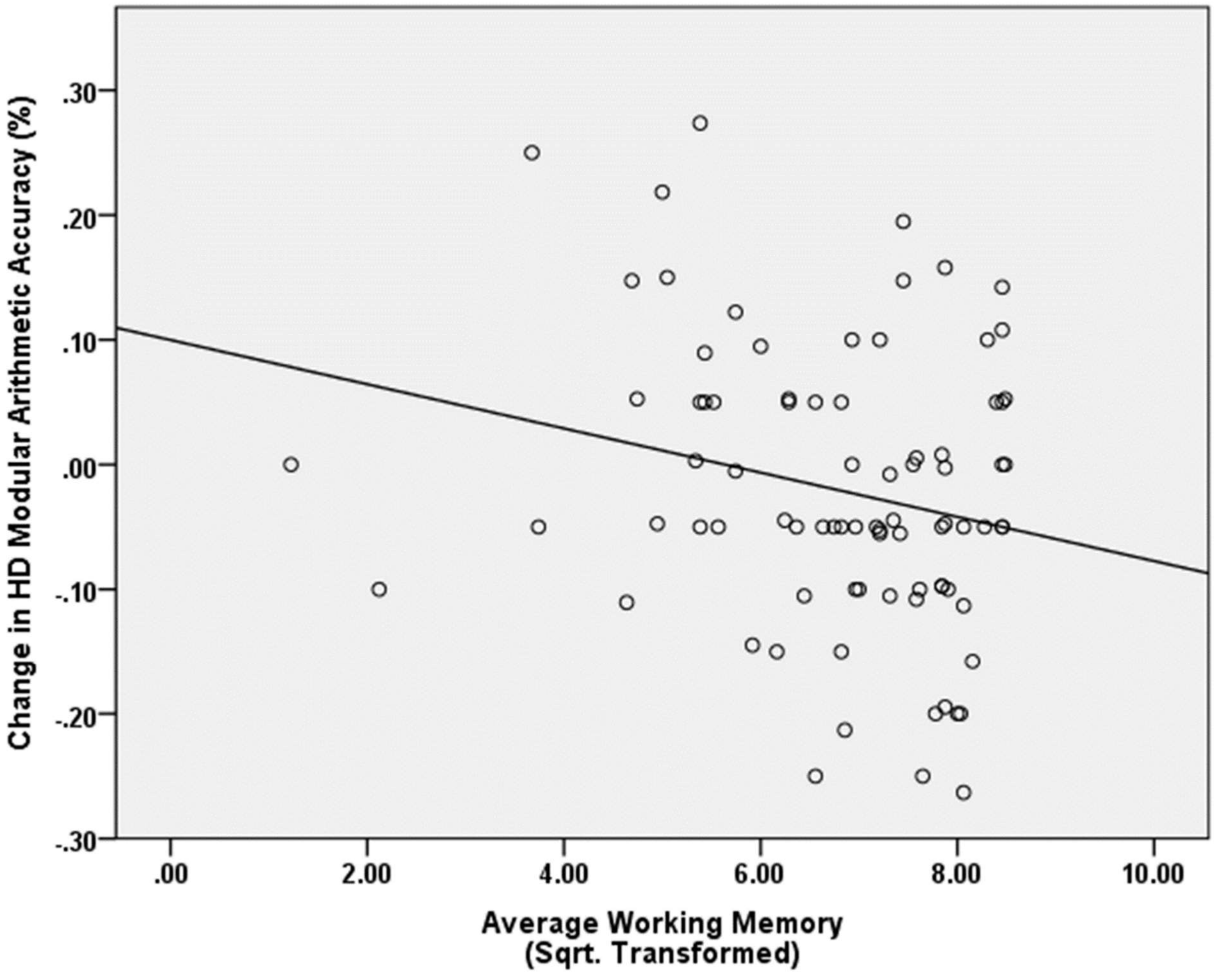
Table 1. Descriptive Statistics of Pre- and Post-Pressure Manipulation Data in Experiment 1

	STAI		Low Demand Math RTs		High Demand RTs		Low Demand Math Acc		High Demand Math Acc	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Pre-Pressure	35.34	9.39	2545.90	835.71	8487.96	3419.00	.9729	.038	.8718	.1030
Post-Pressure	40.51	11.15	2068.33	659.47	7563.34	3409.54	.9735	.036	.8513	.1028

We further explored working memory's relationship to performance by creating a math difference score in which we subtracted pre-pressure from post-pressure high-demand math accuracy. Although working memory was not correlated with either pre-pressure accuracy ($r=.17$, $p=.12$) or post-pressure accuracy ($r=-.08$, $p=.50$), working memory did significantly correlate to the change in high-demand math accuracy ($r=-.24$, $p<.05$). Again, this reflects the above finding that as participants' working memory increased, there was a larger decrease in working memory demanding cognitive performance due to our pressure manipulation (see Figure 2).

[1]The same ANCOVA accounting RTs of correct, high-demand math problems revealed a main effect of pressure ($F(1,81)=17.03$, $p<.01$, $\eta^2=.17$) but no interaction with working memory ($p>.05$), indicating that the interaction of pressure and working memory in accounting for accuracy was not the result of a speed-accuracy trade-off

Figure 2. Relationship of WM & Change in Cognitive Performance in Experiment 1



Note. Scatterplot showing the relationship of Working Memory with the change in high demand (HD) modular arithmetic accuracy (%) due to pressure; as scores were calculated as post-pressure accuracy minus pre-pressure accuracy, a negative change score indicates that performance became worse after experiencing pressure

Math RTs. The RTs for correct math problems were analyzed in a 2 (Pressure: low, high) x 2 (Demand: low, high) ANOVA. A main effect of demand revealed that RTs were much faster for low demand problems compared to high demand problems (F(1,81)=375.37, p<.01, η^2=.82), a main effect of pressure showed that RTs were faster after our pressure induction (F(1,81)=23.74, p<.01, η^2=.23) and an interaction of pressure and demand (F(1,81)=5.38, p<.03,

η^2=.06) revealed that pressure increased the speed of high demand modular arithmetic trials (by 1073.9ms) more than it did low demand modular arithmetic trials (by 462.75ms).

Flanker Performance

A complete table of means and standard deviations for flanker accuracy RTs are reported in Table 2.

Table 2. Correlation Matrix with Descriptive Statistics in Experiment 1

			Correlations							
	Mean	SD	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
[1]Working Memory (sqrt)	6.79	1.45	1							
[2]HD Math Difference Score	-.02	.11	-.224*	1						
[3]Flanker Acc (C)	.9497	.0513	.090	.049	1					
[4]Flanker Acc (I)	.8793	.0887	.073	.198	.687*	1				
[5]Flanker RT (C)	403.86	50.44	-.196	.160	-.059	.267*	1			
[6]Flanker RT (I)	436.86	52.75	-.171	.126	.031	.307*	.944*	1		
[7]Flanker Difference Score	38.52	23.36	.185	-.039	.150	.013	-.069	.205	1	
[8]Overall Flanker RTs	420.07	50.87	-.186	.144	-.013	.292*	.985*	.987*	.072	1

Note: * denotes p<.05; (C) denotes *congruent trials*, (I) denotes *incongruent trials*

Flanker Accuracy. Flanker accuracy was first analyzed in a repeated measures ANOVA to compare congruent and incongruent trial types, showing that congruent flanker trials (M =.95, SD =.05) were much more accurate than incongruent trials (M =.88, SD =.09; F(1,82)=96.94, p<.001, η^2=.54). Neither congruent nor incongruent flanker accuracy correlated with working memory (both p>.41).

Flanker RTs. Flanker RTs were similarly analyzed in a repeated measures ANOVA to compare congruent and incongruent trial types, showing that congruent flanker trials (M =.95, SD =.05) were much more accurate than incongruent trials (M =.88, SD =.09; F(1,82)=308.39, *p*<.001, η^2=.79). Working memory did not correlate with flanker RTs for congruent trials, incongruent trials or a difference score between the two trial types (all *p*>.07).

Indices of Attentional Control from the Flanker Task. Our first index of attentional control was a difference score that subtracted the RTs on congruent trials from RTs on incongruent trials. For this measure we used only correct flanker trials in order to mirror previous research showing that a higher working memory relates to lower flanker RT difference scores (and assumed higher attention; Redick & Engle, 2006). Within our data, although this flanker difference measure did not significantly relate to working memory, the relationship was marginal and in the expected direction (*r* =-.19, *p*>.09).

Our second index of attentional control was simply comprised of flanker RTs across all trials (congruent + incongruent). We reason that if participants are matched on flanker accuracy, then lower overall RTs indicate a relatively increased ability to sustain attention to the task at hand throughout the course of the flanker task. This may be especially so given our lengthy flanker task, as it consists of over twice the amount of trials previously used to compare working memory scores to flanker RT measures (see Heitz & Engle, 2007; Redick & Engle, 2006). Similar to our first attentional control measure, overall flanker RTs did not significantly relate to working memory, but the relationship was marginal and in the expected direction (*r* =-.19, *p*>.09).

Pressure, Working Memory & Attentional Control

The first goal of this research was to replicate that individuals higher in levels of working memory are more susceptible to pressure-induced decreases in working memory demanding cognitive performance, a finding we confirmed and described above. Our second goal was to explore if measures of attention control interact with working memory to further predict who would be most susceptible to choking under pressure. We chose a multiple linear regression (MLR) to predict the change in working memory demanding cognitive performance due to pressure (post- minus pre-pressure high-demand math accuracy) using the independent variables of working memory, attention and an interaction of the two. As we remain agnostic as to which of our two attention control measures (if any) may interact with working memory to account for pressure-induced cognitive deficits, we performed a separate MLR for either of our two attentional control measures.

Our first MLR model predicted the change in high-demand modular arithmetic accuracy using working memory (square root transformed), our flanker RT difference score and an interaction of the two. All variables were mean-centered before being included in the model. This regression model did not significantly account for variance in pressure-related cognitive performance ($F(3,79)=1.55$, $p=.21$) and will not be analyzed further.

