ERROR RELATED NEURAL PROCESSES IN REAL-WORLD TASKS

TOWARDS AN EXAMINATION OF ERROR RELATED NEURAL PROCESSES IN REAL-WORLD TASKS: ERP EVIDENCE OF UNCERTAINTY, EXPECTANCY, DIFFICULTY AND ANXIETY

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ABSTRACT

In four experiments I addressed factors that affect human performance monitoring as indicated by neural correlates observed in response-locked event related potentials. Specifically, I examined modulations of the error related negativity (ERN), the correct response negativity (CRN), and the error positivity (Pe) components across a variety of conditions. These components, all thought to be generated in the anterior cingulate cortex, represent activation of the performance monitoring system. Experiments 1 and 2 used stimulus congruency and visual noise to manipulate response and stimulus uncertainty in an extension of previous research. These manipulations, together with a between experiment task manipulation, examined the role of cognitive/attentional load in performance monitoring. Replication of previous findings and a task specific modulation of ERN amplitudes provided support for a role of cognitive load in performance monitoring. Further, these two experiments used a novel task and novel stimuli to replicate previous research and extend our knowledge of how uncertainty affects performance monitoring. In stark comparison to all previous research in this area, Experiments 3 and 4 both employed complex and somewhat ecologically valid tasks. Standard ERN/Pe results in Experiment 3 (touch typing task) revealed that it is possible to examine the ERN in more complex, real world-like tasks. Further, an expectancy manipulation elicited marginal differences in the response-locked Pe but resulted in large N1 and P3 differences suggesting a possible role of attention in early expectation driven performance monitoring adjustments. Experiment 4 examined the role of task difficulty, anxiety level and exposure (i.e., time on task) for effects on ERN and Pe amplitudes. By comparing how math anxious people perform in a math environment, this study represents the first to pit a specific anxiety against a specific anxiety provoking situation. This complex paradigm again replicated general ERN findings providing further support for the validity of complex task usage. Findings surrounding the difficulty manipulation and anxiety measures provide new insight into the role of difficulty in performance monitoring and support the importance of considering personality characteristics in self-regulation.

Preface

The present thesis represents a project of work I have undertaken over the last five years. Over this time I have investigated questions related to the neural correlates of performance monitoring in the laboratory of Dr. J. M. Shedden. This work has culminated in the preparation of three manuscripts for publication reported here, and represents four experiments I conducted for this thesis. All the research was part of a collaborative effort that included contributions from Dr. Shedden, Dr. Watter, undergraduates (Jessica Cohen) and myself. For the experiments in the manuscripts that follow I designed the experiments and generated the hypotheses. It was my responsibility to implement the experiments, collect and analyze data. The coauthors assisted in collecting and analyzing data. Preparation of the manuscripts was a collaborative effort. There is no doubt as to my position in the authorship of these manuscripts.

Acknowledgements

Such a large undertaking at this point of my life would not have been possible without the support of a great many people. First and foremost I have to thank my family. Natalie, Alex and now Daniel, thank you for putting up with my need to do this and thank you for always taking me back when I came home. Without you this really would not have been worth it. To my parents, Tina and Dan, thank you for making me the person that I am today and although a choice few may disagree, I think you did a great job. I'm forever in your debt.

I really don't know what to say about my wonderful in every way supervisor, Dr. Judy Shedden. She put up with my every problem, my comings and goings, my lack of correspondence, my lab messiness, all with some reservation I'm sure but without obvious hesitation nevertheless. Thank you for being in my corner and seeing me through this. Nothing compares.

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If there is a heaven, I hope special attention is paid to my committee members. Dr. David Shore, Dr. Bruce Milliken, Dr. Scott Watter and of course Dr. Judy Shedden. You gave me all the rope I needed but didn't let me hang myself with it. Thank you. I value your feedback and advice nearly as much as your friendship.

I would also like to note here that this department is one of a kind. I've been exposed to many university departments and never have I seen so many people cooperate and collaborate on a daily basis. It is to the point now that I feel spoiled and will likely frown on all future departments, they will not live up to my model of how a department should be. Thank you for that experience.

Wendy Selbie, Sally Presutti and Nancy Riddell are the most important cogs in the McMaster psychology wheel. Perhaps they are why the department is as collegial as it is because Wendy, Sally and Nancy have said that is the way it is going to be. Wendy, keep that jacket on. Sally, maybe someday you'll get a real fireman for your birthday. Nancy, I really can't say enough. Thank you. I'll miss you….and your war mongering child! (ha)

Finally, some specific thanks before signing off:

To my classmates I say, “I hate Monty hall.”

To Dr. Aimee Skye I say, “I’ll never meet another like you. Stay the same you fruitboat hating darling.”

To Jim Greenlee I say, “Thank you.” and most importantly “Soto.”

To Stewart, Greenlee, Ferguson, Mardel, Ashton et al., “I miss you.”

To my sister Beth I say, “I love you like heavy blankets on a chilly day.”

To my parents, Tina and Dan, I say, “Hoo-ahhh.” and “You are my heroes. My very own Wonder Woman and Superman, without which my world, *the* world for that matter, would be in jeopardy.”

To Natalie…Babe there is so much to say but put as simply as possible, “Your understanding and patience know no bounds although I think I stretched them to the limit. Thank you for being stretchy. You are my old shoe, my nirvana, my love and my life, my wonderland.”

Finally, to Sheila Ashton I yell very obnoxiously, “Philippines!”

Table of Contents

Experiment 1

Experiment 2

Appendices

List of Tables

List of Figures

Chapter 1

Introduction: *Towards an Examination of Error Related Neural Processes in Real World Tasks*

Cognitive scientists recognize that monitoring performance is a vital part of our learning process. If mistakes are not detected, the need for adaptive or compensatory behaviour is not recognized and improvement is not possible. I could not write/type these words correctly without simultaneously monitoring my actions. A skilled secretary or stenographer is able to perform some of these same motor functions at a skill level that exceeds the ability of most. A large portion of this skill level owes to practice, the recognition of errors in performance, and taking the necessary steps to try and avoid the same mistakes in the future.

There has been a great deal of research devoted to how we learn a skill and how we react to the mistakes made. The processing of errors has been a focus of learning theorists, with the idea that understanding this performance monitoring component should help to improve our understanding of the learning process. Until recently, performance monitoring investigations have been behavioural in nature, but advances in electroencephalograph (EEG) and functional magnetic resonance imaging (fMRI) have opened new avenues of research into performance monitoring. This coupling of behavioural data with functional brain data now constitutes a powerful method aimed at additional advances in understanding the human performance monitoring system. This thesis mainly examines the performance monitoring system in its role of a detector of response competition, errors and generally worse than expected events although this is not the only function of the system. Performance monitoring is importantly further defined to include the modulation of future behavior through the signaling that behavioural adjustments are necessary. The means that were employed to measure this system included the measuring of response times and accuracy rates. To complement the behavioural approach, much like the research discussed in this opening chapter and in the experimental chapters that follow, I investigated performance monitoring using electroencephalography, specifically event related potentials (ERP).

The examination of faulty information processing may provide insight into general error processing mechanisms and allow us to address a range of questions. How does the brain respond to errors of judgment, such as driving while intoxicated, or errors of commission, such as pressing the wrong key on the keyboard? How are deficits in the error processing system involved in clinical pathologies such as attention deficit hyperactivity disorder, depression, and anxiety? In this chapter I provide general information regarding neural correlates of error processing, current theories about the functional significance of these neural correlates, background on the accepted site of the neural correlate generators, and information about how personal and environmental factors affect these correlates.

In subsequent chapters I report investigations of performance monitoring as measured by event related potential (ERP) components, specifically the error related negativity (ERN) and the error positivity (Pe). The main theme of this thesis involves exploring the effects that changes in task and situation have on these electrophysiological correlates of error processing. I explored the neural responses to different kinds of errors under conditions that contrasted congruency and certainty in a global/local task, expectancy in a typing task, and the interaction of difficulty with state math anxiety levels in an arithmetic task. In the two global/local experiments, both using the same hierarchical visual stimuli, one task required selecting local information and ignoring global and the other task required comparing global and local information. The typing experiment was designed to manipulate expectancies to produce different kinds of errors in a typing task performed by touch typists. In the arithmetic task I contrasted math anxious individuals with control participants in a task that was directly relevant to their specific anxiety. Underlying all of these studies was a push towards examining performance monitoring in tasks that map easily to real world situations. I think it is important to remember that as cognitive scientists we often attempt to reduce the complexity of processes that we measure by controlling as much as possible in our laboratory experiments. Yet, some of the more interesting properties of performance monitoring may only be observable in complex task environments typical of real world situations. In this thesis I was interested in examining ERP correlates of performance monitoring using tasks that approach the complexity of tasks that people perform every day.

Basic Neurophysiology of Performance Monitoring

In the early 1990s two groups (Gehring, Coles, Meyer, & Donchin, 1990; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990) independently discovered a negative ERP component specific to error trials. Gehring referred to the component as the error related negativity (ERN) and Falkenstein called it the error negativity (NE). I will use the term error related negativity in this manuscript. In recent years there has been a proliferation of work using the ERN as an index of performance monitoring

The Error Related Negativity

The error related negativity is a response-locked ERP component that has been consistently shown to be present on error trials while largely absent on correct trials (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer & Donchin, 1993; Dehaene, Posner, & Tucker, 1994; Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996). This component is frontocentrally maximal, usually topographically observed at electrode sites Cz or FCz (10/20 nomenclature; Jasper, 1958), and is hypothesized to be generated in the anterior cingulate cortex (ACC). The ACC literature will be reviewed in a later section.

The ERN is observed consistently across a variety of stimulus and task modalities and the amplitude and latency has been shown to vary somewhat on the basis of a number of variables. Typically, the ERN deflection begins its descent just prior to the response and peaks between 0 ms and 100 ms post-response (see Figure 1: note that the intersection of axes at time zero represents the overt behavioural response). Although measurement of the ERN requires time-locking to the overt response it has been suggested that the generation of the ERN is highly influenced by processes leading to the response (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000) allowing for some variation in both the onset of the ERN and in its peak latency. Thus, the latency of the

ERN may differ between tasks of different complexity. As you will see in the experimental chapters, the onset and peak of the ERN elicited in my experiments is relatively early, although the overall morphology is the same as observed in many prior studies. I focus primarily on amplitude differences rather than latency differences between critical conditions in the experiments reported in this thesis.

Based on results from speeded response tasks, one early suggestion was that the ERN reflects a motor aspect of error correction. However, Falkenstein et al. (1996) compared ERPs for both corrected and uncorrected errors and found no significant ERN differences between the two. Furthermore, in a go/no-go task (i.e., participants respond to stimulus A (Go trial) but withhold that response to stimulus B (no-Go trial)) where one type of error is a go on a no-go trial, an ERN is generated even when there is no possible way to correct the response. That is, there is no alternative motor choice to make. These results clearly demonstrate that the ERN is not a simple indication of an error *correction* process.

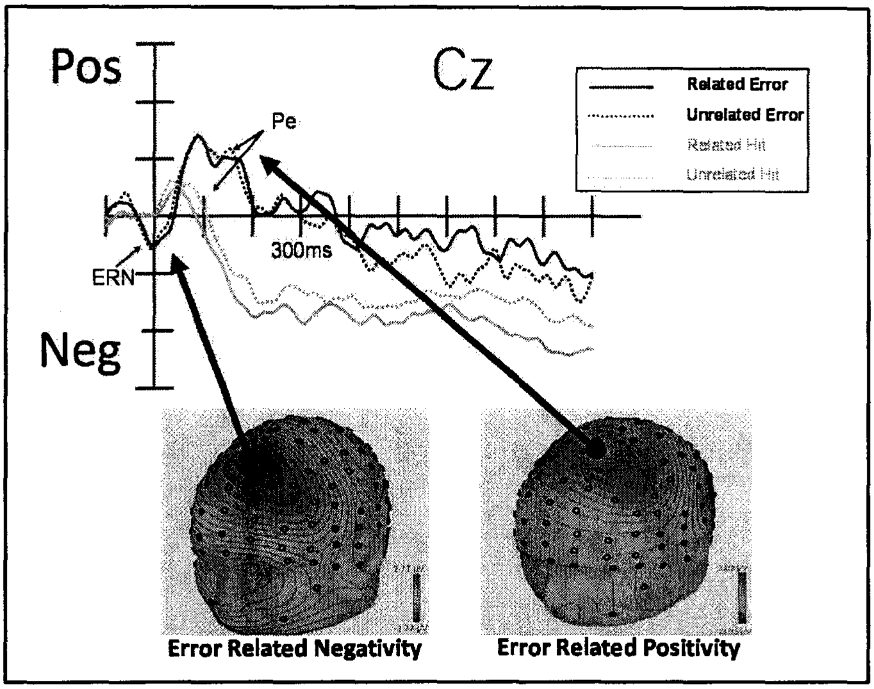

Figure 1: The waveform in the upper half depicts the typical morphology of a response-locked waveform. Taken from chapter 3, the black lines represent error responses and grey lines represent correct responses. The displays on the bottom represent scalp topographies of the ERN (left) and PE (right).

There are several factors that modulate ERN amplitude. One important factor is that time pressure produces smaller ERN amplitudes as time pressure increases (Gehring et al., 1993; Falkenstein et al., 1994). For example, error responses produced significantly smaller ERNs in a task deadlined to 350 ms compared to 550 ms (Falkenstein et al., 1994). Furthermore, even in a task that was not deadlined, stressing speed over accuracy produced smaller ERNs (Gehring et al., 1993). Although it was possible that the shortened RTs were responsible for the decrease in ERN amplitude, when comparing fast and slow errors within either of the two conditions, there were no ERN differences observed. Therefore, the difference was due to the time pressure itself and not the speed of responding.

Another factor that affects the amplitude of the ERN is the perceived salience of the error. Consistent findings show that the larger the degree of 'mismatch' between the correct response and committed error response, the larger the ERN amplitude. Furthermore, the larger the mismatch, the earlier the error signal may be elicited, which results in an earlier onset of the ERN. For example, Scheffers et al. (1996) showed that a false alarm on a go/no-go task produced earlier and larger ERNs compared to selecting an incorrect response on a two alternative forced choice task. The suggestion was that the false alarm was a more salient error. Additional support comes from Bernstein et al. (1995); in a four alternative forced choice task participants were required to respond with one of two fingers on either their left or right hand. ERNs for finger errors were significantly smaller than ERNs for hand errors. The mismatch for hand errors may be more salient than the mismatch for finger errors. Across the upcoming experimental chapters the role of error saliency will be addressed.

The robustness of the error related negativity has been shown across a variety of tasks and stimulus-response mappings, including visual and auditory stimuli paired with manual (Gehring et al., 1993), pedal (Gehring & Fenscik, 2001), verbal (Masaki et al., 2001) or ocular (Nieuwenhuis et al., 2001) behavioural responses. The ERN is consistently observed in these experiments on error trials. An extensive review of the literature, compiled in Appendix A, shows that this area of research has used many methods to answer a large variety of interesting questions. These experiments are designed to *observe mechanisms* that are important in solving real world tasks, however, I am interested in observing the neural correlates of performance monitoring while participants *perform tasks* more similar to their everyday activities. Experiments with better ecological validity may provide additional insight into the performance monitoring process. This thesis observes ERNs in tasks that require touch typing (Chapter 3) and performing mental arithmetic (Chapter 4) which are more like everyday tasks that involve performance monitoring and control to avoid errors.

Theories of the Functional Significance of the ERN

Three theoretical frameworks have been forwarded to explain the functional significance of the error related negativity. I will first talk about the Error Detection account (a.k.a. Mismatch Theory) of ERN generation. I will then discuss the two alternative theories, the Conflict Monitoring theory and the Reinforcement Learning theory, that have been forwarded following more recent findings.

Error Detection Account

The first prominent theoretical account of the ERN was the Error Detection theory, which posits that the ERN reflects the simple detection of an error. This detection is the result of a comparison between the actual response and the intended response (Falkenstein et al, 1990, 2000; Coles et al., 2001; Gehring et al., 1993; Scheffers et al., 1996., Sheffers & Coles, 2000). This theory claims that the ERN reflects processing at or subsequent to the time of the response. In some cases the errors may be produced because an incorrect response was selected before stimulus processing was completed. In other cases errors may be produced at a later stage of response execution. These are very different kinds of errors but both result in an ERN, which this theory interprets to be an error detection signal.

A key piece of support for this theoretical account was reported by Scheffers, Coles, Bernstein, Gehring, and Donchin (1996). Scheffers et al. evaluated an alternative hypothesis for the functional significance of the ERN, that in addition to error detection the ERN is also related to error correction or compensation. In particular, they asked whether the error detection signal would be observed on a go/no-go task even when there was no possibility of correcting the error. The presence of an ERN would support the idea that the ERN reflects error detection independent from error correction or compensation. Clear ERNs were observed when 'errors of action' were made on no-go trials. Given that no compensatory adjustments were possible on these trials, the authors concluded that the ERN was indeed indicative of an error detection process.

Conflict Monitoring Theory

The Conflict Monitoring theory was offered as an alternative to the Error Detection theory in an attempt to account for additional research findings. Proposed by Carter et al. (1998) and elaborated further by Botvinick et al. (2001), this general theory of action monitoring was thought to be able to explain error related signals by way of cognitive, response driven conflict. This conflict is said to occur when an incorrect dominant response is in competition with the desired or intended correct response. The standard Stroop effect provides a good example of response conflict. In a colour Stroop task participants are presented with words whose font colors match or mismatch with the meaning of the word, and they are asked to respond to the font colour while ignoring the word. When presented with the word RED in blue font, the correct answer is blue but the dominant response tendency is red. An ERN arises when the dominant response wins out and the participant answers red. However, the ERN is not the detection of the error in this case but rather the presence of increased conflict between the two competing responses. In the case of the Stroop task, therefore, incongruent trials (the word RED in blue) should be more likely to produce an ERN than congruent trials (the word BLUE in blue).

A unique property of the conflict monitoring theory is that even if the response is correct, a high level of response conflict can still produce an ERN-like response. This theory further suggests that the response-locked ERN is in fact equivalent to a stimulus-locked N2, which is also typically maximal at FCz or Cz. The anterior N2 has been consistently shown to be indicative of the presence of response conflict. The ERN is simply indicative of conflict that was not completely dealt with prior to responding. In addition, neuroimaging studies have shown that neural activity associated with ERN production occurs both on correct trials high in response conflict and on error trials (Bench et al., 1993; Carter et al. 1998; Botvinick et al., 1999; Macdonald, Cohen, Stenger, & Carter, 2000).

Reinforcement Learning Hypothesis

Recognizing an action as an error is a negatively charged event that provides us with feedback signaling that an adjustment in behaviour is necessary. Holroyd and Coles (2002) put ERN and feedback ERN (fERN) findings into the context of a Reinforcement Learning hypothesis of the ERN. The fERN is a negative going ERP component time-locked to the onset of a feedback signal and is indicative of a reaction to that feedback (Miltner et al., 1997). In a time estimation task an fERN was observed when participants were given feedback regarding their performance approximately half a second after responding. This finding was at odds with both the Conflict Monitoring and Error Detection theories as too much time had passed for this negativity to be a result of conflict processing or simple error detection. Instead the authors explained these and standard ERN findings in a reinforcement learning framework.

It has been suggested that error processing is a result of midbrain dopaminergic activity that arises due to the non-occurrence of an expected event. That is, a dopamine system in the medial frontal cortex (MFC) that responds to reward predicting stimuli (i.e., correct responses) shows a decrease in activity when an event other than the expected rewarding event occurs (Schultz, 2002). Converging evidence from a number of disciplines suggests that error related activity in the MFC is a result of a disinhibition of the dopamine neuronal activity. Using single cell recordings, Ito et al. (2003) in monkeys and Williams et al. (2004) in humans showed this same disinhibition in the absence of or decrease in an expected reward. Using fMRI Bush et al. (2002) also replicated these same MFC findings in a performance monitoring task. These results support the reinforcement learning hypothesis and the idea that the ERN may reflect a response to the absence of expected reward.