Our second MLR model predicted the change in high-demand modular arithmetic accuracy using working memory (square root transformed), overall flanker RTs and an interaction of the two. Again, all variables were mean-centered before being included in the model. This regression model significantly accounted for over 7% of the variance in pressure-related cognitive performance, ($F(3,79) = 3.2$, $p < .03$; $R^2=.11$, Adjusted $R^2=.074$). Multicollinearity was not an issue within our model, as the variance inflation factor did not exceed (VIF < 1.2) for any of our independent variables. In accounting for pressure-related cognitive performance, the predicted two-way interaction between working memory and our measure of attentional control was significant ($\beta=-.23$, $t=-2.04$, $p<.05$). The complete regression model can be seen in Table 3.

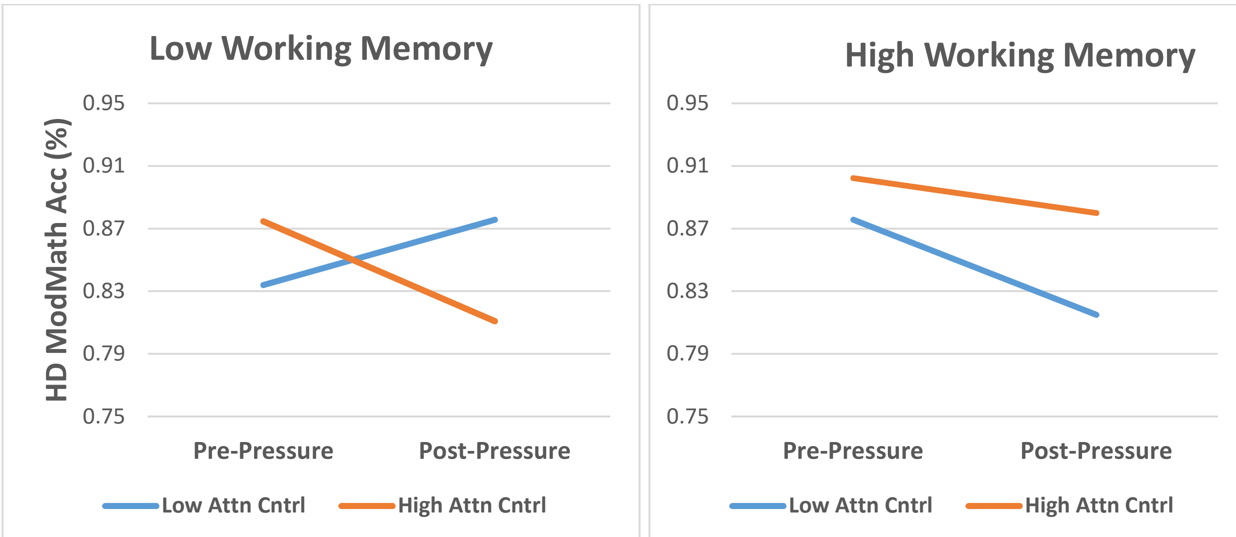
Table 3. Model of the Multiple Linear Regression in Experiment 1

Coefficients	Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
(Constant)	-.027	.013		-2.181	.032
Working Memory	-.011	.009	-.140	-1.247	.216
Overall Flanker RTs	.000	.000	.143	1.301	.197
WM * Overall Flanker RTs	.000	.000	-.227	-2.043	.044

Note. Model significantly accounted for over 7% of the variance in the DV (change in cognitive performance due to pressure; R^2=.108, Adj. R^2=.074, p<.03)

To visualize how working memory and attentional control interacted to account for the change in high demand modular arithmetic accuracy due to pressure, we predicted this change in accuracy when the means of working memory and attentional control were one standard deviation either above or below the mean (Aiken, West & Reno, 1991). Our visualization shows the predicted change in accuracy added/subtracted to our sample's pre-pressure math accuracy when WM and attentional control were low and high. These low and high groupings were made using a median split in our WM and attentional control scores. As shown in the visualization (Figure 3), this measure of attentional control did alter the relationship we found between working memory and cognitive performance under pressure. Generally, those higher in WM showed higher cognitive performance, especially before experiencing pressure. Furthermore, those higher in working memory appear to show significant decreases in performance due to pressure, but only when they were also low in attentional control. Interestingly, it appears that although those low in WM and high in attentional control see performance decreases due to pressure, those low in WM and low in attentional control exhibit a slight increase in their performance after pressure. We further analyzed our model's two-way interaction in a test of simple slopes, finding that increases in working memory related to greater decreases in cognitive performance due to pressure only when individuals were low in this measure of attentional control (β =-.04, t=-4.10, p<.05), but not when individuals were high in attentional control (β=.01, t=1.61, p=.11).

Figure 3. Visualization of Two-way Interaction in Experiment 1



Discussion

Experiment 1 replicates previous work showing individuals higher in working memory are significantly more likely to have their cognitive performance decline due to experiencing high pressure situations. However, we further extended these findings by showing that this relationship of working memory and cognitive performance under pressure changes based upon attentional control. When participants' attentional control was low, an increased working memory related to an increase in pressure-induced error. However, there was no relationship between working memory and cognitive performance under pressure when this measure of attentional control was high. Of interest is that it appears those low in both WM and attentional control actually have a slight increase in performance after experiencing pressure. It may be the case that these individuals lowest in executive resources react to our pressure induction with increased motivation. Furthermore, this group also has the greatest room for improvement in cognitive performance, as they exhibit the lowest pre-pressure cognitive performance. Together this may help explain the improvement they appear to be showing. All together, these findings suggest that when experiencing high pressure situations, differences in attentional control may alter the amount of interfering information allowed into working memory storage. When attentional control is low, individuals typically reliant on their higher working memory resources for advanced problem solving see decreases in their cognitive performance.

It is important to address the overall relationship of working memory and attentional control found in the current study. Although both attentional control measures marginally related to working memory, flanker RT measures in the past have shown a much stronger relationship to measures of working memory. For instance, Redick & Engle (2006) showed that high working memory individuals exhibited significantly smaller differences in RTs between incongruent and congruent flanker trials, as well as faster flanker RTs across congruent trials and incongruent trials compared to individuals low in working memory. Our lack of finding such a strong relationship between working memory and flanker measures of attentional control may be explained by particular differences between our study and previous studies. For instance, the flanker task used in our experiment consisted of nearly twice as many trials as other studies that have compared flanker RTs to working memory scores (Heitz & Engle, 2007; Redick & Engle, 2006). Perhaps this repetition impacted the flanker task such that our measures of attentional control became more similar across participants as the task continued. Additionally, both Heitz and Engle (2007) and Redick and Engle (2006) analyzed the relationship of attentional control and working memory by dichotomizing participants into low and high working memory groups in an individual differences approach. However, in the current research we analyzed working memory as well as attentional control as continuous variables in order to predict changes in cognitive performance surrounding high pressure experiences.

Of consideration is that only one measure of attentional control from our flanker task, overall flanker RTs, significantly interacted with working memory to account for cognitive performance under pressure. In terms of a specific mechanism of attention, it is problematic to truly delineate how this measure of attentional control differs from our flanker RT difference measure. And with the current data set, it is nearing impossibility to understand why it was solely this measure of attentional control that interacted with working memory to account for cognitive performance. However, the purpose of this study was to replicate the previously found relationship between working memory and choking under pressure, and further test if attentional control alters this relationship. Future studies analyzing pressure-related cognitive performance could benefit from using comprehensive measures of attentional control that aid in discerning between different mechanisms of attentional control.

EXPERIMENT 2

In Experiment 1, we showed that the depletion of WM resources by anxiety are avoided when those with relatively higher levels of WM also have a relatively higher level of attentional control. These findings have a fairly large implication for research suggesting that error-related negativity functions as a compensatory mechanism engaged specifically when executive resources (i.e. WM) are depleted by worry (CEMH; Moser et al., 2013). Recall that within this framework, ERN signaling is not a mechanism of attentional control that impacts if worry depletes WM resources, but rather a compensatory process engaged when worry depletes WM resources. If the results of Experiment 1 indicate that not all individuals experiencing worry show a depletion of WM resources, then it follows that not all individuals experiencing worry should show a heightened ERN amplitude in terms of the CEMH. Individuals who are able to prevent worry-induced depletions of WM resources (i.e. those with both relatively higher WM and attentional control) should show relatively attenuated ERN signaling. We tested this by recording levels of trait worry, WM, attentional control and trait ERN signaling, and analyzing if the relationship of worry and ERN was altered by WM and attentional control when predicting ERN amplitudes within a multiple linear regression.

Of course, how the worry-ERN relationship will change based on these variables remains an open question. Our first prediction is that those relatively higher in both measures of executive function (i.e. WM and attentional control) will actually show consistently heightened ERN signaling. Previous research has argued and supported that individuals with heightened levels of executive resources are overall more likely to engage in this error monitoring as measured by ERN (see Miller et al., 2012). However, we do predict that worry will relate to ERN signaling when WM is high and attentional control is low. Those with a relatively higher WM who are low in attentional control may be unable to control attention away from worry, and thus as worry increases, heightened compensatory ERN signaling will follow. Similarly, individuals relatively lower in WM but higher in attentional control will show a relationship of worry to ERN signaling. As worry increases, any worry that manages to impact executive resources despite their relatively higher attentional control will create a demand on already lessened WM resources that will initiate compensatory ERN signaling. For individuals exhibiting the relatively lowest level of executive resources (i.e. lower WM and attentional control), it's not readily clear how ERN signaling will relate to worry. It may be the case that for these individuals, heightened ERN signaling will be seen regardless of levels of worry. Given their much lower level of executive resources, these individuals may be in a continual state of demand on their resources that makes them likely to engage in this error monitoring at any given time. However, we remain agnostic as to a prediction for these individuals.

Providing support for this CEMH framework not only helps validate the hypothesis in and of itself, but it would also suggest that the benefit a relatively high ERN provides to cognitive performance may actually only occur for individuals who have their cognitive resources depleted by worry (i.e. those low in WM or those low in attentional control), but not for individuals who manage to maintain cognitive resources through other means (i.e. high WM individuals with high attentional control).

Methods

Participants

Participants were recruited from the greater Lansing, MI area for reimbursement of $10/hour. Exclusion from analyses occurred if participants committed fewer than six errors on the flanker task (Olvet & Hajcak, 2009) or if EEG activity contained extensive artifacts during post-collection analyses (artifact correction explained below). Three participants failed to return to complete the second session of the study and were thus omitted from any analyses. A total of 65 participants (34 female) were included in the final sample, with ages ranging from 18 to 34 (M = 21.38, SD = 3.87).

Variables

Our measure of Working Memory was identical to Experiment 1. WM scores were calculated as the average of two WM tasks: an automated Operation Span (OSPAN) task (Turner & Engle, 1989; Unsworth et al., 2005) and an automated version of Daneman & Carpenter's (1980) Reading Span (RSPAN) task. The final range of average WM scores was 1.5 to 71.5 (M = 43.82, SD = 15.42).

Analogous to Experiment 1, we used an arrow-based flanker task (Eriksen & Eriksen, 1974) to acquire a measure of trait attentional control. The only alteration made on the flanker task used in Experiment 2 was the inclusion of feedback to participants in between blocks. After each block, feedback prompted individuals to, "Please try and respond faster," if their flanker accuracy was above 90% or to, "Please try to be more accurate," if accuracy was below 75%. Feedback between blocks of flanker trials can be used to facilitate participant-made errors for subsequent analysis of ERN (Hajcak & Foti, 2008), allow us to decrease the number of trials to 240 (12 blocks of 20) while still collecting a reliable ERN amplitude from participants. Attentional control was defined as variation in RTs specifically to incongruent trials, as these are the trials from which ERN amplitudes are collected. Although we used a slightly different definition of attentional control from Experiment 1 (i.e. variability in flanker RTs across all trials), the results reported below reflect the same finding using either measure.

EEG Collection & Data Correction

ERP data was recorded continuously through the flanker task using the ActiveTwo BioSemi system and using 64 Ag-AgCl electrodes that were situated within a stretch-lycra cap. Two supplementary electrodes were placed on the left and right mastoids. Three additional electrodes were used to record and control for electrooculogram (EOG) activity generated by eye movements – one placed below the left pupil and two placed on the left/right outer canthi. Digitization of the signal occurred at 512Hz using ActiView software (BioSemi). Post-collection analyses were completed with BrainVision Analyzer 2 (BrainProducts). Recordings at scalp-electrode sites were re-referenced to the numeric means of the mastoids, band-passed filtered with cutoffs of 0.1 and 30Hz, and corrected for ocular artifacts using the same method described by Gratton, Coles & Donchin (1983). We used a computer-based algorithm to detect physiological artifacts, removing trials from analysis if they had a voltage difference of less than 0.5μV or greater than 200μV within a trial, or a voltage step exceeding 50μV between contiguous sampling points. Trials were rejected from both behavioral and ERP analysis if RTs did not fall within a 200-800ms time range. Segmentation of response-locked data into epochs began at 200ms before response onset and continued for 800ms following response. In order to quantify response-locked ERPs, the average amplitude in the 200ms pre-response window was subtracted from each data point following the response. The ERN and Correct Response Negativity (CRN) was then computed from average voltage within the 0-100ms post-response time range across the central recording site FCz, where amplitudes were maximal.

Procedure

Upon arriving to the lab and signing the consent form, participants immediately underwent setup for EEG collection (described above). After setup for EEG collection was complete, participants completed the arrow-based flanker task (12 blocks of 20 trials; 240 total). After finishing, participants were given a 15 minute break, during which they could clean up from the EEG conductance gel and use the restroom. After this break, participants completed the Penn State Worry Questionnaire (PSWQ; Meyer, Miller, Metzger & Borkovec, 1990), as well as a general demographic survey.

Half of our participants then completed our two complex WM span tasks (OSPAN & RSPAN). The other half of our sample returned to the lab after at least 2, but no longer than 7 days, in order to complete the OSPAN and RSPAN tasks.[2]

[2] Data was originally collected along with a third cognitive task, with the three tasks counterbalanced across two sessions in order to decrease session lengths– this third task is irrelevant to the research question at hand and will not be analyzed further

Results

Worry

The average PSWQ score was 45.02 (*SD*=14.8, range = 16-78). PSWQ scores were unrelated to average WM scores ($r = .01$, $p = .92$). The means and standard deviations for all self-report and behavioral measures can be found in Table 4.

Flanker Performance

Flanker Accuracy. Although flanker accuracy was fairly high overall ($M = .88$, $SD = .06$), a comparison of means for flanker accuracy reveals that accuracy for congruent trials ($M = .96$, $SD = .04$) was much higher than incongruent trials ($M = .75$, $SD = .10$; $t(65) = 18.17$, $p < .001$). PSWQ scores were not related to flanker accuracy either overall or for any specific trial type (for all correlations, $p > .37$). Additionally, there was no relationship between average WM scores and any measure of Flanker accuracy (for all correlations, $p > .10$).

Flanker RTs. Response times for congruent flanker trials ($M = 379.40$, $SD = 34.36$) were significantly faster than for incongruent flanker trials ($M = 430.40$, $SD = 40.91$; $t(65) = -24.35$, $p<.001$). Neither PSWQ scores nor average WM scores were significantly related to flanker RTs either overall or for any specific trial type (for all correlations, $p>.05$).

Error-related Negativity & Worry

A comparison of mean ERP amplitudes between error and correct trials revealed that amplitudes for error trials ($M = -4.50$, $SD = 4.34$) were significantly more negative than for correct trials ($M=1.83$, $SD=3.02$; $t(65) = -10.94$, $p<.001$) within the 0-100ms post-response window. No significant relationship was found between ERN and flanker Accuracy (correlation with any trial type, $p>.62$) or flanker RT (correlation with any trial type, $p>.72$). The relationship between ERN and WM was marginal, suggesting that higher WM individuals in our sample had a smaller ERN (*r* = .23, *p* = .05). The relationship between PSWQ and ERN was also marginal (*r* = -.24, *p* = .06) in the expected direction, such that increased worry symptoms shared a similar "small-to-medium" relationship with enhanced ERN as described in Moser et al. (2013).

ERP amplitudes on correct trials (i.e. CRN) did not relate to PSWQ (*r*=-.13, p=.30) or WM scores (*r*=-.14, p=.28), but was marginally related to ERN amplitudes (*r*=.23, p=.07). CRN did, however, significantly relate to longer response times for congruent (*r* = -.28, *p* < .05), incongruent (*r* = -.26, *p* < .05) and overall flanker trials (*r* = -.26, *p* < .05), as well as slightly higher accuracy specifically for incongruent trials (*r* = -.25, *p* < .05). We additionally created a difference measure of ERP amplitudes between error and correct trials (i.e. ERN minus CRN). However, this difference score (*M*=-6.33, *SD*=4.68) was not significantly related to PSWQ (*r*=.13, *p*=.29).

Table 4. Descriptive Statistics in Experiment 2

			Correlations						
	Mean	SD	*1*	*2*	*3*	*4*	*5*	*6*	*7*
[1]ERN	-4.50	4.34	1						
[2]Worry	45.02	14.8	*-0.235*	1					
[3]Working Memory	43.82	15.42	*0.243*	0.013	1				
[4]Flanker Acc (C)	0.96	0.04	0.014	-0.092	-0.004	1			
[5]Flanker Acc (I)	0.75	0.1	-0.062	-0.058	-0.204	0.390*	1		
[6]Flanker RT (C)	379.40	34.37	-0.046	-0.155	*-0.242*	-0.12	0.419*	1	
[7]Flanker RT (I)	430.40	40.91	-0.036	-0.193	-0.196	0.039*	0.526*	0.914*	1

Note. * denotes *p*<.05; italicized correlations denote a marginal correlation of (.05 < *p* ≤ .06); (C) denotes *congruent trials*, (I) denotes *incongruent trials*

Change in the Worry-ERN Relationship

In the current experiment, we ask if the relationship between worry and ERN is altered based upon differences in both WM and attentional control. To answer this question, we predicted variance in ERN amplitudes based upon worry, WM and attentional control using a multiple linear regression (MLR). Our regression model included average WM scores, worry (PSWQ) scores and flanker response times for incongruent trials (i.e. attentional control), as well as all possible two and three-way interactions between coefficients. Additionally, sex/gender has been shown to relate to ERN (Fischer, Danielmeier, Villringer, Klein & Ullsperger, 2016; Larson, South & Clayson, 2011) and to moderate the relationship between the ERN and worry (Moran et al., 2012; Moser, Moran, Kneip, Schroder & Larson, 2016). Therefore, although not of immediate importance to the current research, we included sex as a main effect within our MLR in order to control for any effect sex may have. All variables were mean-centered before being included in the model; the complete regression model can be seen in Table 5.

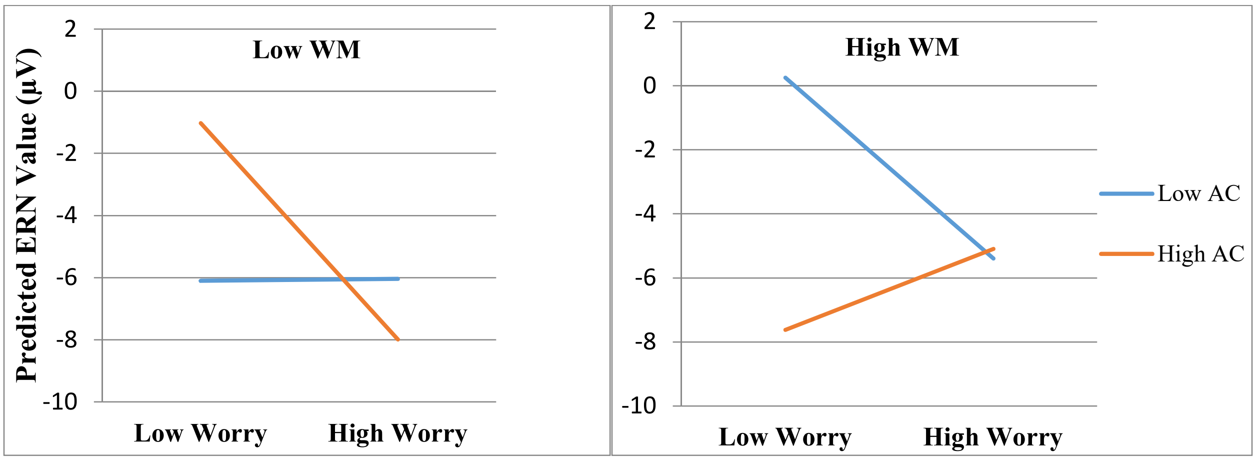
Table 5. Model of the Multiple Linear Regression in Experiment 2