Numerous studies examining the fERN have helped establish the reinforcement learning theory as a contender to explain the functional significance of the ERN. Although the fERN is time-locked to the feedback rather than the response, there are notable similarities of the topography and waveform morphology between the fERN and the ERN. Moreover the fERN is sensitive to the intrinsic value of the feedback with error feedback producing a larger fERN than correct feedback (Holroyd & Coles, 2002). Furthermore, this difference was dependent on expectation; negative feedback produced larger fERNs when positive feedback was expected than when negative feedback was expected. Thus, expectations for reinforcement play a role in performance monitoring. Yet even in the absence of a required response, fERNs have been observed in passive viewing tasks where participants witness non-favorable outcome (Yeung et al, 2005). As the reinforcement learning hypothesis is concerned with learning to perform a task oneself, these observer effects could reflect processes involved in learning through observation.

The Anterior Cingulate Cortex

Although the functional significance of the ERN is still in question, the location of its neural generator seems less uncertain. Several studies suggest that a major contributor to the neural generation of the ERN is the anterior cingulate cortex (ACC). The ACC is the frontal section of the cingulate cortex which is located in the medial wall of the frontal lobes. A simple description is that the cingulate gyrus is a piece of cortex that sits atop the corpus collosum in the middle of the brain with the anterior (i.e., front) portion being the area of interest here. Attempting to define the ACC according to its functions is difficult as it has been implicated in many capacities. A number of brain imaging studies have noted the ACC functions in a cognitive capacity (Posner & Digirolamo, 1998) but emotional functions have also been assigned to the ACC (Bush et al., 2000).

The database of findings that implicate the ACC in higher order cognitive functions seem at odds with a number of lesion results that suggest little or no impairment in cognitive function even when massive damage to the ACC is apparent (Rylander, 1947; Teuber, 1964; Cohen et al., 1999). However, the same damage to the ACC has shown some stable effects with respect to emotion. Individuals with destroyed ACC function typically are described as unemotional and show apparent disregard for personally important, usually emotional events, events such as errors.

Reconciliation of these differences in proposed function has been attempted by imposing subdivisions within the structure of the ACC that are separately responsible for the cognitive and emotional functionality (Bush, Luu & Posner, 2000). Bush et al. (2000)

suggest that the ACC is part of a circuit that regulates both emotional and cognitive processing. The cognitive subdivision, the dorsal ACC (dACC), has substantial connections with parietal cortex, lateral prefrontal cortex and supplementary motor areas (Devinsky et al., 1995), all of which are components in a distributed attentional network. Within this network the dACC has been prescribed functions including conflict monitoring (Bush et al. (1998), response selection (Carter et al., 1999) and error detection (Holroyd & Coles, 2002).

The affective subdivision, located in the ventral ACC (vACC), has connections with the amygdala, nucleus accumbens, hypothalamus and orbitofrontal cortex (Bush et al., 2000). This vACC seems primarily involved with assessing the emotional information attached to stimuli and the regulation of the attached emotional responses.

A meta-analysis of 64 functional magnetic resonance neuroimaging studies showed remarkable support for the cognitive-affective division noted above (Bush et al., 2000). A clear demarcation in anatomy can be seen when neural activations are mapped onto the ACC. Tasks that involved high cognitive demands, such as response competition, divided attention, and working memory tasks, correlated with activation of the dACC and deactivation of the vACC. During tasks that included emotional processing in healthy and patient populations, and induced sadness in healthy individuals, the dACC was predominantly inactive while the vACC was activated (Bush et al., 2000).

Of more interest to the current investigations are the electrophysiological investigations of error processing that have implicated the ACC as part of a performance monitoring system. Although the spatial resolution of ERP studies is not as high as that of

PET or fMRI, source localizations have indicated a frontal midline generator of the ERN. From these studies it is fair to say a generator thought to be responsible for the ERN has consistently been found in the vicinity of the ACC (Dehaene et al., 1994).

It is useful to briefly examine how the function of the ACC fits with the three theories of ERN generation described previously. The error detection account of the ERN assumes that ACC activation reflects error processing. The dACC becomes active when a mismatch between intended and actual response is recognized. It is the recognition of such a mismatch that activates the ACC, which generates the ERN as measured at the scalp by EEG. Findings that show greater ACC activation on error trials when compared to correct trials support this finding (Dehaene et al., 1994). However, the presence of similar ACC activity on correct trials, as in the study by Carter et al. (1998), is not consistent with the error detection view. It has been suggested by proponents of the error detection theory that the ACC activity seen on correct trials is a result of accuracy uncertainty (i.e., participants thought they had made a mistake) and that therefore correct response negativity (CRN) is not inconsistent with the error detection theory.

The Conflict Monitoring theory (Carter et al., 1998) of the ERN suggests that it is not indicative of error detection but rather the monitoring of response conflict. In experiments utilizing an Eriksen flanker task, Carter and colleagues were able to show greater ACC activation as the level of stimulus incongruency increased. Although this finding supports the idea that the monitoring of response competition may be an ACC function, it does not speak directly to the role of the ACC in producing the ERN, as this was an fMRI study. In addition, several results appear to contradict the notion of a strong link between the ERN and response conflict. Ingestion of alcohol has been shown to dampen ERN amplitude in response to errors but does not appear to modulate the response of the ACC to response conflict (Holroyd & Yeung, 2003). Further, lesions of the ACC do not produce the profound cognitive deficits one would expect according to the Conflict Monitoring theory (Rushworth, Buckley, Behrens, Waltony & Bannerman, 2007). Together, these findings suggest that response conflict may not completely account for modulations of ACC activity.

The most recent account of ACC function is Reinforcement Learning theory. Although it is perhaps less specific than the others, ACC function as indicated by the ERN seems best explained by this theory. By less specific I mean that the reinforcement learning theory accepts that there may be different divisions of the ACC, cognitive and affective, and it posits that the ACC detects and monitors situations where an action is different from an expected standard. Whether this mismatch between action and expectation constitutes detection of an error or detection of response conflict is thought not to be important. A study by Frank, Woroch and Curran (2005) used a reinforcement learning framework and found modulation of ERN amplitudes as a function of different types of errors but no response conflict main effect. However, a significant interaction between response conflict and certain personality variables on ERN amplitude was observed showing that the ACC is sensitive to both errors and conflict and hence any theory would be remiss to prefer one over the other. Furthermore, these results point to the importance of recognizing individual differences (e.g., learning types, anxiety levels) that might affect ACC function.

In summary, a number of theories have been offered to explain anterior cingulate function. Yet no single theory appears able to explain ACC function, and as a result the functional significance of the ERN remains questionable. Although the debate is ongoing, there is reasonable consensus that the ERN is generated in the ACC and that it is indicative of error detection, response conflict, and/or error significance.

Individual Differences in ERN Generation

ERN investigations have shown error related brain activity to be sensitive to individual differences. This section reviews literature pertaining to depression, anxiety, substance abuse, and age revealing that individual differences can influence the amplitude of the ERN.

Depression is, in part, a function of a maladaptive monitoring of actions evidenced by a lack of behavioural adjustments in response to previously committed errors (Pizzagalli, Peccoralo, Davidson, & Cohen, 2006; Holmes & Pizzagalli, 2007). Added to this is a tendency in depressives to respond overly negatively to their mistakes and to feedback about their mistakes (Steffens, Wagner, Levy, Horn, & Krishnan, 2001). Together, these findings suggest that depression may be a result of or influenced by a malfunctioning performance monitoring system. The idea that depression has an influence on performance monitoring has received support from EEG research showing an increased ERN amplitude in both flanker (Chiu & Deldin, 2007) and Stroop (Holmes & Pizzagalli, 2008) tasks in depressed compared to control participants.

Individual differences in ERN components are also observed in clinically anxious populations and it has been suggested that anxiety disorders may be driven by a malfunctioning performance monitoring system (Pitman, 1987). Anxiety disorders such as obsessive compulsive disorder (OCD) and generalized anxiety disorder (GAD) have been shown to be comorbid with abnormal error processing as indicated by the error related negativity (Gehring, Himle, & Nisenson, 2000; Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006). In both cases the amplitude of the ERN was significantly larger in the patient sample compared to the control. Interestingly however, this increase in error related activity seems to be predominantly a function of trait anxiety as opposed to state anxiety. Moser et al. (2005) showed that the amplitude of the ERN in arachnophobic participants was not significantly larger in the presence of a phobia provoking stimulus, a tarantula. Further, ERN modulations were not observed in individuals who had undergone successful treatment for their generalized trait anxiety disorder (Hajcak et al., 2008). On the basis of these two findings it seems that permanent dispositions may be more important in influencing error processing than transient situational factors. With that said, the state anxiety provoking stimulus in the Moser et al. (2005) study (i.e., the presence of a spider in the experiment room) was not task-relevant and it seems probable that a higher level of state anxiety stimulation would be produced if the task itself was anxiety provoking. Chapter 4 will examine performance monitoring in individuals with a specific state anxiety in a task designed to influence that particular state anxiety.

Thus it seems that anxious and depressed individuals show abnormal error processing, and in particular show an increased sensitivity to errors and punishment. However, in the absence of studies of error processing for other psychological disorders it is possible that this enhanced ERN is a trademark of all psychosocial pathologies rather than being specific to anxiety and depression. If error related brain activity reacts in an opposite way for patients with 'opposite' symptoms, then a dissociation between ERN amplitude and general pathology would be indicated. One promising avenue of research still in its infancy that may eventually provide this dissociation involves the examination of substance abusers.

Although the research mentioned in regards to clinical anxiety and depression suggested that state variables have no effect on ERN amplitude, the same cannot be said for the consumption of alcohol. Ridderinkhof (2002) found that the ingestion of a moderate dose of alcohol led to a decrease in the detection of errors as indicated by ERN amplitude. A second study showed the same decrease in error related brain activity as a function of moderate and small doses of alcohol (Easdon, Izenberg, Armilio, Yu, & Alain, 2005) but both of these studies examined error processing in healthy volunteers. To date there is only one study that directly examines error processing in substance abusers and I am aware of no study that has examined *state-dependent* (i.e., tested while under a drugs influence) modulations of ERN properties in substance abusers. Franken, van Strien, Franzek, and van de Wetering (2007) utilized a flanker task to compare cocaine dependent participants with control participants and found a decreased ERN in the abuser population. They suggested that this result may be due to a compromised dopamine system, consistent with the reinforcement learning theory of ERN generation. It is possible though that this result is instead caused by a common correlate of substance abuse, impulsivity. Reduced ERNs have been found in individuals who score high on impulsiveness and in individuals who have unusually high error rates (Potts, George, Martin, & Barrett, 2006).

Other pathologies related to affective dysfunction and behavior monitoring problems have been linked to ACC activity and have been examined in performance monitoring studies examining the ERN (ADHD: Groen et al., 2008; anorexia nervosa: Pieters et al., 2007; schizophrenia: Bates et al., 2002). In all three of these populations a reduced ERN on error trials was observed compared to normal control groups owing to an impaired action/performance monitoring system in the patient populations. It appears then that the ERN is not simply enhanced in any psychopathology and instead is differentially affected by different classes of disorders. Further, the individual differences may be more of trait based than state/situation influenced.

These individual difference effects on the error related negativity get even more complicated when participant age is considered. Studies of developmental changes in ERN morphology have produced mixed results. Davies, Seglaowitz & Gavin (2004) found that an observable ERN was not elicited in preteen children (Davies, Segalowitz & Gavin, 2004a) but since then a number of studies have shown the presence of an ERN in children as young as 7 – 11 years of age (Wiersema, van der Meere, & Roeyers, 2007; Hajcak, Franklin, Foa, & Simons, 2008; Kim, Iwaki, Imashioya, Uno, & Fujita, 2007). Furthermore, Olvet and Hajcak (2008) report that they have preliminary data suggesting the presence of a measurable ERN in children as young as five.

Although contradictory results have emerged regarding the presence or absence of an ERN in young children, age-related ERN research commonly finds a relatively robust relationship between ERN amplitude and age with amplitude increasing as age increases. Studies that have examined children of various ages have shown that, although an ERN is observed in a younger population, the amplitudes of the component are significantly smaller than that of an adult. However, Wiersema et al. (2007) showed that children as young as 13 have error related activity similar to that of young adults. Furthermore, studies on older adults have consistently found a decrease in ERN amplitude compared to young adults, suggesting that the age related increase in ERN amplitude we see at young ages peaks at some point and eventually begins to decline at an advanced age. As of yet there are not enough data to accurately plot this non-linear trend but since age adds variability to error related activity, it is an important variable to consider and control for in any ERN investigation.

Error Positivity (Pe)

Although research into error processing has resulted in a substantial increase in our understanding of performance monitoring, the research has been largely focused on the ERN. The positive going wave that immediately follows the ERN on incorrect trials has been largely overlooked and is emerging as an important correlate of the action monitoring process. The Pe has a more posterior topography than the ERN and is typically observed most clearly at CPz or Pz compared to FCz or Cz as is the case for the ERN. Pe topography is similar to that of a P3. The Pe may be a P3-like component elicited by the behavioural response. A P3 is typically thought to signify a reaction to a salient stimulus or event and may be indicative of some sort of working memory updating or contextualizing process (Donchin & Coles, 1988).

It has been suggested that the Pe component is representative of performance monitoring processes occurring after error detection, perhaps error recognition or error salience (Falkenstein et al., 2000). Nieuwenhuis et al. (2001) supported this contention by finding a relationship between Pe and the subjective awareness of making a mistake. Specifically, when participants were unaware that they made a mistake the Pe was substantially reduced while no effects were observed in ERN morphology.

Falkenstein et al.(2000) also examined Pe amplitude as a function of error correction and found no significant Pe modulation. Furthermore, Bernstein et al. (1995) found no Pe modulation in their examination of finger versus hand errors whereas significant ERN changes were apparent. Inconsistent with these findings, a number of studies have suggested that Pe amplitude may be correlated with error associated affective variables. Hajcak, McDonald and Simons (2004) found significantly smaller Pe amplitudes on error trials in participants who reported a high level of general negative affect, while Murphy, Richard, Masaki and Segalowitz (2006) found a significantly smaller Pe in sleep deprived individuals compared to controls. This result was interpreted to imply that sleepiness reduced the motivation to adapt behaviour and, in turn, lowered motivation to perform well.

In a review of the literature, Falkenstein (2004) stated that there were several viable descriptions concerning the functional significance of the Pe. Conscious error recognition may be manifested in the Pe component. Findings reveal significantly smaller Pe amplitudes in response to errors on more difficult tasks possibly because detecting an error is more difficult (Nieuwenhuis et al., 2001). A second suggestion was that the Pe reflected an adaptation in response strategy following a detected error. With that said, in a number of studies Falkenstein found no correlation between Pe amplitude or latency and the degree of post-error slowing, which argues against the proposed link between Pe and strategy adaptation.

A third possible explanation is that the Pe is indicative of emotional error processing, the "Oh shit-response" as the ERN and Pe have anecdotally been labeled. The findings that the Pe is reduced in participants with high error rates (Nieuwenhuis et al., 2001) and that the Pe has been localized in the rostral ACC (Van Veen & Carter, 2002a, 2002b), which is linked to emotional processing, supports this interpretation. Further, unlike the ERN, which is found on partial errors, the Pe only differs from correct trials when a fully executed, incorrect response is elicited (Nieuwenhuis et al., 2001).

Manipulations and Questions of the Current Investigations

In line with the literature presented in the previous sections, I examine a number of different variables across a variety of tasks. The three empirical chapters to follow consist of four experiments designed to examine performance monitoring, specifically error monitoring processes as indicated by the ERN and Pe, in tasks that have substantial overlap with real world situations. The notion that cognitive experiments should be more ecologically valid is not a new one, and has recently been expressed by a number of authors (Kingstone et al., 2006; Kingstone et al., 2008; Smilek et al., 2007; Smilek et al., 2008). These researchers recognize that we live in a complex, cognitively demanding environment and suggest that the standard tasks used to test human cognition may actually distort our understanding because they measure processes that have little to do with the cognitive challenges we face in the real world. For example, they demonstrate that the methods typically used to investigate change blindness distorted the overall understanding of the phenomenon because these methods had little to do with cognitive challenges faced in real world activities (Smilek et al., 2007). They suggest that although it is important to keep experiments controlled and specific, we may be missing important information by not extending the tasks to more closely parallel everyday activities.

As there is room for many interpretations for what tasks are and are not similar to real world situations it is important to operationalize what I mean. Human behaviour is largely context dependent such that perception, interpretation, and responses are influenced by the situation. However, it is the underlying assumption for the majority of cognition research that the mechanisms of the system are largely invariant. It is assumed that the processing that occurs in response to the stimulus presented on a computer screen in isolation of other situational factors is the same as it would be in the real world. Although this assumption is widespread in the field and accurate enough that we do learn about cognitive and neural mechanisms, the questioning of the assumption's veracity is rare and the quantitative testing of this assumption is even rarer. It seems that this is an important question to examine if we are going to be able to make inferences about whether human cognition as studied in the laboratory generalizes to life outside the laboratory.

An extensive and representative review of the performance monitoring neural correlates (ERN and Pe) literature (see Appendix A) shows that although a wide variety of tasks are used, the great majority employ laboratory contrived tasks. Of the 92 studies listed, 75% use one of four tasks. The most common task employed is the standard Flanker task (37%) or slight variants of the task. This task involves presenting a stimulus on the screen that at its center has a target stimulus and is surrounded or flanked by some number of distractor stimuli (e.g., < < > < <). The task is to identify the central target (e.g., does the arrow point left or right) by pressing one of two response buttons.

The second most common task is the Go/No-Go task (19%). Here participants are required to only respond to a target stimulus and to withhold responding to any other non-target stimulus in this case by making a keypress (e.g., press the button in response to the red X but not to any of the blue or green Xs).

The third most common task is what is referred to as a Gambling task (13%) which has little to do with any actual participating in a gambling activity except that the outcome determines whether the participant has gained or lost money. Typically, in these tasks the participant is asked to select one of some number of 'doors' (e.g., squares) or 'balloons' (e.g., circles) behind which is an outcome. It is also important to note here that the studies utilizing this task are not directly examining the ERN but instead are examining the feedback related negativity (fERN). More on this component will be discussed in Chapter 3.

The fourth most frequently used task is a Stroop task (6%). A Stroop task presents stimuli that have two potential features available for analysis. One feature is typically more practiced or dominant while the other feature requires relatively more effort and possibly active suppression of the dominant feature. For example, the stimulus may be the word BLUE printed in blue ink. Most adults are more practiced reading words than naming colours, and reading may be considered the dominant process. Naming the ink colour is more difficult when the word is incongruent with the ink colour (the word RED printed in blue ink) than when the word is congruent with the ink colour (the word BLUE printed in blue ink).

These types of tasks are used to examine the error processing systems and may tap into the mechanisms of the system very well but because they are consistent in their simplicity, I would suggest that these and the majority of the lesser used tasks presented in Appendix A do very little to mirror real-life situations that we may encounter on a regular basis. I have provided 'real life scenario' examples below to show how I attempt to take one step closer to real situations in my experiments. It is easy to argue that Experiment 3 (touch typing task) and Experiment 4 (arithmetic task) use tasks that many people encounter every day. I have had to use a great deal of imagination to place Experiments 1 and 2 in this same category. Experiment 1 and 2 use hierarchical global/local stimuli with some of the same featural properties as colour Stroop stimuli (e.g., global level processing is dominant over local level processing). The global/local stimuli are clearly laboratory creatures which simulate visual hierarchical structure. I have presented the following 'real life scenario' for the global/local experiments, however, I am not arguing that these experiments approach 'real life' situations to a greater extent than the experiments in the literature (Appendix A). Rather, the global/local experiments offer a comparison of two tasks designed to produce errors and

ERNs, one which parallels the literature (e.g., selection of information from a relevant stimulus dimension while ignoring information from an irrelevant dimension) and one which generates errors very differently (e.g., comparison of information from two relevant dimensions). The global/local task is new to this avenue of research and findings from these experiments will help extend the performance monitoring literature. Thus, Experiments 1 and 2 take the first step away from the methods used in the literature, and Experiments 3 and 4 take another step toward understanding error processing in everyday tasks.

In the next few paragraphs I present very brief synopses of the experiments and an example of an everyday situation that may be reflected by the experimental design.

Experiments 1 and 2 (Chapter 2):

Experiments 1 and 2 utilized a global/local task that varied across two levels of stimulus congruency. Additionally, the stimuli used in Experiments 1 and 2 were combined with different levels of Gaussian distributed visual noise, which permitted the inspection of performance and the corresponding neural correlates under different levels of stimulus uncertainty and response uncertainty. As a result of these manipulations, and in conjunction with previous findings, I was able to elaborate on the role of stimulus and response uncertainty in performance monitoring. Also, by using the same stimuli across two different experimental tasks, I was able to examine the effect of cognitive load on performance monitoring. Chapter 2 addresses these issues and others.

Real World Scenario 1: Occasionally we are faced with making binary decisions based on pieces of information that are sometimes incongruent with each other. For example, a cautious pedestrian realizes that relying on a driver's hand signals alone is not the best thing to base a life or death decision on. Instead, prior to making the decision to cross the road, the pedestrian decides to weigh both possible pieces of evidence: the presence or absence of a signal to cross and whether the driver has or has not reduced speed. If the two evidentiary avenues lead to the same conclusion (i.e., congruent evidence) then the pedestrian will cross, otherwise (i.e., incongruent evidence) the pedestrian will not cross. Further, what happens if this decision is being made in the rain, at a distance, or whenever the visual representation of the signaling is compromised by some sort of visual interference? In Experiment 1 participants are asked to attend to both the global *and* local properties of the same stimuli that will be used in Experiment 2 with the task of reporting if the two properties were congruent or incongruent. This task was performed under different visual noise conditions (i.e., stimulus uncertainty).

Real World Scenario 2: Another pedestrian crossing the street needs to decide whether to cross the road in the face of an oncoming car that may or may not stop at the crosswalk. Incongruently, a driver may signal for the pedestrian to cross the road but the driver may not have reduced speed; or congruently the driver may signal for the pedestrian to cross and reduce speed. If the signaling to cross is the most valid indicator (i.e., local property) for the decision making process then it should be selected for attention while the speed of the car (i.e., global property) should be ignored. In Experiment 2 participants are asked to report a local stimulus property, again under different conditions of visual noise, while ignoring the global stimulus property.

To reiterate, the first two experiments are not meant to represent real world situations as operationalized in the previous section but are instead meant to extend the results of standard tasks to a more complex task and subsequently towards the use of more real world related tasks as the latter two experiments clearly achieve.

Experiment 3 (Chapter 3):

Experiment 3 used a novel task, method, and population to examine the role of expectancy, in particular the violation of expectation, in the generation of error related negativity and error positivity. In this case, expert typists were recruited to take part in a typing task. This is a deviation from the norm in this area of research since most tasks employed to date have been relatively simple and largely laboratory contrived. By recruiting touch typists to partake in my typing task, Experiment 3 represents a more ecologically valid investigation of performance monitoring. By replicating past findings (i.e., increased response-locked negativity on incorrect trials compared to correct trials) I showed that the conclusions drawn by the performance monitoring literature can be extended to more complex tasks and, to some extent, real world applications. Furthermore, modulations of Pe amplitudes as a function of participant expectancies (i.e., larger amplitudes for errors due to expectancy violations) allow us to support previous suggestions concerning the functional significance of this error positivity.

Real World Scenario 3: Over time we learn to expect certain things. The violation of these expectations can lead to errors in performance. When transcribing notes, upcoming words in a sentence that are not expected can lead to transcription errors.

Further, misspelled words or words with multiple spellings can lead to errors in transcription. For example, I would likely make a mistake when transcribing the word 'color' since, as a Canadian, I learned to spell the word with a U. So instead of typing C-O-L-O-R I may type C-O-L-O-U before realizing my mistake. The interesting question here is if the performance monitoring system reacts differently in response to expectation violation errors compared to non-expectancy related errors. In Experiment 3, using a letter by letter typing task, I violated participant expectations by either replacing the final letter stimulus with a letter inconsistent with expectations or by not presenting a letter stimulus at all.

Experiment 4 (Chapter 4):

Experiment 4 provided a further extension of performance monitoring research to new tasks, manipulations, and populations. Chapter 4 investigates ERN and Pe modulation as a function of task difficulty and state anxiety levels. Although the role of anxiety in error monitoring has been previously examined, this study represents the first to associate specific anxieties with tasks directly related to the anxiety. Specifically, I examined math anxious and non-anxious people in an arithmetic task where stimuli differed across three levels of difficulty. Different patterns of performance monitoring correlates were observed across difficulty levels, and as a result I was able to draw further conclusions about the role difficulty plays in error monitoring. More importantly, I observed interactions between my manipulations and the participants' math anxiety levels. I found an adjustment in performance monitoring on the basis of state anxiety that partially contradicts previous research.

Real World Scenario 4: You and three friends have just received the bill for a meal that you all equally shared. The bill is $120 and your friend states that you all owe $30 each. You mentally do the math and decide that the division is correct and you pay your $30. This type of 'simple' arithmetic is present in everyday life and generally people are quite capable. However, what if the bill was $132 or what if it was not the meal but rather the restaurant you were buying at the cost of $912,428? How does your performance monitoring system react to these different levels of difficulty? Further, what if you happen to have a fear of mathematics? Is your performance monitoring system influenced by this aversion to math and is the aversion effect dependent on difficulty level? Experiment 4 examines changes in the performance monitoring system of math anxious and non-anxious participants in response to mental arithmetic problems of different levels of difficulty.

Chapter 5:

The final section of this thesis, Chapter 5, provides a summary of specific findings in Experiments 1 through 4 along with an analysis of those findings as a whole. Does ERN morphology change as a function of task and error type? How do uncertainty, subject expectancies, task difficulty, and individual differences affect the ERN? Is the use of more complex, ecologically valid, tasks fruitful based on my findings or should research stick to laboratory contrived tasks?

Chapter 2

Uncertainty and Attentional Load Effects on Performance Monitoring as Indicated By the ERN/Pe Complex

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AUTHOR'S NOTE:

The experiments reported in this chapter have been written with the intention of submitting the work for publication. Therefore, the literature review in the introduction of this chapter may be somewhat repetitive with a portion of the literature review presented in Chapter 1. References are presented at the end of Chapter 5.

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Chapter 2

Uncertainty and Attentional Load Effects on Performance Monitoring as Indicated By the ERN/Pe Complex

Abstract

It has been suggested that the amplitudes of the error related negativity (ERN) and correct response negativity (CRN), response-locked event related potential (ERP) components, are influenced by uncertainty. I used identical global/local stimuli, under different conditions of visual discriminability, across two experiments to address the effect of stimulus and response uncertainty on performance monitoring as indicated by the ERN and CRN. Further, to assess the role of cognitive load on performance monitoring, Experiment 1 had participants compare the global *and* local stimulus properties in order to arrive at a same/different decision while Experiment 2 had participants *only* identify the local stimulus property (i.e., left/right) while attempting to ignore the global dimension. Comparisons within and between experiments revealed different patterns of response locked error related ERPs in regards to uncertainty and cognitive load. Using new tasks and manipulations, the results solidify previous findings regarding the effects of uncertainty in performance monitoring. Further, the differential modulations of ERN and CRN amplitudes across experiments indicated that cognitive demand influences the performance monitoring system and that further investigation of task effects is justified and important.

Introduction

Research concerning performance monitoring has seen a resurgence of interest in recent years, in part due to the discovery of potential underlying neural correlates. The event-related potential (ERP) component termed the error related negativity (ERN; Gehring, Coles, Meyer & Donchin, 1990) or error negativity (Ne; Falkenstein, Hohnsbein, Hoormann & Blanke, 1990) is thought to be associated with the processing of errors, an important aspect of human performance monitoring.

Numerous studies have revealed the presence of this response-locked component. Observed on grand averaged incorrect response trials, while largely absent on correct trials, the ERN is a negative midline frontal component, typically maximal between 50 and 150 ms post-response (Gehring, Goss, Coles, Meyer & Donchin, 1993). Evidence from ERP source analysis (e.g. van Veen & Carter, 2002), and fMRI experiments (e.g. Mathalon, Whitfield & Ford, 2003) place the generator of the ERN in the anterior cingulate cortex (ACC), although the exact location within the ACC is unresolved.

There are currently three main general theories of ERN function. The Error Detection theory suggests that the ERN is a neural correlate of a general error monitoring process, with the ERN itself related to the error-detection portion of the system (Dehaene, Posner, & Tucker, 1994). This theory defines the ERN as representative of a mismatch between subjects' intended and actual responses (e.g. Falkenstein, Hohnsbein, Hoormann and Blanke, 1991) and has been modified to include the processing of errors occurring outside a subject's conscious awareness (Luu, Flaisch, & Tucker, 2000), factors of strategic task control (Bartholow, Pearson, Dickter, Sher, Fabiani, & Gratton, 2005), amongst others.

Somewhat counterintuitive to this definition of the ERN is the presence of a smaller negativity observed on correct trials. Termed the correct-response negativity (CRN), this component is both morphologically and topographically similar to the ERN, although its amplitude is typically smaller. Current opinion would suggest that the CRN is generated when correct performance is subjectively perceived to be errorful, although the details of mechanisms underlying these effects are in dispute (e.g. Bartholow, et al., 2005; Ghering & Knight, 2000; Pailing & Segalowitz, 2004). In general, if participants make a veridically correct response, but subjectively believe they made an error—whether due to uncertainty arising from stimulus noise, task difficulty, inattention, or other factors—an ERN is produced relative to that response. When this type of trial is averaged along with other correct trials, a smaller ERN-like negativity is produced, namely the CRN (Coles, Scheffers & Holroyd, 2001).

A second theory addressing the functional significance of this ERN suggests it is not generated in response to internal error detection, but rather is a correlate of a conflict monitoring system. On the basis of evidence from fMRI activation in the ACC on both correct and incorrect high conflict trials, Carter, Braver, Barch, Botvinick, Noll, and Cohen (1998) suggested that the ACC was involved not with detecting errors per se, but rather with detecting response competition, under which conditions the likelihood of an error is increased. Carter, et al. (1998) theorized that the ERN reflected persisting activation between co-activated conflicting responses, and that errors were simply the cases in which this response competition was 'won' by the incorrect choice. Work by

Botvinick, Braver, Carter, Barch and Cohen (2001) refined these ideas, developing a model wherein the ERN represents a conflict signal arising from continued post-response stimulus processing in cases of unresolved response competition.

While this response competition theory of the ERN has been challenged for its apparent inability to account for a variety of ERN-related findings, Yeung, Botvinick and Cohen (2004) presented a series of simulation studies demonstrating that their response competition model directly predicted a large range of data previously taken as evidence favoring an error detection account of the ERN. One such finding is the S-R congruency effect observed by Scheffers and Coles (2000), where ERN amplitudes generated on error trials in a flanker task were larger for congruent than incongruent stimuli. While it would seem to be a prediction of the response competition theory that incongruent flanker trials should have a greater degree of conflict, and hence show larger ERN amplitudes compared with congruent trials, the dynamics of this response competition model reveal the opposite prediction, in line with prior data. When an error is made on a congruent trial, continued stimulus processing drives the correct trial response significantly more than in incongruent trials due to available stimulus information, giving high levels of activation for both competing responses, resulting in high conflict and a large ERN; for incongruent trials, relatively less evidence from the stimulus results in a slower activation of the correct response via continued processing, resulting in less response competition, and hence a smaller ERN (Yeung, Botvinick and Cohen, 2004).

A third contender in this functional significance debate suggests that recognizing an action as an error is a negatively charged event that provides us with feedback signaling that an adjustment in behaviour is necessary and as such the ERN is generated as part of a reinforcement learning system (Holyrod & Coles, 2002). Using evidence gathered from both ERN and fERN investigations the Reinforcement Learning Hypothesis suggests that error processing is a result of midbrain dopaminergic activity that arises due to the non-occurrence of an expected event. A dopamine system in the medial frontal cortex (MFC) that responds to reward predicting stimuli (i.e., correct responses) shows a decrease in activity when an event other than the expected rewarding event occurs (Schultz, 2000) is proposed. Evidence from a number of disciplines suggests that error related activity in the medial frontal cortex is a result of a disinhibition of the dopamine neuronal activity. Using single cell recordings, Ito et al. (2003) in monkeys and Williams et al., (2004) in humans showed this same disinhibition in the absence of or decrease in an expected reward. Using fMRI Bush et al. (2002) also replicated these same MFC findings in a performance monitoring task. These results support the reinforcement learning hypothesis and that the ERN may reflect a response to the absence of expected reward.

In a 2004 investigation, Pailing and Segalowitz investigated the effects of uncertainty in task performance on ERN and CRN components as a test of the Error Detection and Conflict Monitoring theories. When either stimulus or response uncertainty was increased, they observed a greater similarity between ERN and CRN components, with attenuation of ERN and enhancement of CRN amplitudes. Pailing and Segalowitz (2004) argued that this trade-off between ERN and CRN amplitudes under conditions of increasing uncertainty was strong evidence for an error detection theory of the ERN. In their series of investigations they created uncertainty by manipulating attentional demands required between two tasks (i.e., flanker vs. letter discrimination); perceptual (stimulus) uncertainty in an auditory discrimination task; and task difficulty resultant from increasing the number of response choices in a flanker task.

The findings from Pailing et al., (2004) suggested that the presence of uncertainty, either stimulus or response driven, influences the performance monitoring system as indicated by the differential modulations of ERN and CRN amplitude. The authors used an *auditory* discrimination task that had participants decide if a tone they heard was either short (100 ms) or long (150 ms for the easy condition and 125 ms for the difficult condition) as a manipulation of stimulus uncertainty. Response uncertainty, and in turn task difficulty, was manipulated using a modified flanker task where participants conditions included two (easy) or three (hard) potential responses. To examine the role of attention on generation of the ERN participants compared ERP waveforms generated from a flanker task completed under single and dual task conditions.

It is important to state that I do not question the validity of the results of the aforementioned study. Instead, since the stimulus uncertainty manipulation used an auditory task I wanted to determine if their findings could be replicated in the more standard visual cognition domain while simultaneously using new tasks involving unique variable manipulations. As a result, the current study was conducted to extend the findings using a *visual* manipulation of stimulus uncertainty (i.e., three levels of Gaussian distributed visual noise); within task response uncertainty manipulations (i.e., stimulus congruency and response mapping); and a between experiment cognitive load comparison.

Examination of the waveform patterns between experiments across the manipulations mentioned in the previous paragraph leads to the second, somewhat more global objective of examining the consistency of ERP correlates of performance monitoring. It has been shown that the ERN is consistently generated in a number of tasks and across response modalities (see Appendix A). Further, the amplitude of the ERN is influenced by instructions. In studies where the focus was placed on response accuracy instead of speed, a more negative ERN was observed compared to the opposite instruction (Gehring et al., 1993). Following from this, the current research tested this seeming robustness of the performance monitoring system as indicated by the ERN. Specifically, by using identical stimuli but changing the task demands I sought to show that ERN morphology, and hence the performance monitoring system, is consistent regardless of task or attentional demands. By comparing waveform morphology from Experiments 1 and 2 I was also able to address this question.

In Experiment 1, using congruent and incongruent global/local stimuli which varied on levels of visual noise, participants performed a same/different decision on global and local stimulus dimensions to assess the influence of stimulus and response uncertainty on ERN/CRN amplitudes. Using the identical stimuli as Experiment 1, Experiment 2 had participants perform a less demanding task by having them respond to local stimulus features only. Experiment 2 served two purposes. First, it could be argued that the task in Experiment 1 is non-standard compared to the ERN literature since both stimulus dimensions are task relevant compared to the popular flanker task in which only one element of the stimulus is task relevant and the other(s) are task irrelevant. Therefore the replication of standard ERN findings in Experiment 2 would help to validate the stimuli and procedure used in Experiment 1. Secondly, the role of attentional demands will be assessed via a comparison of component amplitudes across these two experiments. Specific hypotheses will be presented at the start of each experimental section.

EXPERIMENT 1

In regards to behavioural data, I hypothesized that mean error rates will increase as noise level increases and will also be higher for incongruent compared to congruent trials. For correct trials, response times will increase significantly as stimulus noise level increases with this effect being most prominent for incongruent trials. These behavioural findings will validate my stimulus and response uncertainty manipulations.

In regards to electrophysiological data, I hypothesized that the ERN will be more negative on error trials compared to correct trials and that the Pe will be more positive for error trials compared to correct trials, replicating previous research. Furthermore, I hypothesized that ERN amplitudes will become less negative as noise level increases while CRN amplitudes will become more negative as noise level increases as a result of stimulus uncertainty. Finally, I propose that ERN amplitudes will be more negative on incongruent trials compared to congruent trials, as a result of response uncertainty. This difference is expected to be largest at low noise with the effect decreasing as noise increases.

Method

Participants

Twenty volunteers (9 male, aged 18 to 24 years) from the McMaster University undergraduate community participated in the study. All participants were right-handed and reported normal or corrected-to-normal vision. Eligible participants received course credit for their participation and the remainder volunteered without compensation.

Informed consent was obtained from each participant.

Apparatus and Stimuli

Stimulus presentation and manual response measurement was performed using Presentation® experimental software (version 0.81, www.neuro-bs.com) running on a Pentium 4 computer under the Windows 2000 operating system. Stimuli were presented on a 17" CRT monitor, at a resolution of 1024x768 pixels at a frame rate of 75 Hz. The experiment was run in a dimly lit room, with a fixed chin rest used to limit head and upper body motion. A viewing distance of approximately 80 cm was kept constant.

Stimuli were sets of small black arrows on a white background, all pointing in one of four directions: top-right, bottom-right, top-left, and bottom-left. In each stimulus, these small arrows were arranged to form a larger arrow, pointing in the same or opposite direction as the small arrows, to give congruent and incongruent local/global stimuli, respectively. These stimuli were modified by one of three levels of high-frequency noise (black on white background, 0%, 15% and 30% Gaussian distributed speckle Adobe Illustrator filter), giving 24 distinct but matched stimuli in total, examples of which are shown in Figure 2.1. Stimuli were presented for 50 ms on a black screen background, subtending approximately two degrees of visual angle vertically and horizontally.

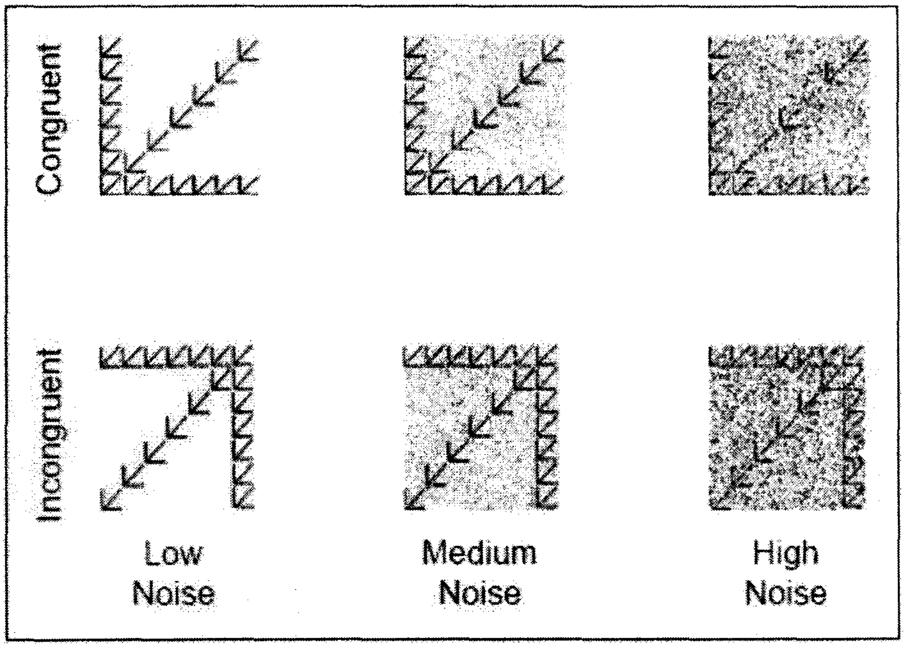


Figure 2.1: Example stimuli from Experiments 1 and 2 as a function of congruency (congruent and incongruent) and visual noise (low, medium, and high) levels

Procedure

Appendix B contains the standardized instructions for Experiment 1 and 2. The task required participants to determine whether the small arrows (local feature) and large arrows (global feature) were pointing in the same or different directions. Participants responded by pressing the "z" or "/" keys on a standard computer keyboard with their left and right index fingers respectively, to indicate "same" or "different" responses. In addition, the mapping of "same" and "different" responses to right and left response keys was alternated every block, in order to increase the overall degree of difficulty and response uncertainty in the task. Blocks were separated by an instruction screen that provided participants with the response mapping information necessary to perform the subsequent block. Participants were asked to respond as accurately as possible while also responding as quickly as possible. To stress accuracy over speed, they were informed that a greater number of accurate responses would shorten the overall length of the experiment. This instruction was intended to increase motivation to do well and to focus attention on the task. This statement, however, was false and participants were informed of this in the debriefing process. They were informed that they would have a maximum of approximately 1.5 s to respond before presentation of the next stimulus. All participants were tested individually with participants initially completing a practice block of 24 trials (a single presentation of all 24 stimuli) with the experimenter present. Following this practice block, the experimental session consisted of twelve blocks of 96 trials each, with all combinations of noise and congruency factors counterbalanced, and presented randomly.