	Unstandardized Coefficients		Standardized Coefficients		
Coefficients	B	Std. Error	Beta	t	Sig.
(Constant)	-4.88	.743		-6.564	.000
Sex	.933	1.119	.108	.834	.408
Worry	-.085	.038	-.289	-2.249	.028
WM	.027	.036	.095	.745	.460
Attentional Control	.014	.015	.128	.923	.360
Worry * WM	.002	.003	.106	.766	.447
Worry * Attentional Control	.000	.001	-.032	-.227	.822
WM * Attentional Control	-.002	.001	-.408	-2.398	.020
Worry * WM * Attentional Control	.000	.000	-.685	-3.484	.001

Our regression model significantly accounted for almost 20% of variance in ERN, ($F(8,56) = 2.78$, $p < .015$; $R^2 = .28$, Adjusted $R^2 = .18$). For any measure within our model, the variance inflation factor did not exceed (VIF < 1.5), providing evidence that multicollinearity was not an issue. In accounting for ERN, a main effect of worry was found ($\beta = -.29$, $t(65) = -2.26$, *p*<.03) along with a significant two-way interaction between WM and attentional control (β=-.37, *t*(65)=-2.26, *p*<.03). Moreover, the hypothesized three-way interaction between worry, WM and attentional control significantly accounted for significant variance in the ERN, (β=-.63, *t*(65)=-3.48, *p*<.005).

In order to visualize our three-way interaction, we predicted the amplitude of the ERN based upon our regression when the means of worry, WM and attentional control were located one standard deviation either above or below the mean (Aiken et al., 1991). As seen in the visualization of our regression model (Figure 4), both WM and attentional control greatly altered the relationship between worry and the ERN. Readily noticeable is that for individuals relatively higher in WM, increases in worry only appear to relate to increases in ERN when attentional control is relatively lower. Consistent with our hypothesis, those relatively higher in both measures of executive functioning (i.e. higher WM and higher attentional control) show consistently heightened ERN amplitudes regardless of worry. However for low WM individuals, increases in worry appear to relate to increases in ERN only when attentional control is high. Individuals with the lowest relative levels of executive resources (i.e. low WM and low attentional control) exhibit consistently high ERN signaling. We further confirmed these findings by investigating our three-way interaction using tests of simple slopes (using variable means +/-1SD). For those lower in WM, the relationship of worry and ERN was only marginally different from zero when attentional control was high (see Figure 4, left-hand side; β=-.24, *t*=-1.7, *p*=.09); when attentional control was lower, those with a lower WM showed no relationship of worry and ERN (β=.002, *t*=.02, *p*=.99). For those higher in WM, there was no relationship of worry and ERN signaling when attentional control was also higher (β=.09, *t*=.64, *p*=.52); however, there was a trending relationship of worry and ERN when those relatively higher in WM exhibited a lower level of attentional control (β=-.2, *t*=-1.37, *p*=.17).

Figure 4. Visualization of Worry, WM & Attentional Control Predicting ERN Amplitudes in Experiment 2



Discussion

Similar to previous research (Moser, Moran & Jendrusina, 2012), we found a moderate overall relationship between individual levels of worry and the ERN. Consistent with the framework presented in the CEMH (Moser et al., 2013; 2014), this relationship was strongly impacted by differences in participants' available cognitive resources (i.e. WM) and differences in attentional control that dictate the extent to which interferences load cognitive resources. Although we showed that higher levels of worry related to increased post-error brain activity (i.e. ERN) overall, our predictive model showed us that when WM was relatively high, this worry-ERN relationship only existed when levels of attentional control were low. Presumably when WM was higher but attentional control lower, these individuals may have been less likely to control attention away from worry. Thus as worry increased and placed additional demand on WM resources, heightened compensatory ERN signaling followed. Interestingly, when both WM and attentional control were higher, individuals exhibited consistently high ERN signaling. At first appearing at odds with the idea behind the CEMH, we would expect individuals with the highest levels of overall executive functioning to show consistent engagement in this error monitoring. Previous research has argued that higher levels of executive functioning actually bias engagement in prefrontal mechanisms of attentional control such as ERN signaling (see Miller et al., 2012).

When WM was lower, a different pattern of results emerged. Worry significantly related to ERN only when levels of attentional control were high. For these individuals, any worry that managed to impact executive resources despite their relatively higher attentional control created a demand on their already reduced WM resources. In turn, compensatory ERN signaling increased. For participants exhibiting the relatively lowest level of executive resources possible (i.e. lowest WM and attentional control), consistently high ERN amplitudes were seen regardless of levels of worry. It appears that due to their executive resources being so exceptionally attenuated, these individuals are in a continual state of demand on their resources that makes them likely to engage in this error monitoring.

Altogether, these findings show that the amount of cognitive resources available to an individual can alter the relationship between worry and compensatory ERN signaling. When worry is prevalent, compensatory ERN signaling does not uniformly increase - the extent to which ERN increased with worry depended on both WM and attentional control, two variables that impact the cognitive resources available to an individual. And although previous research would suggest that WM and attentional control do not necessarily operate equally in determining cognitive resources available to an individual (see Engle, 2002), the results of the current study show that both variables interact to alter worry's relation to ERN. This finding supports and extends previous hypotheses (see Moser et al., 2013; 2014) arguing that worry specifically depletes executive resources, and this impact on executive resources leads to increased post-error processing as reflected by increased ERN amplitudes.

One important implication of this study becomes apparent when reminded that worry does not occur in a unitary fashion. Current research on the relationship of ERN and worry typically categorizes worry as a trait variable. This is for a good reason – in a clinical setting, the ERN can act as a reliable neurophysiological marker of the symptomology and cognitive impairment stemming from anxiety/worry (Bress, Meyer & Hajcak, 2014; Carrasco et al., 2013). However, anxiety and worry can also be induced by environments we find ourselves in (see Hofmann et al., 2005). Previous research has shown that whether increases in worry and verbal rumination occur through personal anxieties (i.e. math anxiety; Ashcraft & Kirk, 2001; Ramirez, Gunderson, Levin & Beilock, 2013) or manipulations of one's environment (see Beilock & Carr, 2005; DeCaro et al., 2010; Moser et al., 2013), working memory resources are impacted and behavioral performance diminishes. As the current findings support the idea that worry's load on cognitive resources ultimately increases ERN, this suggests that state inductions of worry would modulate the ERN as well. Worry inductions would increase internal ruminations that cause cognitive resources to diverge from task-relevant goals and thus ERN may increase in order to compensate. Although initial anxiety inductions have failed to impact ERN amplitudes (Larson et al., 2013; Moser, Hajcak & Simons, 2005), these studies have focused on the anxious arousal dimension of anxiety and not the cognitively-loading worry described herein. However, the anxiety inductions seen in studies such as Beilock & Carr (2005) and Decaro et al. (2010) would likely prove fruitful in manipulating ERN amplitudes as they are reliably able to increase levels of cognitively-loading worries and apprehensions. However, this remains an empirical question.

EXPERIMENT 3

Throughout the first two experiments, we outlined a fairly clear path of how worry relates to cognitive performance. Individuals are equally susceptible to experiencing state inductions of worry, and some carry with them additional trait worry. These worries act as a drain on WM resources which disrupts cognitive performance, and this is especially so for those higher in WM who typically rely on their advanced WM resources for problem solving. Higher levels of attentional control allow these individuals to maintain cognitive performance when facing high worry, presumably by attending away from interferences and back to relevant information. We support the hypothesis that a drain on WM overall increases compensatory processing (i.e. ERN), and the amplitude of this signaling reliably differs between individuals. As outlined in the background section, individuals who exhibit relatively higher trait compensatory ERNs see a benefit to real-world cognitive performance, and it may be the case that exhibiting performance on level with those not experiencing worry. However, this has yet to be tested within a real-world scenario. If this is the case, our evidence from Experiment 1 suggests that the benefit of a high ERN may only exist (or provide a greater benefit) for those individuals unable to compensate for Worry by some other mean (i.e. high WM/low attentional control).

To our knowledge, no research has provided a comprehensive analysis of the effect of worry on cognitive performance in a real-world setting, while accounting for these differences in WM, attentional control and error monitoring (ERN). In Experiment 3, we provide such an account by measuring individuals' levels of worry, WM, attentional control and ERN at the beginning of an academic semester. We then use these measures to predict GPA scores that are assigned at the end of the semester using a multiple linear regression (MLR). This will allow us to (1) conceptually replicate Experiment 1 within an ecologically valid setting, (2) replicate previous findings on the ERN's relationship to GPA, WM and attentional control while further exploring how executive resources moderate the link of ERN to GPA, and (3) provide additional evidence for the CEMH to test if ERN interacts with worry within a real-world scenario to predict GPA scores.

We first expected to conceptually replicate our findings from Experiment 1 within a real-world setting, showing that when individuals face high degrees of worry, cognitive performance is in part determined by a mix of both WM and attentional control. Given the naturalistic nature of the experiment, we are unable to place participants within a high-pressure situation to manipulate levels of anxiety/worry as we did in Experiment 1. However, we can use individuals' reported levels of trait worry as a general index of the extent to which anxieties/worry derail cognitive resources throughout the semester. We expect to find a three-way interaction between worry, WM and attentional control in predicting semester GPA. When levels of worry are higher, we expect increases in WM to predict lower GPA scores when attentional control is low. Lower attentional control makes it more likely that the interference of worry will impact cognitive resources, and the negative effect this has on cognitive performance increases with WM (i.e. Experiment 1). When both worry and attentional control is high, we expect increases in WM to predict higher GPA scores. When attentional control is relatively higher, interferences presented by worry will be prevented, and thus we will see WM predict higher academic achievement as suggested by previous research (Alloway & Alloway, 2010; Raghubar et al., 2010). When worry is low, we expect higher levels of WM or attentional control to generally relate to higher GPA scores.

Secondly, we expect to replicate findings showing that higher ERN amplitudes are associated with increased with levels of WM (Miller et al., 2012; Coleman et al., 2017), attentional control (Larson & Clayson, 2011), worry (Lin et al., 2015; Moran et al., 2012; Moser et al., 2013) and GPA scores (Fisher et al., 2009; Hirsh & Inzlicht, 2010). Given that the ERN represents monitoring of inconsistencies in information (see Gehring et al., 2012 for a review), and that WM levels relate to ACC-PFC activation during maintenance of information (Faraco et al., 2011) and that attentional control acts to select for relevant information and the ERN relates to behavioral measures of attentional control (Larson & Clayson, 2011), we believe that there will be an interaction between WM, attentional control and ERN in predicting GPA. Those lower in attentional control are less able to select for relevant information and will be assisted by discrepancies being registered by the ACC (i.e. higher ERN signaling). Those with a higher WM will be better able to adapt behavior based upon discrepancies registered by ERN signaling and maintain this information. Thus, those relatively low in attentional control and high in WM will see the greatest increases in academic performance (i.e. GPA) as ERN increases. However, for those with higher measures of attentional control and lower measures of WM, variability in ERN signaling will not result in a change in GPA.

Our final hypothesis aims to test if ERN signaling does interact with levels of worry to predict real-world cognitive performance. As put forward by the CEMH, the ERN may be a compensatory mechanism which acts to increase monitoring of information in response to a depletion of executive resources. If this is the case, our expected replication of worry, WM and attentional control predicting cognitive performance should be altered by ERN in a four-way interaction. Recall, in Experiment 1 (and predicted to replicate here) the individuals most susceptible to depletion of executive resources by worry are those higher in WM but lower in attentional control. If the ERN does represent a compensatory response, we should find that a relatively lower ERN relates to lower a GPA within this most susceptible group. This would provide evidence that the ERN is compensating for worry's depletion of executive resources. However, if ERN and worry only predict GPA in coefficients completely independently of one another, this would suggest that the process the ERN represents operates independent of worry in providing a benefit to cognitive performance.

Methods

Participants

Participants were undergraduates recruited within Michigan State University for reimbursement of 1 course credit/hour. The study was conducted over two academic semesters (Winter/Spring). Recruitment and participation only occurred during the first half of either semester, as to leave a space of time between the in-lab study and the GPA scores later achieved by each of the participants. Participants were excluded from analyses if they committed fewer than six errors on the flanker task (Olvet & Hajcak, 2009) or if post-collection analyses revealed extensive EEG artifacts (artifact correction explained below). One participant failed to provide correct information for collecting their GPA data, and they were thus omitted from any analyses. A total of 79 participants (60 female) were included in the final sample, with ages ranging from 18 to 42 (M = 19.31, SD = 2.82).

Variables

Our measure of Working Memory was identical to both Experiment 1 and 2. An automated Operation Span (OSPAN) task (Turner & Engle, 1989; Unsworth et al., 2005) and an automated version of Daneman & Carpenter's (1980) Reading Span (RSPAN) task were averaged to create our measure of WM. The final range of average WM scores was 10 to 75 (M=41.15, SD = 13.95).

As in our previous experiments, we used an arrow-based flanker task (Eriksen & Eriksen, 1974) to measure levels of attentional control. Specifically, we used a flanker task most similar to Experiment 2 which included feedback to participants in between blocks in order to facilitate participant-made errors for analysis of ERN (Hajcak & Foti, 2008). There were a total of 240 trials (12 blocks of 20). However, there was one difference in this flanker task compared to our previous experiments. This flanker task still required participants to indicate the direction of a center arrow placed in a series of five total arrows. Recall, the center arrow was congruent (e.g., <<<<<) or incongruent (e.g., <<><<) with the flanking arrows. However, left and right responses were indicated by the participant pressing a left or right mouse button with their right hand, rather than the two-handed keyboard response used in Experiments 1 and 2. The reason for this methodological difference was to most similarly replicate previous research relating flanker data to real-world academic performance. Although the relationship of ERN to academic performance and GPA has been shown quite a few times (see Fisher et al., 2009; Hirsh & Inzlicht, 2010; Moser et al., 2013), research relating two-choice flanker tasks to GPA data have used single-handed responses (e.g. Moser et al., 2013).

For this study, attentional control was defined as accuracy for incongruent flanker trials. Recall that in Experiments 1 and 2, variability in flanker RTs was used as an index of attentional control. The general logic with the simple, forced-choice flanker task is that when participants are matched across accuracy, then variance in response times will reveal differences in the ability to control attention from irrelevant information, and vice versa. As you can see in the results below, flanker RTs in Experiment 3 were fairly matched across participants while accuracy varied. Therefore, we use differences in incongruent flanker accuracy as our variable of attentional control.

EEG Collection & Data Correction

The EEG parameters, procedure and post-collection cleaning of data to acquire ERP amplitudes was identical to that of Experiment 2. The ERN and Correct Response Negativity (CRN) was computed from average voltage within the 0-100ms post-response time range across the central recording site FCz*,* where amplitudes were maximal. The final ERN signal used in data analyses is a difference score computed as the difference between each participant's ERN CRN amplitude.

Procedure

Upon arriving to the lab, participants immediately provided consent for participation in our lab study as well as consent for acquiring their future end of semester and cumulative GPA scores. After providing consent, participants immediately began setup for EEG collection (described in Experiment 2). After setup was complete, participants completed the arrow-based flanker task (12 blocks of 20 trials; 240 total). After finishing, participants were given an optional 15-minute break during which they could clean up from the EEG conductance gel and use the restroom. Following the break, participants completed the Penn State Worry Questionnaire (PSWQ; Meyer et al., 1990), as well as a general demographic survey.

After the surveys were complete, participants completed our two complex WM span tasks (OSPAN & RSPAN) and signed to acknowledge receipt of the course credit they would be awarded for the study.

Results

Worry

The average PSWQ (Worry) score was 54.24 (*SD*=12.78). There was a marginal relationship between PSWQ scores and average WM scores (r = -.21, p = .08), such that higher levels of worry related to lower levels of WM. However, PSWQ scores did not correlate with GPA (p>.05) The means and standard deviations for all self-report and behavioral measures can be found in Table 6.

Table 6. Descriptive Statistics and Correlation Matrix in Experiment 3

	Mean	SD	*Correlations* 1	2	3	4	5	6	7	8
[1]ERN	-6.27	3.62	1							
[2]Worry	54.23	12.78	.19	1						
[3]WM	41.15	13.95	-.26*	-.20	1					
[4]GPA	3.40	.56	*-.21*	-.02	.10	1				
[5]Flanker Acc (C)	.93	.04	-.38*	-.13	.16	.07	1			
[6]Flanker Acc (I)	.79	.09	-.40*	.05	.17	*.21*	.53*	1		
[7]Flanker RT (C)	365.92	32.83	.11	.14	-.15	.13	.13	.50*	1	
[8]Flanker RT (I)	401.40	36.94	-.02	.07	-.11	.06	.37*	.53*	.89*	1

Note. * denotes p<.05; italicized correlations denote a marginal correlation of (.05 ≤ p ≤ .07); (C) denotes *congruent trials*, (I) denotes *incongruent trials*

Flanker Performance

Flanker RTs. Response times for congruent flanker trials (M = 365.92, SD = 32.83) were significantly faster than for incongruent flanker trials (M = 401.40, SD = 36.94; t(78) = -18.57, p<.001). There was no relationship between any flanker RT measure and PSWQ scores, WM scores, ERN amplitude or GPA (for all correlations, p>.20).

Flanker Accuracy. Flanker accuracy was fairly high overall (M = .86, SD = .06). However, comparing the means of congruent and incongruent flanker accuracy revealed that accuracy for congruent trials (M = .93, SD = .04) was much higher than incongruent trials (M = .79, SD = .09; t(78) = 16.46, p < .001). PSWQ scores did not relate to flanker accuracy for either trial type (both p > .26).

Index of Attentional Control from Flanker Task. Attentional control in this experiment is defined as accuracy on incongruent flanker trials, rather than response times on these trials. As seen directly above, flanker RTs did not relate to our measure of cognitive performance (i.e. GPA) or any measure of executive function in our task (i.e. WM). However, flanker accuracy for incongruent trials did marginally correlate with semester GPA (p = .065), while congruent accuracy did not (p=.56). This relationship suggests that those who showed higher flanker accuracy when conflicting (i.e. incongruent) information was presented to them also had higher levels of GPA months later. Furthermore, incongruent flanker accuracy showed a trending relationship with WM scores (p=.13) while congruent flanker accuracy did not (p>.15). Seeing these differences in flanker accuracy while flanker RTs remained similar across participants gives us strong reason to use incongruent flanker accuracy as our metric of attentional control.

Error-Related Negativity

We compared mean ERP amplitudes between error and correct trials to reveal that amplitudes for error trials at site FCz (M = -5.17, SD = 3.71) were significantly more negative than for correct trials (M=1.10, SD=2.36; t(78) = -15.37, p<.001) within the 0-100ms post-response window. Each participant's final error-related negativity (ERN) was calculated as a difference score by subtracting the average amplitude from correct trials from the average amplitude from error trials. The average of this ERN measure was (M=-6.27, SD=3.62).

ERN amplitudes did not correlate to flanker RTs for either incongruent or congruent trials (for both correlations, p>.35). However, there was a relationship between ERN and both flanker incongruent accuracy (r= -.40, p<.05) and congruent accuracy (r= -.38, p<.05), such that higher accuracy related to higher ERN signaling.

Interestingly, our ERN amplitudes additionally show numerous relationship that parallel previous findings within physiology literature. ERN significantly related to WM scores (r= -.26, p<.025), showing that higher levels of WM related to higher ERN signaling (Coleman et al., 2017; Miller et al., 2012). Furthermore, ERN amplitudes marginally related to future GPA scores (r= -.21, p=.07), such that higher ERN amplitudes marginally related to higher future GPA scores (Hirsh & Inzlicht, 2010). However, we found no relationship in the current data set of PSWQ scores with ERN amplitudes (r=.19, p>.05; Lin et al., 2015; Moser et al., 2012).