Electrophysiology

The ActiveTwo Biosemi electrode system (BioSemi, Amsterdam, the Netherlands) was used to record continuous electroencephalographic (EEG) activity from 128 Ag/AgCl scalp electrodes plus 4 additional electrodes placed at the outer canthi and just below each eye for recording of horizontal and vertical eye movements. Two additional electrodes, common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode were also used. These electrodes replace the "ground" electrodes used in conventional systems (http://www.biosemi.com/faq/cms&drl.htm). Because the BioSemi system is an active electrode system there is no conventional reference electrode; a monopolar signal is stored for each active electrode and all rereferencing is done in software after acquisition. The continuous signal was acquired with an open pass-band from DC to 150 Hz and digitized at 512 Hz.

Continuous EEG data for each subject's experimental session was digitally filtered from 0.03 to 30 Hz, with subsequent averaging of ERP data and ERP component analyses conducted via EEProbe software (ANT, www.ant-software.nl). Eye-blinks were identified and corrected using an automated detection procedure, and epochs containing other eye movements and large artifacts were rejected. Response-locked epochs were comprised of a 200 ms baseline and a 900 ms post-event interval. All trials, both correct and incorrect, not contaminated with artifacts were analyzed. Data for all response and stimulus locked epochs were averaged for each individual subject. Subsequently, individual averages were then combined to form a grand average waveform for each of the conditions of interest.

Data Analysis

Data from six subjects were excluded from analysis due to excessive artifacts in their ERP data. Data from two additional subjects were excluded due to at-chance behavioral performance on the experimental task. Data from the remaining 12 subjects were analyzed as described below.

Reaction time data for correct trials and error rate data were assessed by separate 2 x 3 repeated measures Analysis of Variance (ANOVA), with factors of global/local stimulus congruency (congruent, incongruent) and stimulus noise (low, medium, high). Response-locked peak minimum amplitude and latency data for ERN/CRN components were assessed by 2 x 2 x 3 repeated measures ANOVA, with factors of trial accuracy (correct, error), global/local stimulus congruency (congruent, incongruent), and stimulus noise (low, medium, high).

Results

Mean response time data for correct trials and mean error rate data are presented in Figure 2.2. An overall error rate of 19.4% was observed, with participants making more errors as stimulus noise increased, supported by a main effect of stimulus noise, $F(2,22) = 23.52$, $p < .05$. Trials with incongruent global/local stimuli had a higher error rate than congruent stimulus trials at low noise, with this effect diminishing as stimulus noise increased, supported by an interaction of stimulus noise and stimulus congruency, $F(2,22) = 5.72$, $p < .05$. For correct trials, overall mean response time for correct trials was 736 ms; response time was faster for trials with congruent versus incongruent stimuli, $F(1,11) = 63.86$, $p < .05$; and response times for congruent stimuli were slower as stimulus noise increased, but incongruent stimulus response times were almost identical across noise conditions, reflected by the main effect of stimulus noise, $F(2,22) = 4.21$, $p < .05$, and the interaction of stimulus congruency and stimulus noise, $F(2,22) = 10.40$, $p < .05$.

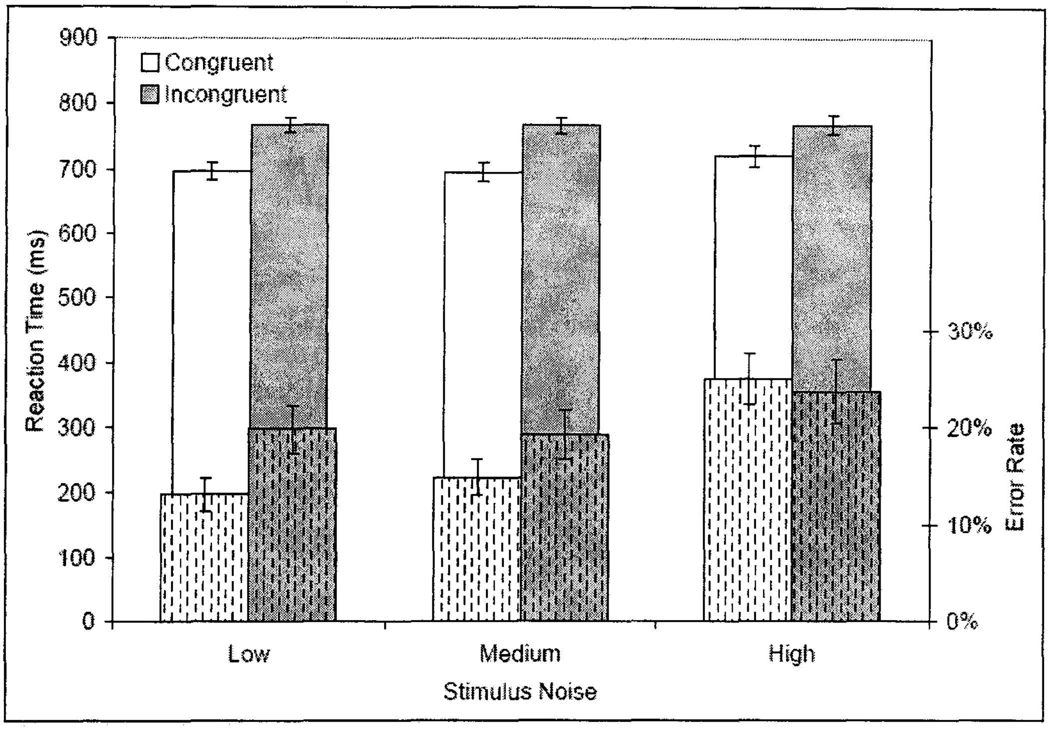


Figure 2.2: Mean response time (correct trials) and error rate data for Experiment 1 as a function of congruency visual noise levels.

Grand mean waveforms for response-locked ERN/CRN components at electrode FCz are shown in Figure 2.3. No effects of peak latency were observed for these ERN/CRN data. Peak amplitude was larger overall for ERNs than CRNs, F(1,11) = 24.15, p < .05, and ERN/CRN peak amplitude was observed to decrease with increasing stimulus noise, reflected by a main effect of stimulus noise, F(2,22) = 4.89, p < .05. Within these effects, the amplitude difference between ERN and CRN components appeared to diminish as stimulus noise increased. CRN amplitude remained fairly consistent at approximately -2 μV over different levels of noise, while overall ERN amplitude appeared to decrease with increasing levels of stimulus noise. This observation was partially supported by a marginal interaction of trial accuracy and stimulus noise, F(2,22) = 3.08, p = .08. The seemingly larger congruent vs. incongruent ERN apparent in the medium noise condition was not supported statistically, with no significant interaction of stimulus congruency and stimulus noise, F(2,22) = 2.44, p = .11, and no interaction of these factors with response accuracy, F < 1.

Mean Pe amplitudes were significantly more positive for error trials compared to correct trials, F (1, 11) = 8.89, p < .05. Furthermore, there was a significant Accuracy x Noise Level interaction, F (2,22) = 3.85, p < .05, due to errors at Medium Noise Levels being inexplicably more positive than at Low and High Levels.

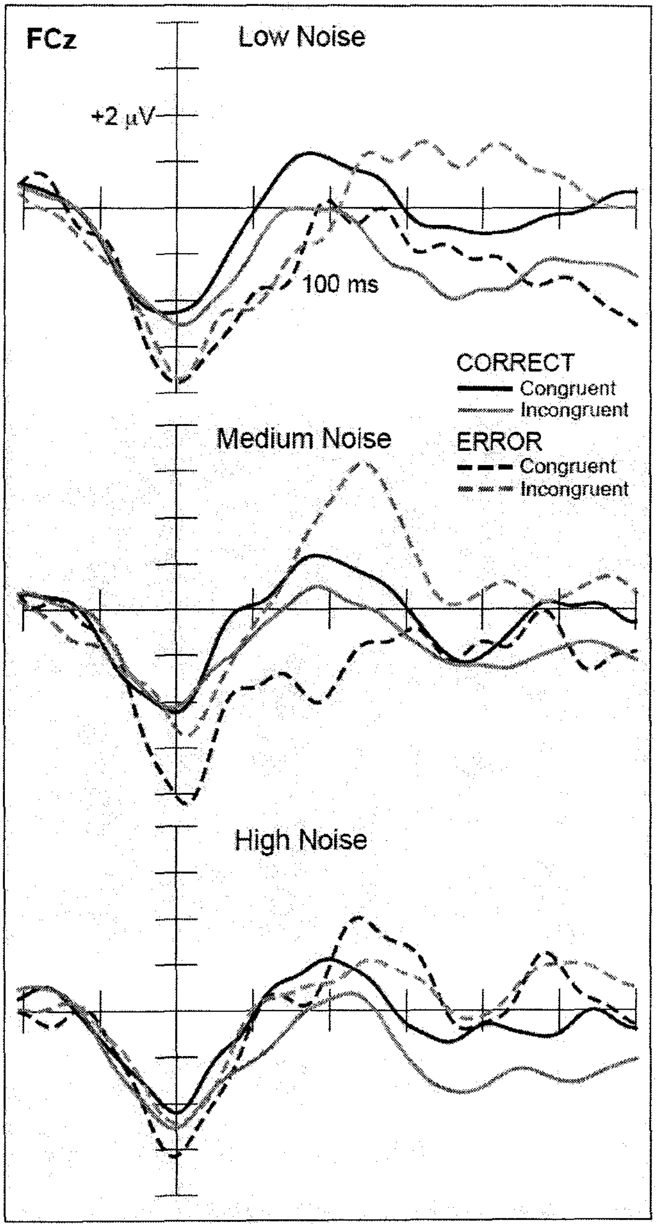


Figure 2.3: Response locked grand mean waveforms for ERN/CRN components at electrode FCz (Experiment 1).

Discussion

Experiment 1 was conducted as a general test of whether the task and stimulus attributes used in the present experiment could replicate known ERN effects from the literature. Additionally, by manipulating stimulus and response uncertainty I tested my task and stimulus design in a visual cognition domain opposed to the auditory design used by Pailing and Segalowitz (2004). As stated earlier, Pailing and Segalowitz (2004) demonstrated effects of stimulus and response uncertainty on ERN and CRN component amplitudes, showing that ERN magnitude decreased and CRN magnitude increased with increasing uncertainty in performance. This pattern of results suggests that as task performance becomes more uncertain, subjective representation of errorful performance is increasingly similar for objectively correct (CRN) and incorrect (ERN) trials (Pailing & Segalowitz, 2004). In this experiment I was able to increase response uncertainty by using stimuli that differed in levels of congruency and using alternating response mappings. Further, by varying the levels of visual noise I manipulated levels of stimulus uncertainty. This allowed an approximation of critical influences as per Pailing and Segalowitz (2004) and allowed me to observe any effects these manipulations had on the ERN/Pe complex.

As expected, results from Experiment 1 replicated a number of the critical effects observed by Pailing and Segalowitz (2004). In the present data, ERN and CRN amplitudes became increasingly similar as stimulus noise increased, though analyses supporting this contention fell just short of significance ($p = .08$). Pailing and Segalowitz (2004) suggested that this reciprocal sensitivity of ERN and CRN components to uncertainty in task performance was strong evidence for an error detection account of the ERN. Although this previous finding was consistent with expectations, I found no discernible effects of response uncertainty on ERN amplitude as indicated by the non-significant differences between congruent and incongruent error conditions. It is possible that alternating the response mapping, such that the opposite response pattern was required every other block, did not generate the same degree of response uncertainty generated in the dual-task procedure Pailing and Segalowitz employed. It is also possible that the congruency manipulation alone did not produce a comparable amount of response uncertainty, although this seems at odds with the response time data that support the presence of response uncertainty in the task (i.e., longer RTs to incongruent stimuli). Pairing the congruency manipulation with the required changes in response mapping should only have served to increase levels of response uncertainty. Although attempting to interpret null findings is problematic these findings suggest that response uncertainty may not influence the performance monitoring system to the extent previously suggested.

Importantly, these results show that my general task and stimulus design appear to be able to generate and replicate reasonable ERN data. The extension of research questions to new, unique tasks is an issue that will be addressed throughout this thesis and although the task of the present experiment is not overly complex compared to the real world, it is more cognitively taxing than a typical global/local task and the standard tasks utilized in ERN research (see Appendix A). To show that these results were actually in keeping with prior literature and not simply a quirk of an unusual procedure, Experiment 2 was conducted. Using the identical stimuli from Experiment 1, a standard global/local task (i.e., identify the local stimulus property) was used in Experiment 2. A replication of the standard ERN findings using this simple task will help solidify the validity of Experiment 1 findings and the use of the same/different task. Further, because the only difference between these two experiments will be the task performed a comparison of results between experiments is possible. The same/different task presented previously has subjects consciously assessing two stimulus parameters in order to perform the task while the task here in Experiment 2 asks participants to ignore one parameter (i.e., global dimension) to focus on another (i.e., local dimension). Experiment 1 may be more cognitively taxing in terms of stimulus dimensions that require attention for the comparison process. Directly comparing behavioural and electrophysiological results from Experiment 1 and 2 allows me to address the role of cognitive and/or attentional load on performance monitoring.

EXPERIMENT 2

All hypotheses presented in Experiment 1 were re-examined here in Experiment 2 and the additional hypotheses presented next are in regards to between experiment comparisons.

Specifically, compared to Experiment 1, response times will be shorter and accuracy rates will be higher in this experiment. It was further expected that noise levels would affect accuracy and RT data differently across experiments, especially at the high noise levels where the attention demanding task of Experiment 1 is expected to result in longer response times and a higher error rate compared to Experiment 2.

It was further hypothesized that since a more cognitively demanding task may interfere with the processes needed to monitor performance normally, between experiment ERN and CRN amplitude differences are expected. A larger CRN is expected for Experiment 1 compared to Experiment 2 reflecting the greater effect of uncertainty about whether an error was made due to cognitive load, and this effect should be modulated by stimulus uncertainty. ERN amplitudes will decrease as noise level increases in both experiments.

Method

Participants

Eighteen volunteers (10 male, aged 18 to 23 years) from the McMaster University undergraduate community participated in the study. All participants were right-handed and reported normal or corrected-to-normal vision. Eligible participants received course credit for their participation and the remainder volunteered without compensation. Informed consent was obtained from each participant.

Procedure

The task required participants to determine which direction the small arrows (local feature) were pointing while ignoring the direction of the large arrow (global feature). Participants responded by pressing the "z" or "/" keys on a standard computer keyboard with their left and right index fingers respectively, to indicate "left" or "right" responses. Response mapping remained consistent throughout this experiment. All other instructions were the same as in Experiment 1.

Data Analysis

Data from four subjects were excluded from analysis due to excessive numbers of artifacts in their ERP data, and data from a further two subjects were excluded on the basis of at-chance behavioral performance on the experimental task. Data from the remaining 12 subjects were analyzed as described in Experiment 1.

Results

Mean response time data for correct trials and mean error rate data are shown in Figure 2.4. An overall error rate of 11.18% was observed, with participants making more errors as stimulus noise increased, supported by a main effect of stimulus noise, F(2,22) = 13.91, $p < .05$. Participants also made more errors on trials with incongruent global/local stimulus dimensions, with this difference decreasing as stimulus noise increased, supported by an interaction of stimulus noise and stimulus congruency, F(2,22) = 4.29, $p < .05$. Overall mean response time for correct trials was 571 ms, with response time increasing as stimulus noise increased, supported by a main effect of stimulus noise, F(2,22) = 22.34, $p < 0.05$. Incongruent trials were slightly faster than congruent trials, supported by a main effect of stimulus congruency F(1,11) = 7.03, $p < 0.05$.

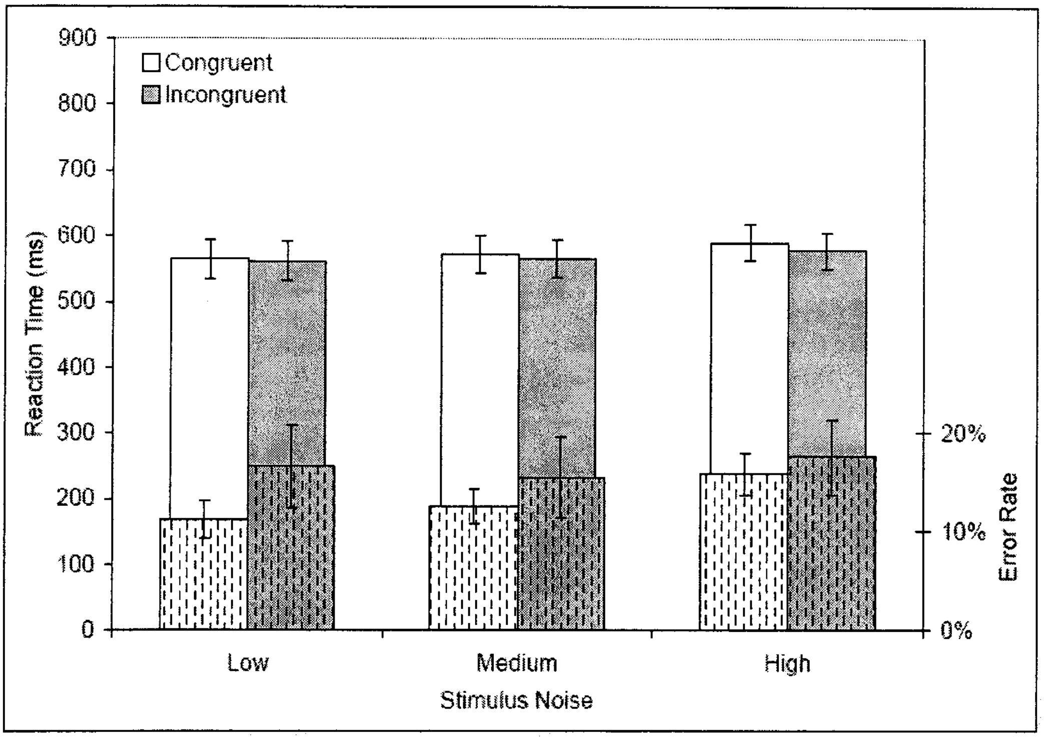


Figure 2.4: Mean response time (correct trials) and error rate data for Experiment 2 as a function of congruency visual noise levels.

Grand mean waveforms for response-locked ERN/CRN data at electrode FCz are shown in Figure 2.5. The average peak CRN latency (-18.9 ms) was observed to occur earlier than the average peak ERN latency (-6.9 ms), relative to the overt task response, $F(1,11) = 6.79$, $p < 0.05$. No other effects of peak latency were observed.

Peak amplitude was larger overall for ERN than CRN components, $F(1,11) = 25.32$, $p < .05$. Stimulus congruency effects were observed to vary over levels of stimulus noise for ERN components. ERN amplitude to congruent stimuli was larger than incongruent stimuli with high levels of stimulus noise, but this pattern reversed under low stimulus noise conditions, where ERN amplitude was significantly larger to incongruent stimuli, with approximately equal ERN amplitudes to congruent and incongruent stimuli at medium noise levels. In contrast, CRN amplitudes did not appear to vary substantially in response to stimulus noise or congruency manipulations. These observations were supported by the significant interaction of stimulus congruency and stimulus noise, $F(2,22) = 4.09$, $p < .05$, and the three-way interaction of these two factors with trial accuracy, $F(2,22) = 4.28$, $p < .05$.

Pe amplitudes were significantly more positive for error trials compared to correct trials, $F(1, 11) = 5.52$, $p < .05$, but comparisons of Pe amplitude across noise and congruency conditions revealed no significant differences or variable interactions, ($p > .05$).

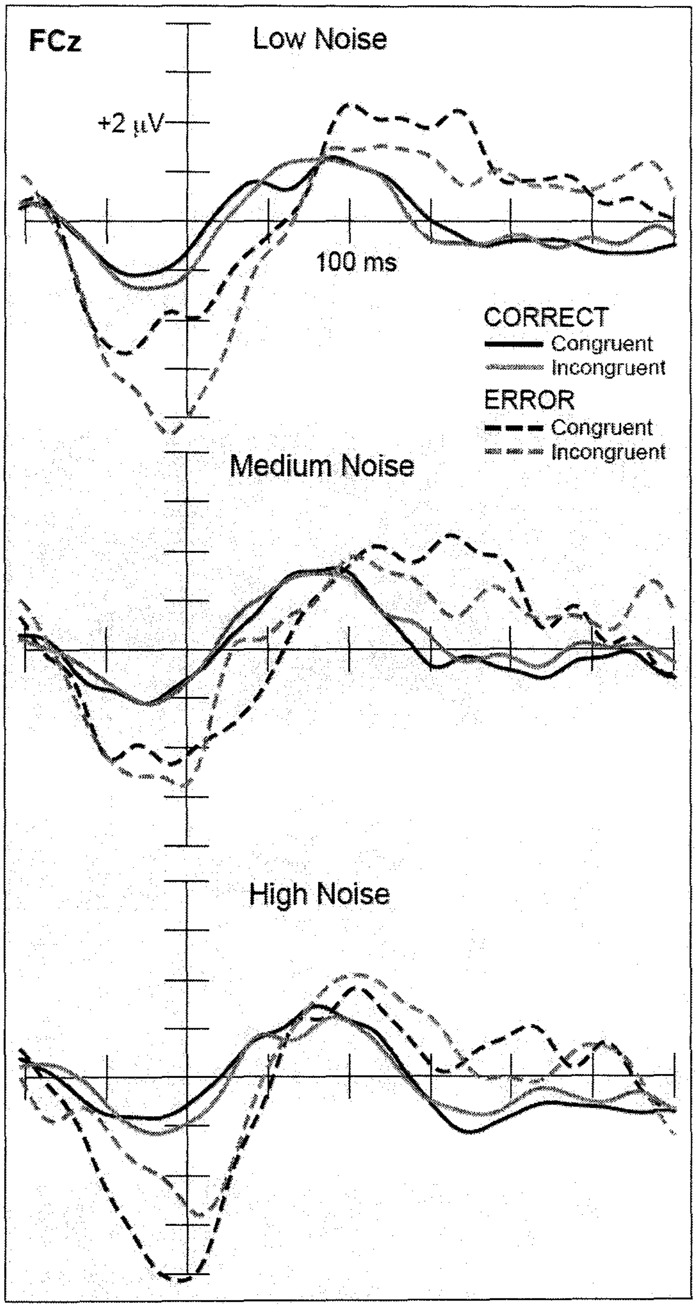


Figure 2.5: Response locked grand mean waveforms for ERN/CRN components at electrode FCz (Experiment 2).

Discussion

Experiment 2 served two main purposes, one of which was to validate the findings of Experiment 1 by the hypothesized replication of standard ERN findings, namely the increased amplitude negativity and positivity on error trials for ERN and Pe amplitudes respectively. The second purpose, which will be addressed later in this section, was to assess the role of cognitive load on performance monitoring by comparing the results of this experiment with the results of Experiment 1.

Due to the non-typical nature of the task used in Experiment 1 it might be argued that the ERN/CRN findings are a result of this particular procedure and stimuli rather than the experimental manipulations. The replication of common behavioural findings suggests that this is not a concern. Further, error responses in Experiment 2 to this simpler, less cognitively taxing, global/local task yielded fairly typical ERN waveforms. More negative ERNs on error trials and the presence of very small CRNs on correct trials closely mirrors the majority of previous research. With that said, the reversal of ERN amplitude patterns seen for congruent and incongruent errors at low and high noise levels is interesting.

This pattern reversal of ERN amplitudes does not readily fit with any existing theory of ERN functional significance. Both Bartholow, et al. (2005), and Hajcak, et al. (2005) suggested that current models of ERN function may need some revision to accommodate new additional influences observed on ERP morphology. Bartholow, et al. (2005) suggested that ERN and CRN morphology are related to higher-order representations of task processing conflict, including task strategy representations, and not simply conflict arising from competing response alternatives on a single trial or simple error detection. Data from Bartholow et al. (2005) also demonstrated greater CRN and ERN amplitudes for incongruent vs. congruent stimuli, through a flanker procedure that modulated the relative expectancies of compatible and incompatible flankers. Yeung, Botvinick and Cohen's (2004) response competition model cannot easily account for the crossover interaction of congruency and stimulus noise on the ERN. It may be necessary to allow an additional mechanism representing top-down strategic influences to bias contribution to an ERN-generating response competition process. Data from Hajcak, et al. (2005) showing enhancement of ERN amplitudes due to the subjective salience of errors, without any other notable differences in performance, further emphasizes the likely contribution of higher-level processes to ERN generation.

In terms of the observed effects of congruency and stimulus noise on ERN amplitude, consideration of task-level strategic effects and error salience within this context suggest one possibility. Stimuli were presented randomly in this experiment, and participants had no warning or cuing as to what degree of noise upcoming stimuli would have. The likely attentional strategy in this task would have been to maintain a relatively high attentional state, so as to allow reasonably good processing of high-noise stimuli when they occurred. This would have been reinforced strongly on one third of trials with high-noise stimuli, and reinforced to some degree on medium-noise trials. This would allow relatively good performance on all trials, without the additional cognitive cost of adjusting task control parameters in anticipation of stimulus differences. Maintaining a lesser degree of preparation (e.g. optimized for medium- or low-noise trials) would likely produce substantial additional performance costs on high-noise trials, which were not seen here. The alternative possibility, where participants might seek to optimize their preparation with regard to each upcoming stimulus seems unlikely for several reasons—participants had no pre-stimulus information as to what level of noise an upcoming stimulus would have, and so would only be able to do this preparation after the stimulus was presented. This deliberate differential allocation of attentional investment for every trial, based on the contents of every stimulus, would be an effortful addition to an already substantial attentional load. Again, the relatively small increases in response time across noise levels here in Experiment 2 suggest this kind of task performance was unlikely.

If participants were employing a task-level strategy of maintaining a level of attentional preparation for high-noise trials, what effect might this have on high- and low-noise stimulus trials? Possible mechanisms that could account for larger congruent versus incongruent ERN components observed for high-noise trials are in keeping with prior data from Scheffers and Coles (2000), and model predictions from Yeung, Botvinick and Cohen (2004). For low-noise trials presented in a context of high-noise preparation, a high degree of attentional allocation towards extraction of local stimulus features in noise would likely lead to a very strong and rapid extraction of both global and local feature information in a low-noise situation. Responses driven by an unexpectedly fast and available global feature may appear subjectively more salient to participants, in the sense of their making an error based on obviously available and misleading information. In contrast, errors on low-noise congruent trials may be subjectively less salient, with no obvious source of having been misled through overinvestment in the task. While this suggested explanation is of course post-hoc, the key mechanisms invoked are those previously demonstrated to influence ERN morphology. Another alternative could be to consider these findings with respect to Bartholow et al.'s (2005) demonstrated effects of expectancy on ERN and CRN amplitudes, though it is harder to establish independent measures of expectancy and congruency in the present study. Manipulations of expectancy will serve as the main independent variable in Experiment 3.

Comparing Experiments 1 and 2: Examining the Influence of Cognitive/Attentional Load

The same stimuli and experimental design were used in both Experiments 1 and 2 but a task change was implemented in order to assess the role of cognitive load on the performance monitoring system. The same/different task employed in Experiment 1 (compare global and local) was thought to be more challenging and attention demanding than the task in Experiment 2 (identify local). A comparison of the behavioural results between experiments indicated that this supposition was correct. Participants committed significantly more errors in Experiment 1 (19.4%) compared to Experiment 2 (11.18%), $t(22) = 2.11$, $p < .05$. Furthermore, when error rates are subjected to a 2 x 3 ANOVA with Experiment as a between subjects factor and Noise Level as a within subjects factor, a significant interaction is observed, $F(2, 44) = 4.16$, $p < .05$. This interaction, as can be seen in Figure 2.6, results from a significantly higher error rate at the high noise level in Experiment 1. This interaction indicates that the high noise level had a larger adverse effect on performance in the same/different task. It seems that the extreme noise interacted with the additional attention requirement to impact negatively on performance. Importantly, within each experiment the error rate increased as the stimulus uncertainty level increased suggesting that stimulus uncertainty was treated in similar ways in each experiment. Additionally, in both experiments more errors were committed on incongruent trials compared to congruent trials. Regarding response times, an Experiment x Congruency x Noise Level ANOVA revealed that correct responses in Experiment 1 (736 ms) were on average significantly longer than correct response times in Experiment 2 (571 ms), $F(1, 22) = 59.19$, $p < .05$. Further, a significant Experiment x Congruency x Noise Level interaction was observed, $F(2, 44) = 4.20$, $p < .05$. Although there were no effects of Congruency on RT in Experiment 2, in Experiment 1 RT on correct congruent trials increased as noise level increased while RTs for incongruent trials remain constant as noise increased.

Similar to the marked differences that were observed in the behavioural findings, inter-experiment differences between grand mean waveforms were also revealed. Comparisons of ERN amplitudes revealed a significantly higher degree of negativity in Experiment 1, $t(22) = -3.32$, $p < .05$. The higher cognitive demand required to perform Experiment 1 did have an influence on the performance monitoring system however, this increased negativity in the more difficult task is in contradiction with the attentional demand findings of Pailing and Segalowitz (2004) since dual task errors led to significantly smaller ERNs compared to single task errors. Comparing ERN amplitudes within each noise level between experiments revealed no significant differences at any individual noise level. Interestingly however, the reversal of ERN patterns observed across noise and congruency levels seen in Experiment 2 was not present in Experiment 1. A number of potential explanations for this reversal were stated in a previous section but the lack of a similar pattern in Experiment 1 suggests that the reversal is dependent on attention or task difficulty.

Also seen in Figure 2.7, CRN amplitudes were significantly more negative in Experiment 1, $t(22) = -3.23$, $p < .05$ with this difference consistently observed across all noise levels (Low: $t(22) = -2.41$, $p < .05$; Medium: $t(22) = -2.36$, $p < .05$; High: $t(22) = -1.95$, $p = .07$). However, within each experiment the CRN amplitudes did not differ as a function of noise ($p > .05$). The between experiment CRN difference is also inconsistent with the Pailing and Segalowitz experiment although it was consistent with their initial hypotheses. Since the CRN is thought to result from an uncertainty in accuracy judgments, a larger CRN in a more difficult task is expected. The lack of within experiment CRN modulation as a function of noise is however, somewhat inconsistent with the previous statement. An increase in stimulus uncertainty should result in a decrease in accuracy detection which in turn should lead to an increase in CRN negativity. This contradiction is difficult to readily explain and further exploration is necessary.

CONCLUSION

The two experiments presented here investigated the impact of stimulus uncertainty, response uncertainty, and cognitive load on the neural correlates of the performance monitoring system, namely the ERN, CRN and Pe. Experiment 1, in a visual cognition context, replicated a number of the key effects of stimulus uncertainty observed in an auditory paradigm used by Pailing and Segalowitz (2004). Mainly, as stimulus uncertainty increased the amplitudes of the ERN and CRN became more similar due to an increase in CRN amplitude as noise level increased. Surprisingly, response uncertainty seemed to have no effect on the performance monitoring system in Experiment 1.

In Experiment 2 an interesting pattern of ERN amplitudes was observed such that for incongruent trial errors the ERN amplitude decreased as noise increased but the opposite pattern was observed on congruent trials. It seems that in this simpler task ERN amplitude is influenced by an interaction of stimulus and response uncertainty. It is unclear why the opposite pattern is observed in trials with lower levels of response uncertainty. It may be a result of attentional allocation strategies and is a question requiring further research.

To determine what effect cognitive/attentional load had on the ERN/Pe complex, and hence the performance monitoring system, results of Experiments 1 and 2 were compared. Different behavioural results supported the proposed distinction between experiments. The increase in cognitive load in Experiment 1 revealed significantly larger ERNs and CRNs compared to Experiment 2. This main finding suggests that cognitive load may influence the performance monitoring system. However, it is important to remember that ERN/CRN patterns differed between experiments in regards to the interaction between response and stimulus uncertainty levels. It seems the effect of uncertainty in the monitoring of performance is dependent on task demand.

A general purpose of this experiment was to further establish the robustness of the ERN/Pe complex in the performance monitoring process. Numerous investigations utilizing a number of tasks have all shown the presence of this response-locked error related ERP component. Until now, no study had used this experimental design, stimuli set, or visual noise manipulation. Therefore the basic finding of an increased ERN and Pe on error trials lends credence to the more complex stimuli, task and manipulations used here. Further, this replication of standard findings in a non-standard task helps open the door for more complex investigations of performance monitoring.

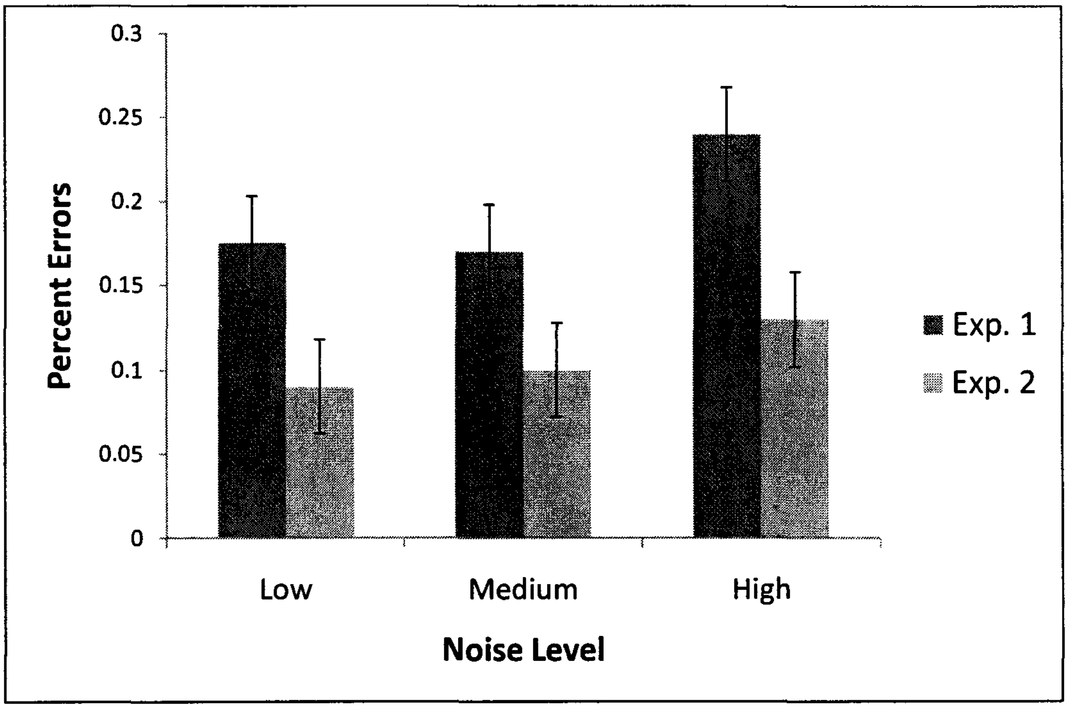
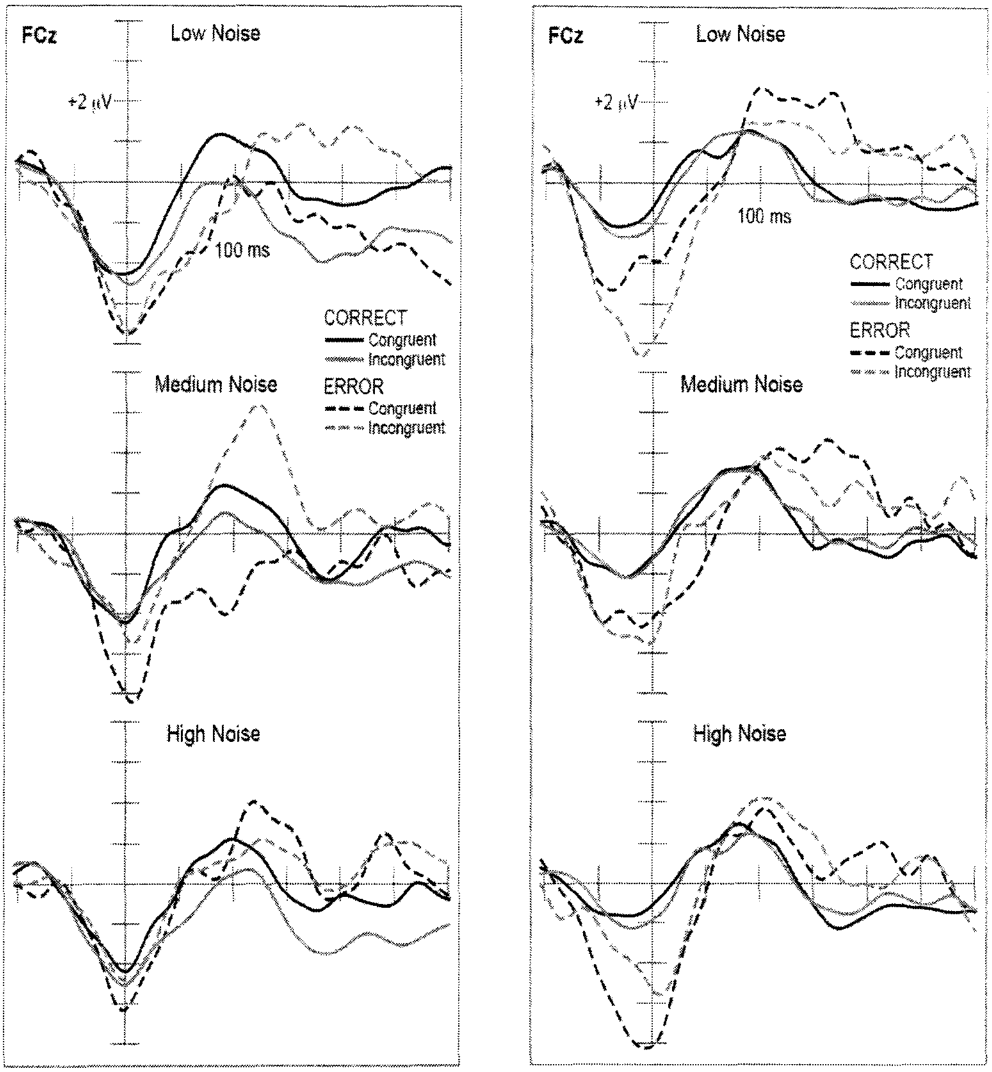


Figure 2.6: Error rates across experiments as a function of Noise Level.



E1: Same/Different Task **E2: Identify Local Task**

Figure 2.7: Response locked grand averaged waveforms for Experiment 1 (E1: Left panel) and Experiment 2 (E2: Right Panel) observed at FCz.

Chapter 3

Expected and Unexpected Variations of ERN and Pe Morphology Due to Expectation Violations in a Complex Typing Task

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AUTHOR'S NOTE:

The experiments reported in this chapter have been written with the intention of submitting the work for publication. Therefore, the literature review in the introduction of this chapter may be somewhat repetitive with a portion of the literature review presented in Chapter 1. References are presented at the end of Chapter 5.

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Chapter 3

Expected and Unexpected Variations of ERN and Pe Morphology Due to Expectation Violations in a Complex Typing Task

Abstract

Performance monitoring is a complex process but relatively simple tasks are usually used to study the ERP components purported to index performance monitoring (ERN: error-related negativity; CRN: correct response negativity; Pe: error positivity). To help to validate the inference from simple to complex I used a more complex task to examine the same neural correlates. I studied expert touch typists on a touch typing task to examine the influence of expectancy violations on performance monitoring neural activity. Results indicated that the complex nature of the task did not change the electrophysiological findings typically observed in the performance monitoring literature: the ERN was significantly more negative and the Pe more positive for error trials compared to correct trials. This finding validates the use of more complex tasks in the study of performance monitoring and in turn substantiates the claims made by studies employing more simple tasks. Furthermore, although no ERN differences were observed across levels of expectancy violation, the Pe findings showed a trend suggesting that Pe amplitude may be sensitive to expectation.