Predicting GPA

We ask in the current experiment if trait measures collected at the beginning of a university's semester could predict a student's future, end-of-semester GPA. Specifically, we asked if a physiological measure of error processing (i.e. ERN), two behavioral measures of executive function (i.e. working memory & attentional control) and trait levels of a construct known to decrease executive resources (i.e. worry) could predict future GPA. To answer this question, we predicted variance in semester GPA based upon worry, WM, attentional control and ERN using modelling through multiple linear regression (MLR).

Initially, our regression model included worry (PSWQ) scores, average WM scores, attentional control (incongruent flanker accuracy) and ERN amplitudes as IVs, and the model included all possible interactions between these four variables. All variables were mean-centered before being entered into the MLR. Similar to Experiment 2, we included sex as a covariate in our model since sex/gender has been shown to relate to ERN (Fischer et al., 2016; Larson et al., 2011), as well as moderate its relationship to variables such as worry (Moran et al., 2012; Moser et al., 2016). Because half of our sample was collected in the first (Winter) semester, and half was collected in the second (spring) semester, a dichotomous variable controlling for semester was included in the model, as well. Although this first 'full model' significantly predicted over 23% of the variance in GPA (F=2.4, p<.01, Adj. R^2=.231), it was not a satisfactory representation of the data as it contained numerous high-level interactions of which the coefficients were insignificant (see Table 7).

Table 7. Initial full model of Multiple Linear Regression in Experiment 3

Coefficients	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	3.010	.200		15.040	.000
Sex	.161	.151	.123	1.063	.292
Semester	.277	.122	.246	2.266	.027
Working Memory	.005	.005	.131	1.008	.317
ERN (FCz Diff)	-.038	.020	-.247	-1.876	.065
Worry	.002	.006	.035	.248	.805
Attentional Control	.399	.831	.061	.480	.633
Worry * WM	-1.948E-005	.000	-.007	-.048	.962
Worry * Attn.Ctrl	-.189	.084	-.321	-2.259	.027
Worry * ERN	-.003	.002	-.263	-1.530	.131
WM * ERN	-.004	.002	-.312	-2.157	.035
Attn.Ctrl * WM	.075	.074	.136	1.019	.312
Attn.Ctrl * ERN	.865	.224	.489	3.870	.000
Worry * ERN * WM	-5.303E-005	.000	-.081	-.391	.697
Worry * WM * Attn.Ctrl	.014	.007	.325	1.938	.057
Worry * ERN * Attn.Ctrl	.007	.026	.044	.265	.792
WM * ERN * Attn.Ctrl	-.033	.026	-.206	-1.281	.205
Worry * WM * ERN * Attn.Ctrl	.001	.002	.063	.297	.767

Note. Initial 'full' MLR model; model significantly predicted for over 23% of variance in our DV (semester GPA; Adj. R^2=.231, F=2.4, p<.01)

We reduced the model in a stepwise-fashion, removing the highest-level, non-significant interactions and analyzing the model along the way. The model formed at the end of this reduction can be seen in Table 8. Our model predicted 24% of the variance in semester GPA,

$F(12,66) = 3.04$, $p<.01$; $R^2=.36$, Adj. $R^2=.24$. Multicollinearity was not an issue within our model, as the variance inflation factor did not exceed (VIF < 1.8) for any given coefficient. In accounting for semester GPA, there was a three-way interaction between worry, WM and attentional control (β=-.26, $t(78)=2.25$, $p<.03$). Additionally, ERN interacted independently with two measures of executive function to account for GPA: WM (β=-.27, $t(78)=-2.04$, $p<.05$) and attentional control (β=-.38, $t(78)=-2.25$, $p<.03$).

Table 8. Final Multiple Linear Regression in Experiment 3

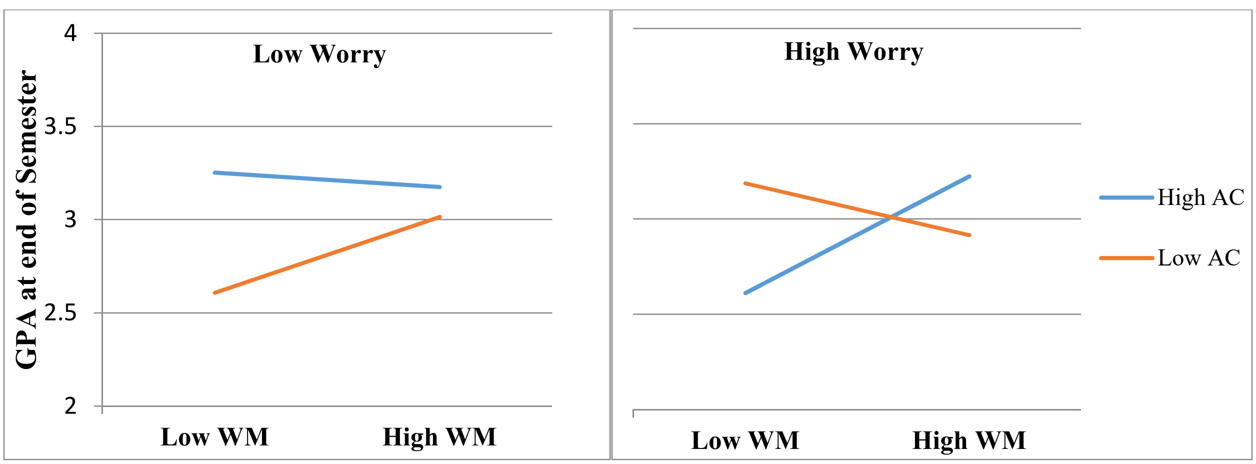
Coefficients	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	2.999	.195		15.392	.000
Sex	.114	.147	.087	.778	.440
Semester	.282	.118	.250	2.386	.020
Working Memory	.006	.004	.149	1.383	.171
ERN (FCz_Diff)	-.031	.019	-.198	-1.613	.111
Worry	-.001	.005	-.025	-.215	.831
Attentional Control	.783	.768	.119	1.020	.311
Worry * WM	.00001	.000	.003	.028	.978
Worry * Attn.Ctrl	-.123	.068	-.208	-1.789	.078
WM * Attn.Ctrl	.042	.063	.076	.662	.510
ERN * WM	-.003	.002	-.269	-2.039	.045
ERN * Attn.Ctrl	.670	.196	.379	3.412	.001
Worry * WM * Attn.Ctrl	.011	.005	.263	2.245	.028

Note. Final regression model; model significantly predicted for 24% of the variance in our DV (semester GPA; Adj. $R^2=.24$, $F=3.04$, $p<.005$)

For visualizing the three-way interaction, we predicted semester GPA using our regression when the means of worry, WM and attentional control were located one standard deviation either above or below the mean (Aiken et al., 1991). When levels of worry were high, increases in WM appear to predict to higher GPA scores when attentional control is also high.

However, when attentional control was low, increases in WM seem to relate to lower GPA scores. Follow-up simple slopes analyses reveal that this is the case. Increases in WM predicted higher GPA when attentional control was high (see Figure 5, right-hand side; β=-2.58, *t*=2.20, *p*<.04) and lower GPA when attentional control was low (β=-2.57, *t*=-2.18, *p*<.04). We next turned to when levels of worry were relatively low, looking at how WM related to GPA when attentional control was low and high. Simple slopes analyses revealed that that when levels of worry were relatively low, the relationship of WM and GPA was not significantly different from zero whether attentional control was low (see Figure 5, left-hand side; β=1.42, *t*=1.07, *p*=.29) or high (β=-1.41, *t*=-1.06, *p*=.29).

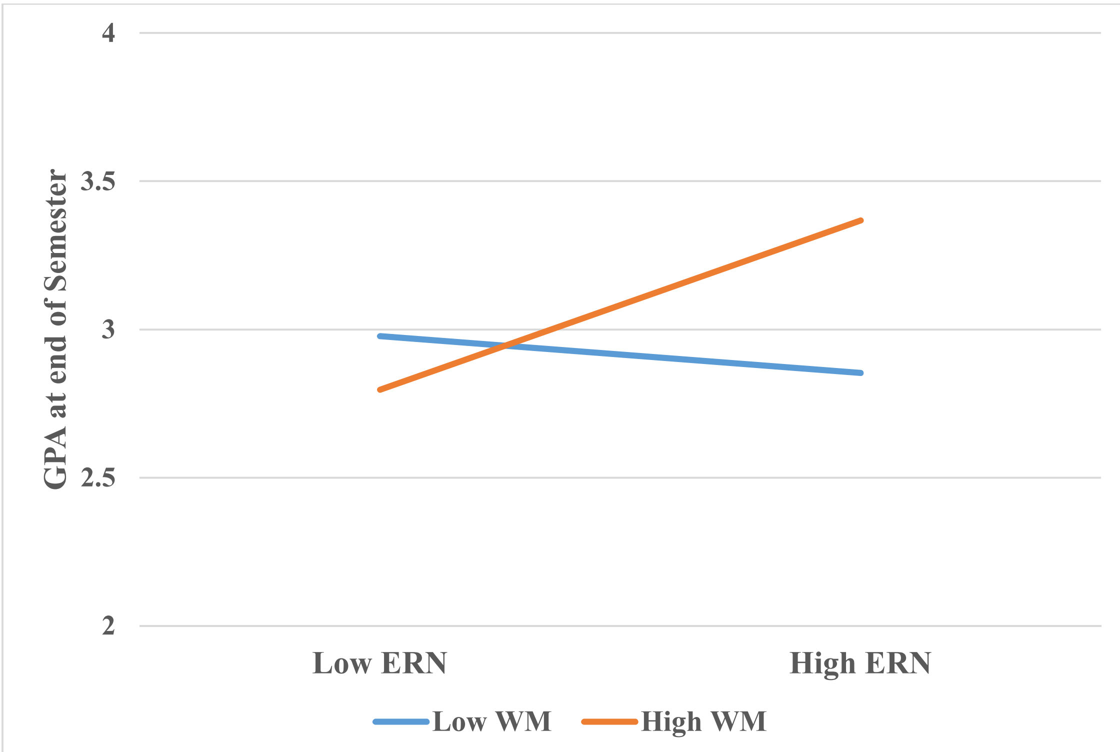
Figure 5. Visualization of Worry, WM & Attentional Control Predicting GPA Scores in Experiment 3



We addressed the two-way interactions found in our regression model in a similar fashion. The two-way interaction of ERN and WM in predicting GPA can be found in Figure 6. When WM was low, the relationship of ERN to semester GPA remained constant. However, when WM was high, increases in ERN also predicted increases in GPA. This was reflected in the follow-up simple slopes analyses: higher ERN amplitudes did predict higher semester GPA when

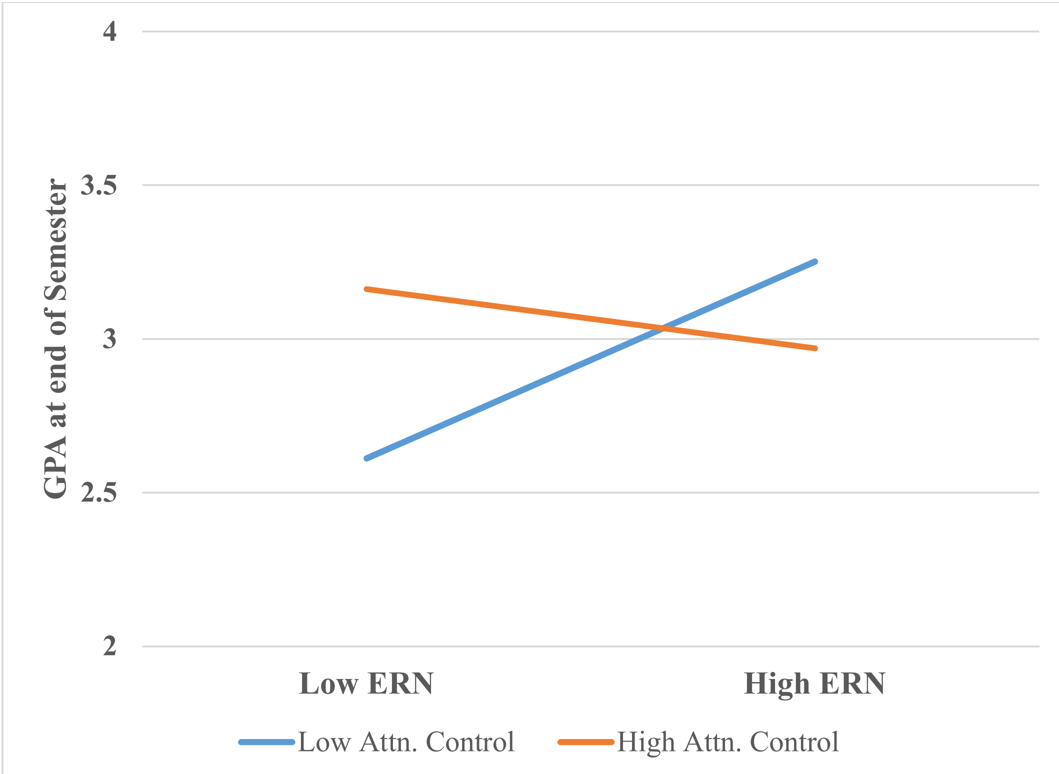
WM was high (β=-.08, t=-2.60, p<.02), but when WM was low there was no relationship between ERN and GPA (β=.02, t=.55, p=.59).

Figure 6. Visualization of ERN & WM Predicting GPA Scores in Experiment 3



Semester GPA was also predicted by an interaction between ERN and our measure of attentional control (see Figure 7). The two-way interaction appears to predict that for those low in attentional control, increases in ERN led to a higher semester GPA. For those high in attentional control, however, changes in ERN do not seem to predict changes in GPA. Follow-up analyses revealed that this is, in fact, the case. This finding was supported by our simple slopes analyses, showing that increases in ERN did predict higher GPAs when attentional control was low (β=-.09, t=-3.02, p<.01), but not when attentional control was high (β=.03, t=1.27, p=.21).

Figure 7. Visualization of ERN & Attentional Control Predicting GPA Scores in Experiment 3



Discussion

Experiment 3 conceptually replicated Experiment 1 by showing that when worry was relatively higher, WM and attentional control interacted to predict cognitive performance. These findings were enhanced by the fact that we predicted future cognitive performance, and that our predicted measure of cognitive performance was a real-world, ecologically valid measure of cognitive performance (i.e. GPA). Similar to Experiment 1, we found that when worry was high and attentional control was low, increases in WM significantly predicted lower GPA scores. However, when worry was high and attentional control was also high, increases in WM actually predicted increases in GPA scores. Although it's been previously shown that those with a relatively higher WM are more susceptible to cognitive deficits brought on by anxiety/worry (see Beilock & Carr, 2005), the results of Experiment 1 and 3 show that in both lab and real-world settings, this is altered by attentional control. When those higher in WM also possess relatively higher levels of attentional control, this attentional control presumably decreases the amount of worry-related information allowed into working memory. In turn, cognitive resources are not depleted and performance does not suffer. However, when worry was relatively low in our sample, there was no significantly relationship of either WM or attentional control with GPA scores.

One interesting pattern from Experiment 3 was seen when those low in both WM and attentional control were high in worry. These individuals' predicted GPA scores were just slightly below the predicted GPA scores of those high in both WM and attentional control. As we discussed in Experiment 1, it may be the case that anxiety-related worries are actually acting as a sort of motivator for these individuals with the lowest level of executive resources, and this demands further investigation.

Overall, our ERN data mirrored a host of previous research. We found that increased ERN signaling significantly related to higher average WM scores (Miller et al., 2012; Coleman et al., 2017), increased levels of our attentional control measure (i.e. incongruent flanker accuracy; Larson & Clayson, 2011) and it marginally related to higher GPA scores (Fisher et al., 2009; Hirsh & Inzlicht, 2010). However, ERN amplitudes did not correlate to PSWQ (worry) scores within our data set. It is of mention that worry scores within Experiment 3 ($M = 54.24$) were markedly higher than in Experiment 2 ($M = 45.02$). This may have played a part in our inability to replicate the worry-ERN relationship.

A two-way interaction between ERN and WM did significantly predict GPA scores. For those with higher levels of WM, increases in ERN predicted higher GPA scores. For those low in WM, however, changes in ERN did not relate to any changes in GPA. Our interpretation is that as the mechanism represented by ERN monitored and registered inconsistencies in information, those with a higher WM were able to update and maintain this information while adapting their behavior to a relatively greater extent throughout the semester. In turn, they exhibited a higher GPA.

ERN amplitudes also interacted with attentional control to predict GPA scores. For those higher in attentional control, changes in ERN did not predict any changes in GPA. Conversely, for those low in attentional control, increases in ERN did predict increases in GPA. Those scoring relatively lower on our behavioral measure of attentional control have an increased difficulty selecting goal relevant information. Therefore, as ERN amplitudes increase and reflect a relatively greater response to inconsistencies in information, those with relatively low attentional control are better able to select for relevant information. In response, they exhibit a higher GPA. Those with a relatively higher attentional control presumably have less difficulty selecting for relevant information, so changes in ERN makes little difference in their ability to select relevant information and ultimate GPA scores.

Although ERN interacted with both of our measures of executive function (i.e. WM and attentional control) to predict GPA, ERN interacted with either measure independently and not in the three-way interaction that we expected. As ERN increased, those lower in attentional control were more able to select for relevant information and those higher in WM were able to update and maintain information in WM. Both resulted in a change in behavior that led to increased GPA scores, but why did WM and attentional control not interact to increase GPA scores? The assumption was that for those both lower in attentional control and higher in WM, they would be able to use discrepancies registered to select for goal relevant information, maintain this information in WM and use it to adapt future behavior to result in the relatively highest GPA scores. However, this may not be the case. One explanation may be that for those with lower attentional control, the benefit of higher ERN signaling isn't coming through the later adjustment of information in WM, but rather through a more direct or "on-line" effect during the active performance of tasks themselves. This may explain why our two measures of executive function are independently interacting with ERN to predict cognitive performance. Further research is needed to know if this is, in fact, the case.

Despite ERN amplitudes interacting with both of our measures of executive function to predict GPA scores, ERN never interacted with worry to account for GPA scores. The four-way interaction of ERN, worry, WM and attentional control initially included in the MLR model (see Table 7) was the first coefficient removed from the MLR model due to it accounting for no significant variance in GPA scores. Recall the CEMH's claim that an increased ERN represents compensatory processing as a response to worry-induced depletions of cognitive resources. With this hypothesis, we would expect to see that for the group most susceptible to depletions of cognitive resources by worry (i.e. high worry, high WM, low attentional control), increases of ERN amplitudes would relate to increases in GPA scores. However, we don't find that within this data set. Furthermore, no coefficient involving an interaction of worry and ERN reached significance throughout the reduction of the MLR.

It is important to note that this doesn't necessarily discredit the claims of the CEMH. To begin with, this study failed to replicate the oft-cited relationship between ERN amplitudes and reported levels of worry (Moser et al., 2013). Thus, the investigation into how worry and ERN intersect to relate to cognitive performance is made difficult. Furthermore, if the CEMH is accurate in stating that the ERN is a compensatory response to worry, it may be necessary to measure adjustments in ERN signaling based upon the presence of worry in order to substantiate a claim. Although previous research has attempted to test modulations of ERN based on environmental changes (see Larson et al., 2013; Moser et al., 2005), neither of these studies focused specifically on the dimension of anxiety that depletes resources integral to cognitive performance: worry.

GENERAL DISCUSSION

The current studies explored the connection of worry to cognitive performance by additionally measuring levels of executive function (working memory (WM) and attentional control), scalp-recorded measures of error monitoring (ERN). Previous research has repeatedly found that WM alters the impact of worry on cognitive performance (e.g. Beilock & Carr, 2005), but this research never accounted for additional measures of executive function that may vary within an individual. We furthermore tested claims that error monitoring compensated for worry impact on cognitive performance.