Introduction

An important aspect of human cognition is performance monitoring. Performance monitoring mechanisms allow individuals to assess the accuracy of their committed response and to adjust their performance accordingly in order to minimize errors. Using a complex typing task in a sample of expert touch typists, I examined the performance monitoring process in a common everyday situation. I further examined the effects of expectation violations on the amplitudes of the event related potential components termed the error related negativity (ERN) and error positivity (Pe). In the paragraphs that follow I briefly review these components and discuss some research relevant to the current investigation.

Gehring et al. (1990) identified an event related potential (ERP) component seemingly specific to errors since similar neural activity was largely absent on correct trials. Termed the ERN, this component is a negative deflection in the electroencephalogram (EEG) data starting just prior to the erroneous motor response. This ERP component typically reaches maximum amplitude approximately 50-150 ms after an incorrect response (Hajcak, Nieuwenhuis, Ridderinkhof, & Simons, 2005), although this latency has been shown to vary depending on task and stimulus properties. The ERN has a fronto-central scalp distribution for which the anterior cingulate cortex (ACC) is thought to be the primary neural generator (Fabiani, Gratton, & Coles, 2000). Neuroimaging research has revealed two subdivisions of the ACC (Polli et al., 2005): the dorsal subdivision, believed to be associated with attention and executive functioning (Carter et al., 1998; Swick & Turken, 2002); and the rostral area, associated with autonomic arousal (Critchley et al., 2003, 2005). The ERN seems to be largely associated with the dorsal (cognitive) subdivision (Polli et al., 2005) with support coming from fMRI studies (Van Veen & Carter, 2002a) as well as BESA (van Veen & Carter, 2002b) and LORETA source analysis (Herrmann, Rommler, Ehlis, Heidrich, & Fallgatter, 2004).

Errors that occur as a result of deciding on and executing an incorrect response, deciding on the correct response but executing the incorrect response (Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996), or missing a deadline (Wiersema et al., 2005) all tend to generate an ERN. Further, this component is observed across many stimulus (i.e., auditory or visual) and response (i.e., hand, foot, or ocular) modalities. However, the vast majority of tasks employed in this avenue of research are simple and the extent to which these findings are replicable with more demanding, complex tasks is an important question.

Holroyd and Coles (2002) suggested that the amplitude of the ERN is sensitive to expectation violations. They posit that the ERN is generated when actual outcomes are worse than expected outcomes (i.e., an error instead of a correct response) and the ERN is a “reward prediction error signal” such that if a participant expects one thing and something else happens then this expectation discrepancy is manifested in an ERN. The degree of expectation violation was positively correlated with error component amplitudes such that larger violations of expectation produced ERNs with larger amplitudes. By examining the feedback ERN (fERN: an ERP component time-locked to feedback that mirrors the ERN in morphology and topography) it was shown that negative feedback resulted in a fERN. Moreover, unfavorable feedback resulted in smaller fERNs when the negative feedback was expected versus unexpected. In a related study, Holroyd, Larson, and Cohen (2004) manipulated the gain or loss of money and found that fERN amplitude was positively correlated with the degree of expectancy violation.

It is important to note that the fERN is an ERP component that is time-locked to the onset of task related feedback unlike the ERN which is time-locked to the committed erroneous response. It is suggested in this literature, however, that the ERN and fERN are indicative of the same process originating in the ACC. It follows then that the ERN should be sensitive to expectancy violations in a fashion similar to the fERN. From this it could be predicted that errors in performance resulting from large expectancy violations should lead to more negative ERN amplitudes. I manipulated participant expectations of upcoming stimuli by making responses only partially predictable. By occasionally violating these predictions, via the deletion or exchange of the last letters of to-be-typed words, I was able to compare non-expectancy related errors and errors due to expectation violations.

Another ERP correlate of error processing is the error positivity (Pe). The Pe is the first positive going wave following the ERN. It occurs approximately 100-200 ms after an error response (van Veen & Carter, 2002b) and is believed to be involved in error awareness and/or the subjective meaningfulness of the error (Hajcak, Moser, Yeung, & Simons, 2005). It has also been suggested that the ERN may be representative of the detection of an error, while the Pe represents conscious error processing and context updating (Herrmann et al., 2004; Wiersema et al., 2005). The Pe seems linked with motivation and emotion and has been localized to the rostral subdivision of the ACC (Weirsema et al, 2005; van Veen & Carter, 2002b) with a central to parietal scalp distribution. If the violation of an expectation is a negatively charged emotional event then the deviation may manifest itself in the morphology of the Pe.

Typically, experiments used to examine performance monitoring from a neurological standpoint have been simple tasks that do not mimic complex real world situations. One purpose of this experiment was to investigate error processing in a situation that is more common in everyday life than most laboratory tasks.

Using a touch typing task, expert touch typists made responses using both hands positioned for touch typing on a standard QWERTY keyboard. Word pairs were presented visually and the task was to type each letter of the second word as it appeared (see Figure 3.1 for a complete trial example). Some word pairs consisted of related words (e.g., doctor – nurse), therefore expectations as to what the second word should be were increased on a letter by letter basis. Furthermore, the second word belonged to one of three different Word Type conditions. Words were either spelled completely (nurse), incompletely (nurs), or misspelled (nursg), as can be seen in Table 1. Both Word Association and Word Type served to manipulate participant expectations of upcoming letters. The last letter presentation on associated word pair trials was expected to reveal the greatest degree of expectation violation and conversely expectation validation. That is, since associated word pairs (i.e., apple – orange) had a clear relationship the participant should be able to predict what the upcoming letter or letters should be by the end of the word. However, on trials where the last letter was replaced with a spacebar press or with a letter that did not correctly complete the word, large violations in expectation would be present. Conversely, participant expectations would be confirmed on the Complete trials where the word was spelled accurately. I hypothesized that these three Word Types would prime different types of errors (related and unrelated to expectancy) and I was interested in investigating if these errors elicited distinguishable neural patterns of activation. Specifically, I was interested in the effects of Association and Word Type on the error related negativity and error positivity.

I hypothesized that Word Association (Related, Unrelated), Word Type (Complete, Incomplete, and Misspelled), and Letter Position would affect participants' performance. Specifically, mean response time should be shorter for Related words compared to Unrelated words. On correct trials, I predicted response times to be shorter on Complete words compared to Incomplete and Misspelled words; response times on the last letter of Misspelled words would be longer than Incomplete words which in turn would be longer than Complete words. No differences were expected on error trials.

Electrophysiologically, I hypothesized a modulation of ERN amplitude as a function of Word Type and Association with the degree of expectation violation being inversely related to ERN amplitude (i.e., inversely because the ERN is negative) and positively related with Pe amplitude. As a result I predicted larger ERN and Pe amplitudes on error trials with a significant Accuracy x Word Association and Accuracy x Word Type interaction. Further, these interactions would be most profound for errors in the Last Letter Position.

Table 1: Examples of the second word in a pair as a function of Word Association (Related – Unrelated) and Word Type (Complete, Incomplete, Misspelled) given that the word DOCTOR was the first word of the pair.

	Word Type		
Word Association	Complete	Incomplete	Misspelled
Related	NURSE_	NURS_	NURSEQ_
Unrelated	APPLE_	APPL_	APPLR_

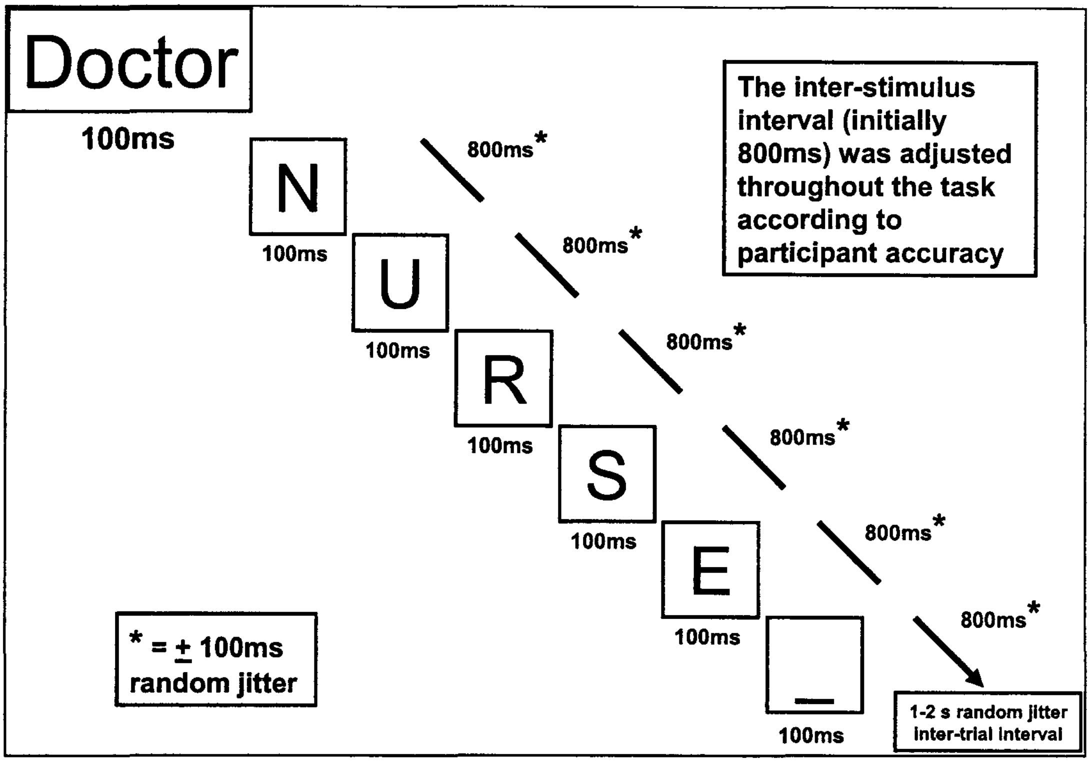

Figure 3.1: An example trial from Experiment 3. The trial shown is for a Related - Complete word condition as the word NURSE follows DOCTOR and is correctly spelled. The interstimulus interval was titrated for each participant throughout the experiment to maintain an overall accuracy rate of approximately 80%

Method

Participants

Twenty female volunteers (aged 19-33, mean = 22.7 years) from McMaster University's undergraduate psychology subject pool participated in the study for course credit or no compensation. All participants had normal or corrected-to-normal vision and were advanced to expert touch typists. Informed consent was obtained from all participants.

Apparatus and Stimuli

Stimulus presentation and manual response measurements were performed with Presentation® experimental software (Version 11.0, www.neuro-bs.com) on a Pentium 4 computer under a Windows XP Pro operating system. The stimuli were presented on a 17" CRT monitor, at a resolution of 1024x768 pixels at a frame rate of 75 Hz. The experiment was run in a dimly lit room, with a fixed chin rest which served to limit head and upper body movements. A viewing distance of approximately 80 cm was kept constant for all participants throughout the task.

The experimental stimuli consisted of 180 simple word pairs evenly divided in regards to their level of Association (i.e., 90 related/90 unrelated). Originally all 180 pairs were related but 90 were drawn randomly from the set and had their second words changed such that they were not commonly associated. Word pairs were approximately matched for word length and frequency of common usage by three independent judges. There were three types of word stimuli (i.e., Complete, Incomplete, and Misspelled) which differed in the way the last letter of the second word was presented. In Complete words the last letter of the second word in the pair was present and spelled correctly. For Incomplete words the last letter of the second word was missing. Misspelled words had the last letter of the second word replaced with a letter that did not complete an English word. Within each of the Word Type categories there were 30 associated and 30 unassociated words that were not repeated across the different conditions (see Table 1 for examples of all Word Type conditions). All trials ended with the presentation of an underscore (_) which served to indicate the end of the word/trial run and participants were asked to press the spacebar in response to this stimulus. It is important to note that the underscore took the place of the last letter in the Incomplete condition.

The experiment consisted of nine blocks of 20 trials. On each trial, the first word of the pair was presented as a whole, followed by the second word which was presented a character at a time (see Figure 3.1). The task was to type each letter of the second word as accurately but as quickly as possible when it appeared on the screen. All words appeared in white, uppercase font in the centre of a black background at a visual angle of approximately two degrees per letter. Word one was presented in the centre of the monitor for 100 ms. After an 800 ms delay (±100 ms of random jitter) presentation of the second word began. Each letter of the second word was presented for 100 ms with an original inter-stimulus interval (ISI) of 800 ±100 ms between each letter of the second word. There was a random inter-trial interval (ITI) between 1000 to 2000 ms between trials within a block. ISI was titrated throughout the task to determine the typist's ISI threshold. Initially set at 800 ms ± 100 ms of random jitter, subsequent ISIs were reduced by 50ms (i.e., 750 ± 100 ms) if the subject performed at an accuracy rate greater than 90% or increased by 50ms (i.e., 850 ± 100 ms) if accuracy was less than 80% on the preceding word pair trial. These adjustments were made continuously throughout the task to ensure that a participant's ISI was at a level ensuring the generation of a suitable number of errors while maintaining an overall accuracy rate of greater than 80%.

Task and Instructions

Prior to the experiment, all subjects completed a standard typing test to evaluate speed and accuracy of touch typing skill. Each participant completed the test twice to ensure reliability. In order to continue in the experiment participants must have been classified as an advanced typist according to their typing speed (greater than or equal to 50 words per minute) and accuracy (greater than or equal to 90% accuracy) on both tests. During the typing test, and the experiment, a cover was placed over the participant's hands and the keyboard so they were unable to look at the keys while typing. The cover did not interfere with the hand movements required for typing. By negating the ability to see the keyboard, the cover helped to limit extraneous movements that might interfere with EEG recording (i.e., watching your finger movements or making eye movements to the appropriate response letter).

Participants were told that a word would first appear on the computer screen followed by a second word presented one character at a time. Participants were instructed (see Appendix C) that their task was to type out the second word letter by letter as it appeared, being as accurate and quick as possible. Participants were not told that the words appeared in the three conditions (Complete, Incomplete, and Misspelled) although participants anecdotally reported that this became readily apparent after only a few experimental trials.

Electrophysiology

The ActiveTwo Biosemi electrode system (BioSemi, Amsterdam, the Netherlands) was used to record continuous electroencephalographic (EEG) activity from 128 Ag/AgCl scalp electrodes plus 4 additional electrodes placed at the outer canthi and just below each eye for recording of horizontal and vertical eye movements. Two additional electrodes, common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode were also used. These electrodes replace the "ground" electrodes used in conventional systems (http://www.biosemi.com/faq/cms&drl.htm). Because the BioSemi system is an active electrode system there is no conventional reference electrode; a monopolar signal is stored for each active electrode and all rereferencing is done in software after acquisition. The continuous signal was acquired with an open pass-band from DC to 150 Hz and digitized at 512 Hz.

ERP averaging and analyses were performed using EEProbe (www.ant-neuro.com) and BESA (www.besa.de) software. The continuous EEG file for each subject was digitally filtered from 0.02 to 30 Hz and re-referenced to the linked mastoids. Eye-blinks were identified and corrected using a regression algorithm procedure. Stimulus locked epochs of 1000ms included a 100ms pre-stimulus baseline and a 900ms interval post-stimulus. Response locked epochs utilized a 200ms pre-response baseline and a 900ms interval post-response.

Data for all response and stimulus locked epochs were averaged for each individual subject and were later combined to generate grand averaged waveforms for each experimental condition of interest. Although I was specifically interested in the response locked error related negativity and error positivity, I also examined stimulus locked waveforms for differences that may reflect early cognitive processing differences. The ERN was defined as the largest negative deflection occurring between -50ms and 100ms and the Pe was the first positive going wave following the ERN prior to 250ms.

Procedure

All participants were tested individually. The task was explained to participants and they were given a letter of consent to read and sign. Any questions were answered, and the participants were informed that they could discontinue participation at any time with no adverse consequences. Participants then completed the typing tests and if their performance met experimental criteria they continued in the present experiment otherwise they partook in another experiment that required no specialized skill sets.

Participants were seated directly in front of the computer monitor and standard instructions were read with the participants asked to restate the task ensuring they knew what was expected of them. Once it was clear that the task was understood, the practice phase of the task began. The practice phase consisted of 20 trials, and was completed with the experimenter present. Practice trials were excluded from further analysis and all of the practice stimuli were complete, correctly spelled words.

Upon successful completion of the practice phase, the experimenter left the room and the participant began the experiment. The experiment consisted of nine blocks with 20 trial runs per block. All trials were randomly presented. At the completion of each block participants were given a break at which point they were able to relax and make any minor motor adjustments they deemed necessary (i.e., blinks or slight movements). Participants controlled the duration of the break and were instructed to press the space key on the keyboard when they were ready to begin the next experimental block of the task. Once the experiment was completed the participants were thanked for their participation and received a written debriefing form along with a verbal explanation of the experimental purpose and hypotheses.

Data Analysis

Response time and accuracy rate analyses were calculated with a 2 (Relatedness) x 3 (Word Type) x 3 (Letter Position) repeated measures analysis of variance. Analyses of ERN and Pe components were examined separately using 2 (Accuracy) x 3 (Word Type) ANOVAs. These ERP analyses were completed on data collapsed across letter positions and again on the last letter position alone.

Results & Discussion

Behavioural

Figure 3.2 shows the means and standard errors for accuracy rates as a function of Word Type (Complete, Incomplete, Misspelled) and Letter Position (Spacebar, Last Letter, Other). In the analyses and figures, Letter Position indicates the three categories of responses. Spacebar: An underscore is presented following the last letter of the word and requires a Spacebar response; on Incomplete trials the underscore is presented sooner than expected, following the penultimate letter of the word. Last Letter: refers to the required response to press the key matching the last letter of the word. On Misspelled trials, this letter is not the expected last letter of the word. Other: refers to responses to all the other letters in the word.

The ANOVA revealed a significant accuracy main effect of Word Type, $F(2,38) = 36.37$, $p<.05$ and a significant Word Type by Letter Position interaction, $F(2, 76) = 7.76$, $p < .05$. Results showed that the manipulation of expectancy was successful; this was particularly evident in the responses to Misspelled words. Participants were less accurate when the Spacebar press was required at the end of a Misspelled word compared to the end of Complete ($t(19) = 8.33$, $p<.05$) and Incomplete words ($t(19) = 6.00$, $p<.05$). In addition, responses were less accurate for the Last Letter of Misspelled words compared to the Last Letter of Complete ($t(19) = 4.25$, $p<.05$) and Incomplete words ($t(19) = 2.98$, $p<.05$). It makes sense that there is no effect of the Word Type condition for the Other responses since those occur prior to the last letter.

Further support that participant expectations were affected by the Word Type manipulation was revealed in the response time (RT) data. Figure 3.3 shows the mean and standard errors for correct trial RTs as a function of Letter Position and Word Type. A main effect of Word Type ($F\ (2, 38) = 56.65$, $p < .05$), a main effect of Letter Position ($F\ (2, 38) = 72.71$, $p<.05$) and a significant Word Type x Letter Position interaction, $F(4,76) = 46.58$, $p < .05$, revealed that participants were significantly slower on Spacebar presses for Incomplete words compared to Complete words ($t(19) = 8.65$, $p<.05$) and Misspelled words ($t(19) = 5.31$, $p<.05$). Further, slower response to the Last Letter on Misspelled trials were observed compared to Complete ($t(19) = 8.39$, $p<.05$) and Incomplete trials ($t(19) = 10.53$, $p<.05$).

With regards to the Relatedness manipulation, it appears that participants were significantly faster for related words, $F(1,19) = 24.92$, $p < .05$ (see Figure 3.4). Furthermore, a significant Relatedness x Word Type interaction, $F(2,38) = 4.70$, $p < .05$, indicated that RT remained relatively stable across Word Types for Unrelated word pairs but differed significantly across Word Types for Related word pairs. Response times in the Complete condition were significantly faster than either the Incomplete or Misspelled conditions $t(19) = -4.51$ and -4.43, $p < .05$, respectively. These results support the hypothesis that there were expectancies generated for the second word of the associated word pairs. However, there were no interactions between Relatedness and Letter Position, suggesting that by the end of typing the second word any effect of word pair associations had dissipated.