In Experiment 1, we measured the cognitive performance of individuals before and after placing them within a high-pressure environment known to induce the negative thoughts and ruminations (i.e. worry) that deplete cognitive resources. By looking at individuals' trait levels of attentional control and working memory (WM), we replicated research showing that those with the higher WM see the largest cognitive deficits due to pressure, and furthered this finding by showing that high levels of attentional control actually prevent these deficits. In Experiment 2, we tested a hypothesis (the CEMH) claiming that cognitive depletions caused by worry result in increased levels of a scalp-recorded neurophysiological signal measuring ACC-generated error monitoring (ERN). We provided support for this hypothesis by showing that the relationship of worry to the ERN was altered based upon levels of WM and attentional control. In Experiment 3, our goal was to replicate Experiment 1 in a real-world setting by predicting future cognitive performance as indexed by GPA using WM, attentional control, worry and ERN. By including ERN as a predictor in Experiment 3, we were able to further test if ERN signaling compensated for worry-induced depletions of cognitive resources, or if the ERN related to cognitive performance independently of worry. Although we did replicate Experiment 1, we found that ERN related to GPA scores independently of worry.

It is important to note the discrepancies in findings between Experiment 2 and Experiment 3. The results of Experiment 2 supported the CEMH hypothesis, showing that ERN signaling increased as a response to cognitive depletions caused by worry, but this failed to replicate in accounting for cognitive performance within Experiment 3. Furthermore, the frequently cited relationship of worry and ERN signaling was found within Experiment 2 but not Experiment 3. Differences were also seen in ERN's relationship to other variables between the two experiments; Experiment 3 replicated previous publications showing a relationship of ERN with both WM and attentional control, while Experiment 2 did not. We pooled our data between samples from Experiments 2 and 3 to see which relationships – if any – were retained. We found that within this pooled sample, ERN did not relate to worry (r=.10, p=.22) or WM (r=.05, p=.57), but it did retain a relationship to Experiment 3's measure of attentional control (Incongruent Flanker Accuracy; r=-.20, p<.03). This inconsistency and overall lack of replicating previous findings of the ERN's relation to other variables likely contributed to our waffling support for the CEMH. And although other research findings of ours (i.e. Experiment 1) were found to replicate across our research studies (i.e. Experiment 3), this discrepancy in support for the CEMH leaves the door open for a number of questions. Do particular research conditions routinely elicit a relationship between the ERN and worry? Would ERN signaling be more likely to compensate for worry-induced cognitive deficits if we measured ERN as a response to worry, rather than a static trait-measure?

Theoretical Implications

At the heart of any research measuring cognitive performance lies the question: how do findings last when tested within a real-world setting? The initial finding that those highest in WM are most susceptible to anxiety-induced cognitive deficits (i.e. Beilock & Carr, 2005) has been replicated in a real-world context specifically within younger populations (Ramirez et al., 2013; Vukovic et al., 2013). By isolating the math-specific dimension of anxiety, these studies found that increased levels of math-specific anxiety related to decreases in math achievement (Ramirez et al, 2013) and math learning over a semeseter (Vukovic et al., 2013) specifically for individuals high in WM. The present research expanded Beilock & Carr's (2005) initial finding by showing that within a laboratory setting, those higher in WM can prevent the anxiety-related depletions of cognitive resources when levels of attentional control are relatively higher. This was then replicated within a real-world setting by showing that individuals higher in WM and lower in attentional control showed significant decreases in GPA scores at the end of a semester. Our current research suggests that findings by Ramirez et al. (2013) and Vukovic et al. (2013) would be altered with the inclusion of a measure of students' attentional control. It is likely the case that within their sample, both academic learning and achievement would suffer for those experiencing worry and higher in WM, but this may be lessened or prevented when these individuals possess relatively higher levels of attentional control.

Given that these cognitive deficits are repeatedly found to exist within real-world settings, the next reasonable step is to test what strategies we may prevent anxiety and worry from depleting cognitive resources – especially for those high in WM. One strategy exists within expressive writing, a clinical task involving individuals writing about negative stressors they are about to face. Based on the fact that this expressive writing does decrease negative thoughts experienced by depressed and anxious population (Graf, Gaudino & Geller, 2008), a recent study assigned expressive writing to half of participants before they solved WM-demanded math problems (Park, Ramirez & Beilock, 2014). Those higher in math anxiety exhibited lower math performance, but only when they did not write expressively about their worries. Those high in WM who wrote expressively presumably decreased their negative anxieties and worries so that they did not deplete WM resources, and in turn, their math performance did not suffer. This same expressive writing effect has been witnessed within a classroom setting (see Ramirez & Beilock, 2011), as researchers showed that expressive writing prior to a test increased students' exam scores. This was particularly true for students reporting high levels of test anxiety.

For preventing cognitive deficits, the current research does suggest a strategy alternate to decreasing levels of worry: increasing attentional control. A number of studies have discovered intervention strategies to alter measures of attentional control. For instance, a 2008 study by Berman, Jonides and Kaplan discovered that exposure to nature increased specifically executive measures of attention such as the executive portion of and Attention Network Task (ANT) and a backward span task. However, one of the most promising studies comes from DeCaro et al. (2010). Similar to previous studies (i.e. Beilock & Carr, 2005), this study induced pressure within participants in order to analyze cognitive deficits caused by anxiety and worry. While individuals who reported higher levels of worry did show poorer WM-based cognitive performance, participants who were led to re-orient their attention to specific task-related steps by speaking through them aloud did not show a decrease in cognitive performance. The results from Experiment 1 and 3 suggest that such an intervention may actively decrease cognitive deficits caused by worry in everyday situations, although further research is required.

We also found a that increased ERN signaling was predictive of higher cognitive performance independent of reported levels of worry. Although this is not a new finding (see Fisher et al., 2009; Hirsh & Inzliht, 2010), it is a finding that requires future research. The Compensatory Error Monitoring Hypothesis (CEMH) supported within Experiment 2 would expect the cognitive benefit related to the ERN in Experiment 3 to only exist when levels of worry are high. However, in our data we did not find that this was the case. Given that the CEMH states that the ERN is a compensatory response to worry's depletion of executive resources, it has been hypothesized that interventions such as the aforementioned expressive writing would actually attenuate ERN signaling, as the effect of expressive writing is largely in decreasing worry's negative thoughts and ruminations. At this point, the research lacks enough clarity to be able to make general claims about if intervention strategies should be concerned with increasing or decreasing levels of ERN signaling, outside of understanding that overall heightened signaling does relate to higher cognitive performance.

Limitations

Throughout our three experiments, the measures of attentional control taken from our flanker tasks did relate to expected measures of WM, cognitive performance and ERN. Flanker measures have been shown to mark executive functioning such as attentional control (see Shipstead et al., 2014) and thus provided us with reason to believe that each measure would be appropriate in indexing each participants' level of attentional control. However, similar to how we measured WM using composite score across multiple WM tasks, it may be prudent to index attentional control in the future using a similar approach. Furthermore, using a task such as the

Attention Network Task (ANT; Fan, McCandliss, Sommer, Raz & Posner, 2002) would allow us to test if our assumed aspect of attentional control (i.e. executive) is independently responsible for our findings, or if perhaps our results also relate to differences in a different domain of attention (i.e. alerting & orienting).

One issue within Experiment 3 was that of sample size. Post-hoc power analyses revealed that Experiment 2 was suitable to find effects within our study ($1\text{-}\beta = .95$), and Experiment 1 was a just a bit under-powered given the interaction we predicted ($1\text{-}\beta = .63$). Within Experiment 3, our sample size was more than adequate for our MLR predicting GPA using an interaction of WM, attentional control and worry ($1\text{-}\beta = .93$). However, if the effect size of Experiment 3's hypothesized interaction of worry, WM, attentional control and ERN predicting GPA is less than our assumed medium-to-large effect (~.25), then our sample in experiment 3 is incredibly under-powered. For example, at an assumed effects size of (.10), our power in Experiment 3 rests at ($1\text{-}\beta = .30$).

Future Studies

There is little debate whether ACC-generated ERP signals of monitoring relate to levels of anxiety and particularly worry (see Moran et al., 2012; Moser et al., 2013; Weinberg et al., 2010). However, the connection of this ERN signaling to levels of worry is not yet clear. We previously reviewed evidence to support the CEMHs claim that the ERN is a compensatory response to the depletion of executive resources, and this depletion of resources may occur through worry. However, no study has tested to see if there are changes in ERN amplitudes in response to experiences of worry. Previous studies have attempted to induce anxiety in order to analyze subsequent changes in ERN signaling, but these studies have focused on the anxious arousal dimension of anxiety by using either fear inductions (Moser et al., 2005) or mood changes via musical stimulation (Larson et al., 2013). Our results suggest that if the ERN increases based on the demand worry places on cognitive resources, future research should use the same paradigm we use within Experiment 1 to induce anxiety and analyze changes in ERN. This paradigm has been repeatedly shown to increase levels of anxiety related to the negative thoughts and ruminations (i.e. worry) that deplete cognitive resources (Beilock & Carr, 2005; Beilock & DeCaro, 2007; DeCaro et al., 2010). One research study has analyzed changes in ERN while increasing the load placed on participants' verbal WM (Moran & Moser, 2012), showing that ERN amplitudes increased as verbal WM increased. However, this study manipulated the depletion of cognitive resources directly, rather than manipulating worry.

A large unexplored area of the connection of the ERN to worry lies in how ERN is catalogued within research. As with most studies – and our Experiments 2 and 3 – the ERN is typically measured as a static, trait-variable. Participants' ERNs are recorded during a single laboratory session, and analyses then make inferences about the ERN's connection to other variables. However, if it is the case that the ERN compensates for worry-induced depletions of cognitive resources, then when analyzing the relation of worry, performance and the ERN, it may be more important to define participants' ERN amplitudes in terms of their relative response to worry. It may very well be the case that individuals displaying relative increases in ERN as a response to worry would be more likely to prevent worry-induced cognitive performance deficits compared to those who exhibit little change in ERN in response to worry. This is an important empirical question, and one that could help illuminate the full path that worry takes to negatively impact cognitive performance.

Conclusions

The experiments described here explored the effects of anxiety/worry on cognitive performance, while accounting for individual differences in executive functioning and error monitoring (ERN). We replicated and expanded on previous research accounting for cognitive performance in both lab-based and ecologically valid settings. Although we found inconsistent support for the claims of the CEMH, this is useful for informing future iterations of studies that aim to analyze the relationship of worry, ERN and cognitive performance. These findings not only present new questions into the nature of how ACC-generated monitoring impacts cognitive performance, but they also present new opportunities to develop interventions aimed at preventing the worry-induced cognitive deficits for those most susceptible in their academic, work and daily lives.

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