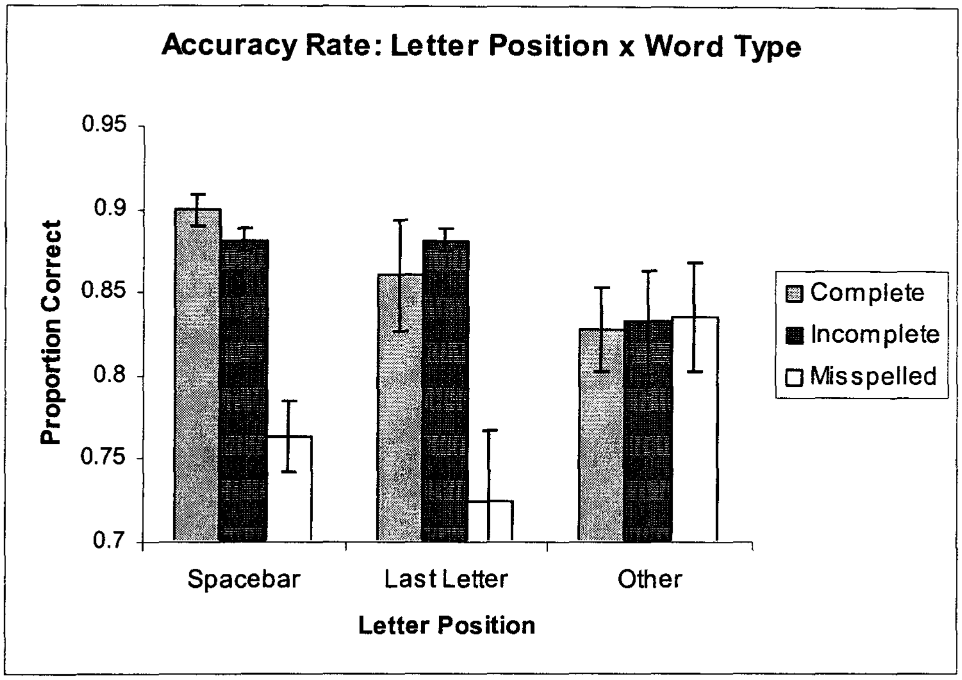

Figure 3.2: Mean accuracy rates as a function of Word Type (Complete, Incomplete, Misspelled) and Letter Position.

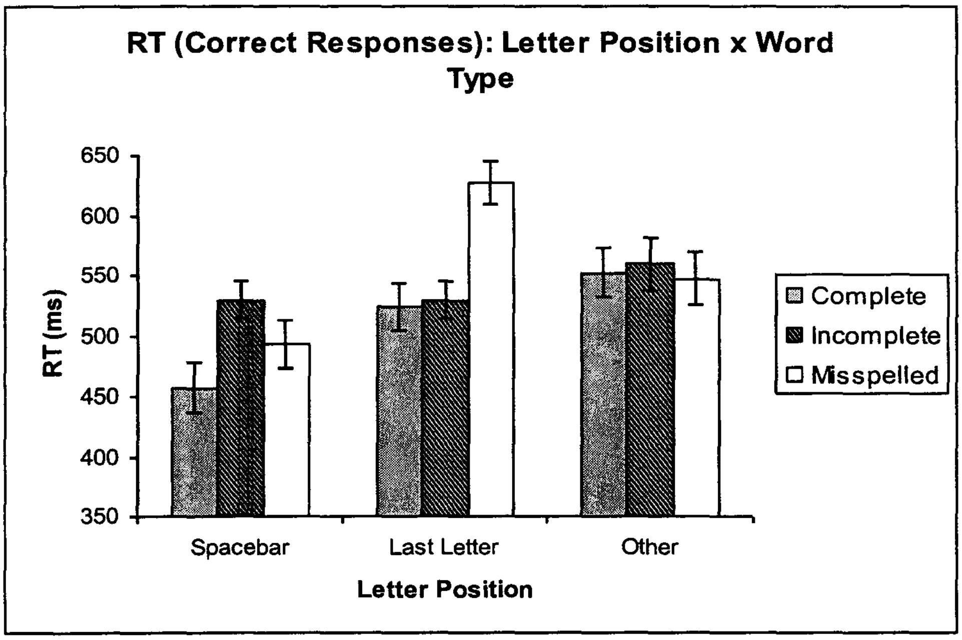

Figure 3.3: Mean response times (RT) for correct trials as a function of Word Type and Letter Position.

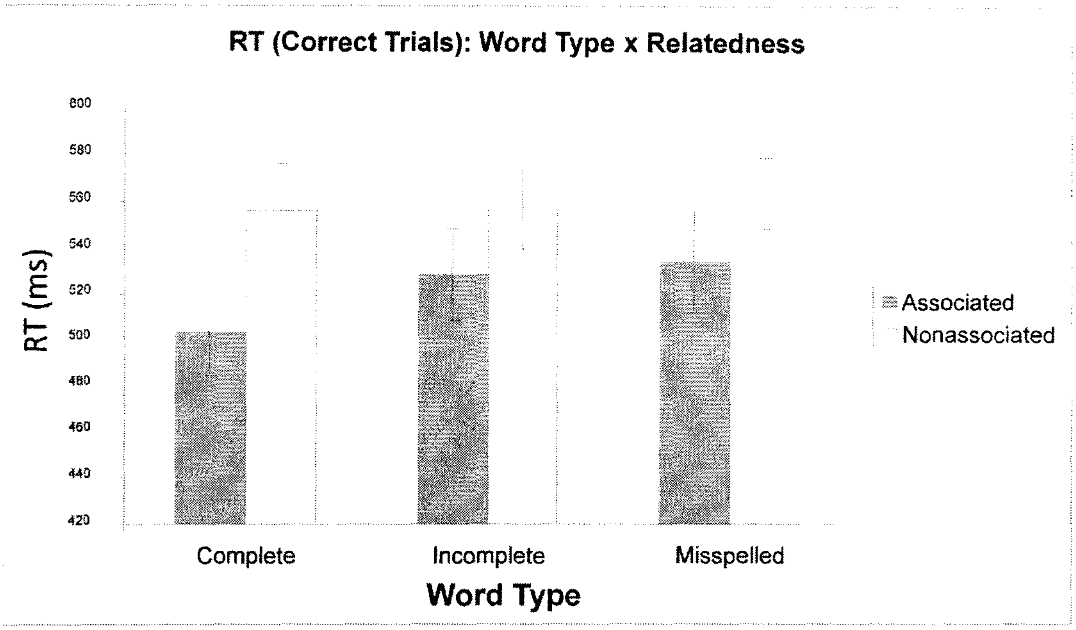

Figure 3.4: Mean response time as a function of Word Association and Word Type.

Electrophysiological

There were two main *a priori* purposes of this investigation. The first was to determine if typical ERN/PE findings (more negative ERN amplitudes and more positive Pe amplitudes on error trials compared to correct trials) would be observed in a more complex and ecologically valid task. To test this question the data was collapsed over all letter positions such that all errors committed were included in the initial set of analyses presented below. The second purpose was to determine what, if any, effects the violation of expectations would have on the ERN/PE complex. Since the expectation violation manipulation consisted of changes made to the last character of the second word, analyses pertaining to expectancy were restricted to errors made in the final letter position.

Analyses Collapsed Across All Letter Position

Results of a 2 x 2 (Accuracy x Relatedness) ANOVA revealed a significant main effect for Accuracy, $F(1,11) = 14.85$, $p < .05$ with ERN mean amplitudes being significantly more negative for error trials than correct trials (see Figure 3.5). Interestingly and in contradiction with my prediction, there were no ERN amplitude differences in terms of Relatedness.

A similar 2 x 2 ANOVA examining Pe amplitude again revealed a significant main effect for Accuracy $F(1,11) = 35.58$, $p < .05$ with significantly higher positive amplitudes on error trials compared to correct trials, but the main effect for Relatedness and the accompanying interaction were not significant. The lack of significant Relatedness effects on both ERN and Pe amplitudes is possibly suggestive of a strategy adaptation. It seems likely that participants would realize that though the words were in fact related 50% of the time, it was disadvantageous to guess what the second word would be especially at the beginning and end of the word given the nature of the task. Further, although related words were high in terms of relatedness, the degree of association would not be perfect across all individuals and words. For example, predictions for the second word of a pair following the word "apple" could just as likely be "juice" instead of "orange". Ignoring relatedness seems a good strategy for participants to adopt since the study's main manipulation dictates that the majority of attention be focused on the end of the word. Further, even if a relatedness effect existed early in the trial run it would likely have dissipated as the trial continued since participants likely had a high probability of prediction for the final letter of the words regardless of the degree of relatedness.

The waveform in Figure 3.6 is suggestive of a Word Type effect on error trials, however, ANOVAs examining ERN and Pe amplitude with Word Type and Accuracy as factors revealed no significant Word Type main effect and no significant interaction for either ERN or Pe amplitude. With that said, the observed trend is in the hypothesized direction. If the Pe is partially indicative of a violation of expectations then you would expect to see the largest Pe in the Misspelled condition followed by the Incomplete and the Complete conditions. The lack of significance is possibly due to a washout of sorts. Given the expectation manipulation occurs on the last letter alone, when collapsed across all letter positions any potential difference may be masked by the non-significant effects at other letter positions.

Analyses of Last Letter Position

As mentioned above, any effects of expectancy would largely be manifested in the Last Letter manipulation in the Misspelled or Incomplete words compared to the Complete word type condition. The manipulation in the Incomplete condition involved the removal of the last letter of the word with it being replaced with an underscore indicating a spacebar press response was required. The underscore being a non-letter was likely a highly salient stimulus. Although the word's incompleteness made the participants' task more difficult due to the violation of expectation, the underscore may have been salient enough to stop many errors from being committed. This seems likely given the accuracy and RT data mentioned previously. As a result, the comparison of Spacebar errors in the Incomplete condition to the last letter errors in the complete or misspelled conditions was problematic due to the potential for changes in processing unrelated to the manipulation of interest. Therefore, Last Letter Position analyses were restricted to errors in the complete and misspelled word type conditions. Separate repeated measures ANOVAs for ERN and Pe mean amplitudes with Word Type and Accuracy as factors revealed that, although the accuracy main effect approached significance, $F(1,11) = 4.23$, $p=.064$, in the predicted direction (i.e., errors were more negative than corrects), no significant Accuracy x Word Type interaction was observed. There was a main effect of Accuracy in regards to Pe amplitude, $F(1,11) = 7.34$, $p < .05$, again with error trials being more positive than correct trials, but there was no Word Type main effect or Word Type x Accuracy interaction. However, visual inspection of the waveforms did show the hypothesized trend. Statistically the lack of Accuracy x Word

Type interactions for ERN and Pe amplitudes suggests that the manipulation of expectancy had no significant effect on either component and in turn suggests that perhaps the ERN and Pe are not sensitive to expectation violations.

Interestingly, although not statistically significant ($p = .07$), there was a larger correct response negativity (CRN: negativity activity, similar to the ERN, observed on correct trials) on correct Last Letter Misspelled trials compared to the correct Complete Last Letter condition. This indicates that the neural response on correct trials where expectations were violated was more similar to the error trial neural response. This is suggestive of the CRN being sensitive to participant expectations.

The substitution of the last letter with a spacebar press in the incomplete condition may have resulted in the spacebar being treated differently compared to the corresponding last letters in the other conditions. Inspection of the stimulus locked waveforms for correct trials (see Figure 3.7) seemed to suggest that this was in fact the case as indicated by observable P3 differences at Pz and N1 differences at PO7. The P3 is typically generated in response to an oddball or rare stimulus which the underscore may be considered given a letter was expected. The N1 is said to be indicative of a discrimination process within the focus of attention which also seems pertinent to the spacebar condition of this task (Vogel & Luck, 2000). Repeated measures ANOVAs revealed mean amplitude differences between the late positive going waves (from 300-700 ms) across the three conditions with amplitudes for the Spacebar press in the Incomplete condition being significantly larger than the Last Letter of the Complete and Misspelled conditions, $F(2,22) = 4.87$, $p < .05$. Revealed also were significant N1 differences between the three conditions with the Incomplete Spacebar press being significantly more negative than either of the other two conditions, $F(2,22) = 3.51$, $p < .05$.

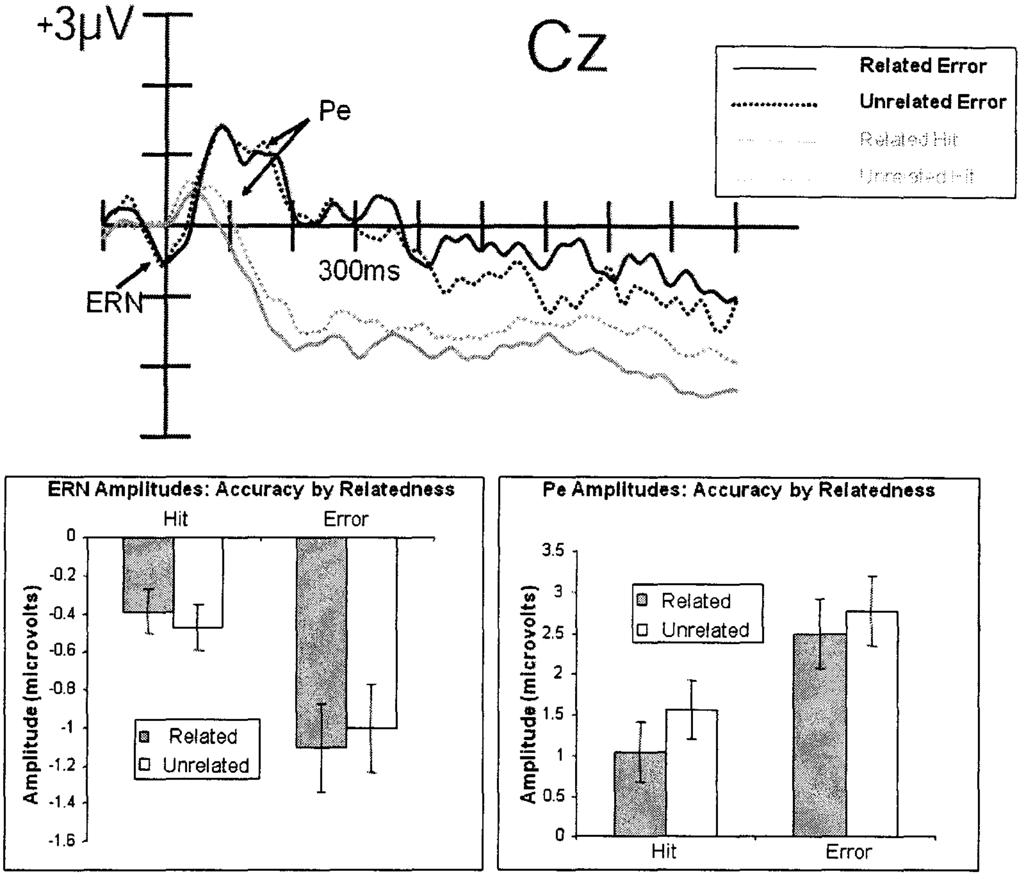

Figure 3.5: Response locked grand averaged waveforms as a function of Word Association (related, unrelated) and accuracy (hit, error). The ERN and Pe components are labeled.

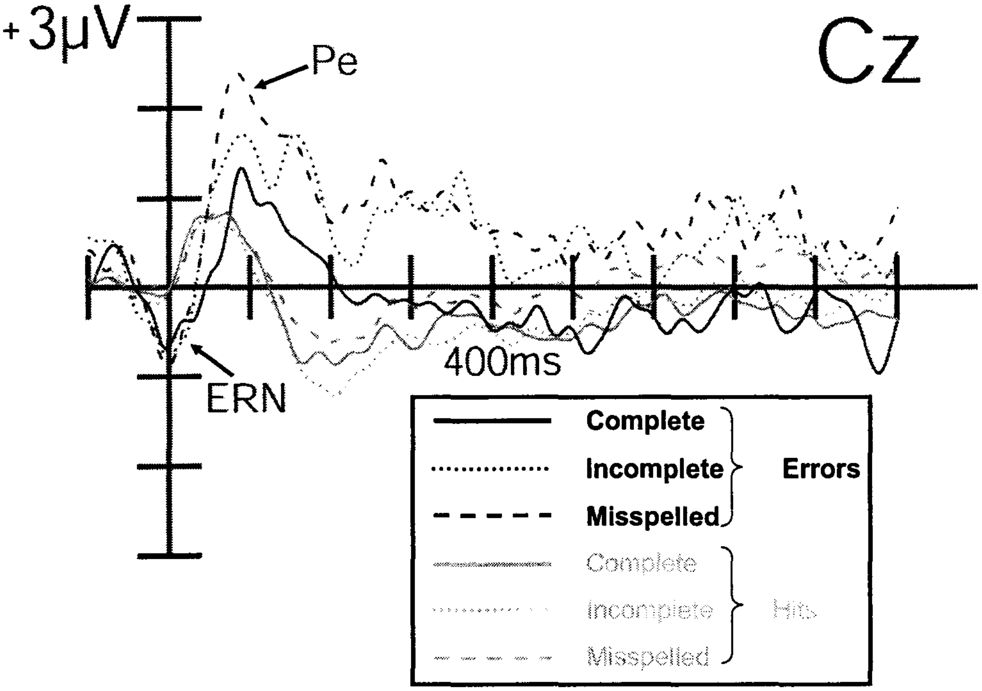

Figure 3.6: Response locked grand averaged waveforms as a function of Word Type (Complete, Incomplete, Misspelled) and Accuracy (Hit, Error)

General Discussion

The results suggest that both the ERN and Pe are largely insensitive to task driven expectation effects, in contradiction to the fERN literature. However, it appears that a good deal of the expectation manipulation, for the incomplete condition at least, manifested itself in the stimulus processing stage of the experiment and any potential response locked differences may have been obscured as a result. Further, the low error rates as a function of letter position were troublesome and without question added unwanted noise to the data.

Although there were only minor differences between word types on the error related negativity, a CRN difference was observed on trials where expectation violations were observed, with a larger CRN being generated when participant expectations were violated. This is suggestive of the CRN being sensitive to things other than strict error detection or uncertainty. However, it is also necessary to concede that participants may have subjectively experienced an error on trials when they expected a different letter although they typed the correct response. Averaging trials where this was the case with trials of 'pure' correctness could possibly also result in the observed waveform. Even then it could be argued that the change in amplitude is a result of an affective process instead of error detection. Another possibility, because participants were primed to press an expected letter, an unexpected letter provoked a higher degree of response conflict. However, it would be expected that response conflict would be manifested in the stimulus locked N2 and results indicated no sign of N2 modulation.

Although this investigation of expectancy violations and their potential role in

ERN/Pe generation revealed results that did not provide support for the experimental hypotheses, the findings are suggestive. Although it is difficult to base conclusions on null results, the fact that expectancy violations had little or no effect on the amplitudes of the ERN and Pe contradicts the results of the fERN literature (Hajcak et al., 2007). It has been largely assumed that the fERN and ERN are functionally equivalent but for this to be the case each component must be modulated in the same way by similar manipulations. Showing that the ERN is not sensitive to expectation violations suggests that these two components (ERN and FERN) may not be indicative of the same cognitive or affective processes. It is also, however, necessary to concede that the complex nature of the task may be masking any potential expectation effects on the amplitudes of the ERN and Pe. Perhaps a manipulation of stimulus probabilities would serve to enhance any expectancy violations that may occur in the present study's design. Having the Misspelled condition occur less frequently compared to the Complete word condition may serve to increase the degree of violation and in turn facilitate the observation of any electrophysiological differences that may exist.

By replicating the morphological ERN/Pe results from standard cognitive tasks, I find support for the cognitive ethology (Smilek et al., 2007; Kingstone et al., 2008) notion of using new and relatively complex tasks advantageously in the study of human cognition, in this case the study of performance monitoring. We are complex animals and we perform amazingly well in complex situations most moments of our waking lives. It seems important that research of this performance utilize appropriate techniques that reflect the rigors our performance monitoring system is usually faced with.

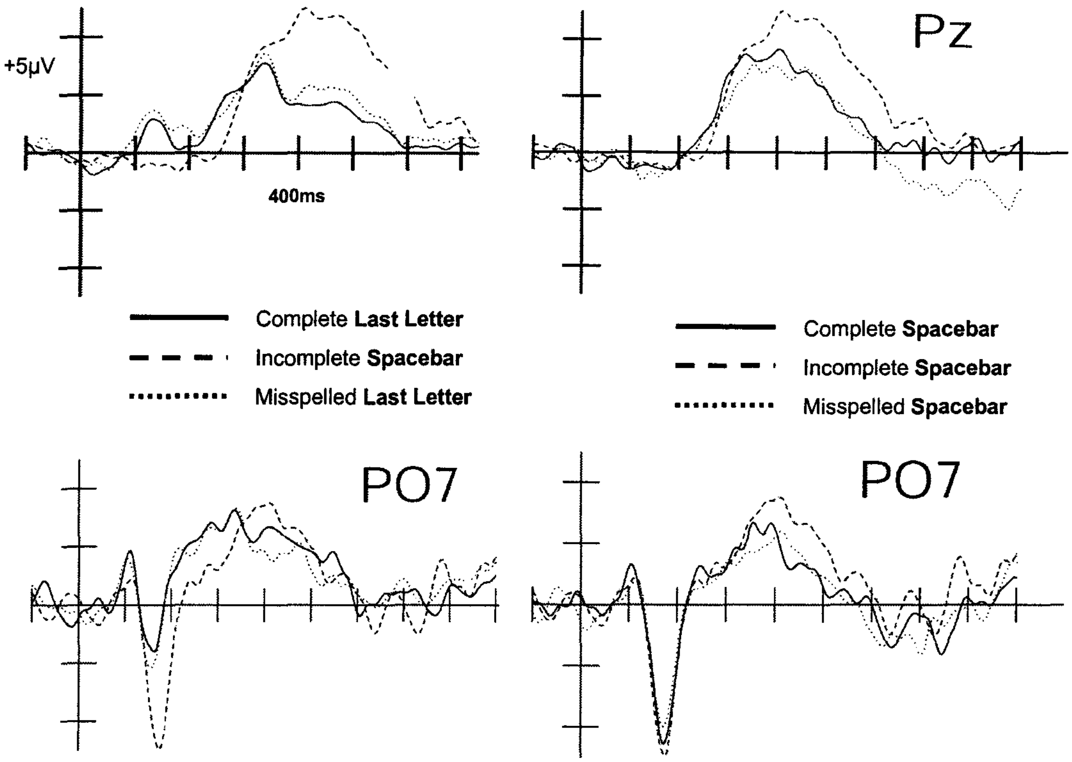

Figure 3.7: Stimulus locked grand averaged waveforms observed at Pz (top two panels) and PO7 (bottom two panels). The left side panels represent correct responses in the Last Letter position. The right side panels represent correct responses in the Spacebar position.

Chapter 4

Performance Monitoring in an Arithmetic Environment: Effects of Difficulty, Practice and Math Anxiety

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AUTHOR'S NOTE:

The experiments reported in this chapter have been written with the intention of submitting the work for publication. Therefore, the literature review in the introduction of this chapter may be somewhat repetitive with a portion of the literature review presented in Chapter 1. References are presented at the end of Chapter 5.

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Chapter 4

Performance Monitoring in an Arithmetic Environment: Effects of Difficulty, Practice and Math Anxiety

Abstract

Past research has revealed that performance monitoring, as indicated by the error related negativity (ERN) and error positivity (Pe), varies in individuals with certain clinical pathologies including generalized anxiety disorder, depression, obsessive-compulsive disorder, and schizophrenia. The present study examines a specific sub-class of the former, math anxiety. Further, this study is unique since it examines an anxious population in a *task* designed to provoke participants' specific anxieties. Specifically, high and low math-anxious individuals were examined for effects of math anxiety on performance monitoring in arithmetic situations that varied in difficulty level. Results revealed significant accuracy effects on ERN and Pe amplitude, a significant main effect of difficulty on Pe amplitude, and no significant anxiety by difficulty interaction for either ERN or Pe amplitudes. This last result is in contradiction with the generalized anxiety disorder findings but consistent with other state anxiety results. The significance of these findings is discussed in regards to the strong validity of this experimental paradigm to study performance monitoring and how the mechanisms underlying the generation of the Pe may contribute to the process of performance monitoring.

Introduction

Recently it has been demonstrated that error processing is affected by perception of error significance (Hajcak, Moser, Yeung & Simons, 2005). Using a flanker task, each trial was assigned either a high or low monetary value with the hypothesis that errors committed on high value trials would be of more personal significance compared to low value trial errors. It was hypothesized that the error related negativity (ERN) amplitude may be sensitive to the perceived significance of an error. As a result, larger ERNs on high value trials compared to low would be expected and this was indeed what the results revealed. A further manipulation investigated how the evaluation of participant performance by others would affect the amplitude of the ERN. Significantly larger ERNs were observed in conditions where participants thought their performance was being evaluated and was taken as evidence that the performance monitoring system is influenced by the perceived value of an error (Hajcak et al., 2005). In as much as the ERN/Pe complex is indicative of a learning process, this finding could equate to being unable to learn or perform in an environment that is overwhelming or stressful beyond some limit.

The ERN has also been shown to differ in amplitude based on a number of pathologies including schizophrenia, Parkinson's disease, attention deficit hyperactivity disorder (ADHD), obsessive-compulsive disorder (OCD) and generalized anxiety disorder. Most relevant to the present investigation are the latter two mentioned. According to the Diagnostic and Statistical Manual of Mental Disorders (DSM IV), OCD is defined as an intrusive disorder involving constant obsessions which cause the subject to experience a state of distress and typically require some form of corresponding compensatory behaviour. Hajcak and Simons (2002) suggested that OCD symptoms or behaviours may be attributed to a dysfunction in cognitive processing, specifically the performance monitoring system. This results in OCD individuals being unable to correctly monitor their actions and performance outcomes. It has been shown that both clinically diagnosed OCD individuals (Nieuwenhuis et al., 2005) and non-clinical individuals with OC tendencies (Hajcak & Simons, 2002) show impaired error processing on simple RT tasks compared to healthy controls. The impairment is manifested as an increase in ERN amplitude which has been hypothesized to reflect an increased significance attached to the errors in the OC groups.

The link between OCD and anxiety and other pathologies such as post-traumatic stress disorder (Rauch et al., 1996), panic disorder (Bystritsky et al., 2001), general anxiety disorder (Hajcak, McDonald & Simons, 2003) and simple phobias (Rauch et al., 1996) is well established and theories suggest that the overarching condition these disorders share is an overactive anterior cingulate cortex (ACC) (Rauch et al., 1996). It has been suggested that the increased ERN amplitude in these pathologies is not specific to the pathology but rather due to their shared co-morbidity with generalized anxiety. As recently as 2006, Ladouceur et al. reported significantly larger ERN amplitudes in children diagnosed with clinical anxiety compared to healthy age-matched counterparts. Interestingly, the ERN amplitudes elicited by the 11 year olds in this study were comparable in amplitude to that of anxious adults. This, taken with the finding that ERN amplitudes increase over maturation suggests that the impaired error processing seen in anxious adults appears to begin at a very early age and further suggests that the ERN may serve as an early warning sign of clinical anxiety.

Although the effect of clinical anxiety on ERN amplitude has been addressed, the role of non-clinical anxiety has largely been overlooked. A recent study by Moser, Hajcak and Simons (2005) examined performance monitoring in spider anxious individuals in the presence and absence of a live tarantula in the testing room. In contrast to expectations and trait anxiety literature, individuals with arachnophobia did not reveal significantly larger ERNs in response to errors in the presence of the anxiety inducing stimulus (i.e., the spider). The robust finding of an enhanced ERN amplitude on error trials in individuals diagnosed with GAD, OCD and PTSD was not replicated in this state specific anxiety situation. This state/trait differentiation merits further investigation.

One potential reason for the lack of significant ERN modulation in the arachnophobic individuals could be the lack of an anxiety provoking task. In the Moser et al. (2005) study a flanker task. The spider was either present or absent in the experimental room. Thus, the task itself did not stimulate anxiety and the spider was not relevant to task performance. The present study attempts to rectify this potential gap by examining neural correlates of performance monitoring with a task that is directly relevant to a specific anxiety.

A common and easily assessed non-clinical form of anxiety is math anxiety. Assessed using the Abbreviated Math Anxiety Scale (AMAS), in the present study I compared the performance monitoring of high and low math anxious individuals while immersed in an arithmetic task. Participants were presented with arithmetic equations that required an answer ranging from 1 to 6 with questions varying on their level of difficulty (easy, medium or difficult). By having math anxious people perform a math task I pitted the specific anxiety against an anxiety provoking task-related context which, I argue, was not accomplished in the Moser, Hajcak and Simons (2005) study.

In some experiments, observed differences in performance monitoring as reflected by neural correlates have been restricted to early portions of the experimental session. It was hypothesized that anxious and OCD individuals tended to disengage from the task over the course of the session resulting in misleading overall findings (Nieuwenhuis et al., 2005). To examine this potential compound I compared performance and EEG results across experimental halves.

Behaviourally, I expected to see no differences in accuracy between anxiety levels and no interaction between anxiety level and question difficulty. However, I did expect to find significant speed/accuracy tradeoffs with highly math anxious individuals taking significantly longer to perform at this same degree of accuracy. That is, anxious participants are expected to be more cautious in their performance and therefore spend more time on each question, especially difficult questions. In regards to the ERN, I hypothesized significantly larger amplitudes for the high math anxiety group. With no specifics concerning directionality, I also predicted a significant anxiety by difficulty interaction since it seems likely that difficulty level will influence anxiety on a trial by trial basis which may produce different responses to errors on difficult vs. easy trials. Specifics regarding the Pe based on previous literature would suggest that a larger Pe on more salient error trials would be observed (Bush et al., 2000; Falkenstein et al., 2000). In this case the most salient kind of errors would be those committed on easy trials, followed by errors on medium trials. Errors on difficult trials would be the least salient simply because it may not be clear that an error was made. However, if the Pe is largely an index of the emotional processing of errors then an interaction between Anxiety groups and Difficulty level for Pe amplitude might be expected. That is, difficult errors may produce a larger emotional response (i.e., larger Pe amplitude) in highly math anxious participants compared to low level math anxiety individuals due to an increase in the anxiety caused by the stimulus.

Method

Participants

Thirty-eight female undergraduate volunteers from McMaster University's subject pool participated for either course credit or for a small monetary compensation ($10). All participants had normal or corrected-to-normal vision and were fluent English speakers. Data from four participants were excluded from subsequent analysis, three due to EEG equipment issues and one due to unacceptably high error rate (32%),. Participants were classified as either math anxious (Anxious) or not (Control) on the basis of their scores on the Abbreviated Math Anxiety Scale (AMAS) which was administered upon completion of the experiment and will be discussed in more detail shortly.

Apparatus, Task, and Stimuli

Stimulus presentation and manual response measurements were performed with

Presentation® experimental software (Version 11.0, www.neuro-bs.com) on a Pentium 4 computer under a Windows XP Pro operating system. The stimuli were presented on a 17" CRT monitor, at a resolution of 1024x768 pixels at a frame rate of 75Hz. The experiment was run in a dimly lit room, with a fixed chin rest employed to limit head and upper body movements. A viewing distance of approximately 80cm was kept constant for all participants throughout the task.

The experimental stimuli consisted of 390 unique arithmetic questions (30 practice stimuli). Of the 360 experimental stimuli, 27 were addition problems, 235 were subtraction problems and 98 were division problems. All questions, experimental and practice, could be answered with the integers 1 – 6 with an even distribution of answers across each of the 6 integers (i.e., 60 trials / integer). The presentation order of the stimuli was randomly determined for each participant.

The problems were divided, post-hoc, into three levels of difficulty based on behavioural results. If the accuracy rate for a particular question was greater than or equal to 75% the question was considered easy; 50-74% medium; and less than 50%, difficult.

Given that six response keys were employed and that I wanted to minimize response mapping related errors, stimulus-response mapping practice was provided prior to beginning the math questions, whereby a single digit was presented on the screen and the participant was required to press the correct response key. Each of the 6 response digits (1 through 6) were presented 20 times (120 trials) and participants received feedback when they responded incorrectly. The integers 1, 2, 3, 4, 5, and 6 were represented by the keys "z", "x", "c" (left hand responses), ",", ".", and "/" (right hand responses), as illustrated in Figure 4.1.

The experiment consisted of 72 blocks of five trials. This low number of trials per block was implemented to ensure the minimization of both body and eye movements during experimental trials by providing frequent blink breaks. On each trial, the mathematical problem (e.g., "14 – 8") appeared on the screen and remained there for a random duration between 2500 and 2800 ms. Participants were instructed to respond at any time subsequent to the presentation of the stimulus but that only their first response was recorded. As in the response-mapping task, the only possible responses were integers ranging from 1 to 6. Between each stimulus presentation a fixation point was displayed (*) and remained on the screen for the duration of the inter-trial interval (400-900ms randomly jittered). An example of a trial sequence can be seen in Figure 4.1. All questions appeared in black Sans Serif font, centered on a white background and were presented at a visual angle of approximately 2° per character. Response feedback was not provided on experimental trials. At the end of each block, a "break" message was presented. The participant controlled the duration of the breaks and initiated the next block by pressing the spacebar.

The Abbreviation Math Anxiety Scale (AMAS)

The AMAS was administered to participants upon completion of the experimental trials and the scores were used to divide participants into either a low or high anxiety group. The AMAS self-report scale includes nine questions assessing how participants feel and react, with regards to anxiety, in mathematical settings (see Appendix E; Hopko, Mahadevan, Bare, & Hunt, 2003). Anxiety is rated on a 5-point Likert scale ranging from low anxiety (1) to high anxiety (5). This leads to possible scores ranging from 9-45. The original notion was to use a median split (median ~ 26) to divide the participants into low and high anxious groups but since a score of 27 could be considered a neutral score (i.e., nine selections of the 3-point) I decided to be conservative and classify only scores above 27 as highly anxious.

The AMAS scores high in terms of internal consistency (Cronbach's $\alpha = .90$) and test-retest reliability ($r = .85$), and reveals a high degree of convergent validity as indicated by its high positive correlation with the Math Anxiety Rating Scale-Revised (MARS-R; $r = .85$), and the Test Anxiety Inventory (TAI; $r = .58$).

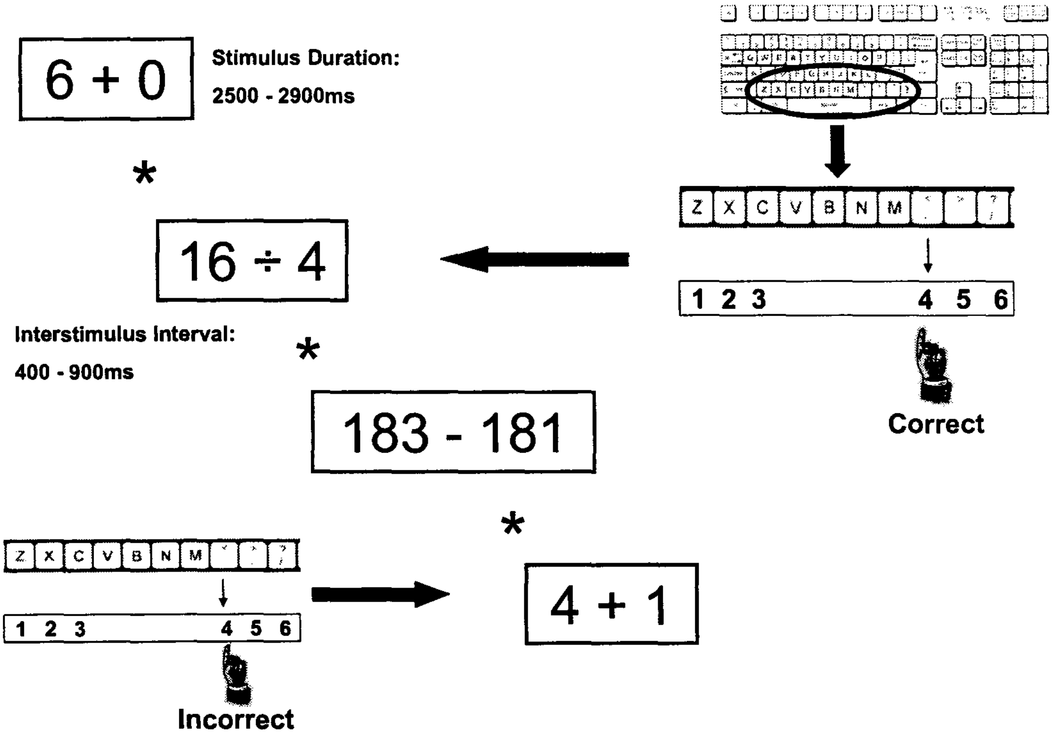


Figure 4.1: An example series of stimuli as seen by participants. On the right (middle) an example of a correct response is shown while on the bottom (left) an incorrect response is represented.

Electrophysiology

The ActiveTwo Biosemi electrode system (BioSemi, Amsterdam, the Netherlands) was used to record continuous electroencephalographic (EEG) activity from 128 Ag/AgCl scalp electrodes plus 4 additional electrodes placed at the outer canthi and just below each eye for recording of horizontal and vertical eye movements. Two additional electrodes, common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode were also used. These electrodes replace the "ground" electrodes used in conventional systems (http://www.biosemi.com/faq/cms&drl.htm). Because the BioSemi system is an active electrode system there is no conventional reference electrode; a monopolar signal is stored for each active electrode and all rereferencing is done in software after acquisition. The continuous signal was acquired with an open pass-band from DC to 150 Hz and digitized at 512 Hz.

ERP averaging and analyses were performed using EEProbe (www.ant-neuro.com) and BESA (www.besa.de) software. The continuous EEG file for each subject was digitally filtered from 0.02 to 30 Hz and re-referenced to the linked mastoids. Eye-blinks were identified and corrected using a regression algorithm procedure. Stimulus locked epochs of 1000 ms included a 100 ms pre-stimulus baseline and a 900 ms interval post-stimulus. Response locked epochs utilized a 200 ms pre-response baseline and a 900 ms interval post-response.

Data for response and stimulus locked epochs were averaged separately for each individual subject and were later combined to generate grand averaged waveforms for each experimental condition of interest. In the response-locked averages, the ERN was defined as the largest negative deflection occurring between -50ms and 100ms and the Pe was the first positive going wave following the ERN prior to 250ms.

Procedure and Instructions

All participants were tested individually. Participants were informed that they were going to participate in an EEG experiment; they were read a letter of information describing EEG procedures; and they signed a consent form. Any questions were answered, and the participants were informed that they could discontinue participation at any time with no adverse consequences. Participants were fit with an electrode cap and standard EEG protocol was followed.

Participants were seated directly in front of a computer monitor and the chin rest was adjusted to the appropriate height. Standard instructions were then read by the experimenter (see Appendix D) and participants were asked to restate the task to the experimenter ensuring they knew what was expected of them. Once it was clear the instructions were understood, the response-mapping phase began which was followed by the experiment, beginning with the 30 practice trials followed by the 360 experimental trials. Upon completion of the experimental trials the AMAS was completed. Participants were then debriefed and thanked for their participation.

Data Analysis

Accuracy was analyzed using a 2 x 2 x 3 mixed design ANOVA with a between-subject factor anxiety level (control, anxious) and within-subject factors of difficulty (easy, medium, difficult) and Experiment Half (first and last half). A similar 2 x 2 x 3 ANOVA examined response times for correct responses over the same three factors

Mean Pe amplitude and peak ERN amplitude were examined across each condition of interest using 2 x 2 x 3 mixed design ANOVAs with factors anxiety level, difficulty, and accuracy (hits, errors). For correct and error trials separately, 2 x 2 x 3 ANOVAs with anxiety level, difficulty and experiment half as factors were examined for effects on ERN and Pe amplitude.

Results & Discussion

Abbreviated Math Anxiety Scale

Scores on the AMAS ranged from 14 - 39 with an average of 26.24. Of the 34 participants included in the analyses, 17 were classified as being highly math anxious (Anxious: mean = 32.12; sd = 3.28) with the remaining classified as low math anxious (Control: mean = 20.65; sd = 3.89).

Behavioural

Stimulus categorization into easy, medium, and difficult trials was completed on the basis of accuracy rates, therefore the significant main effect of difficulty, F(2,64) = 234.03, $p < .05$, is contrived and is presented simply to show the performance differences across the three stimulus sets. As hypothesized for accuracy rates, there was no significant main effect for Anxiety level and no significant interaction of Anxiety level and Difficulty. High and low anxious individuals performed equally well across all levels of difficulty as can be seen in Figure 4.2. No accuracy differences or variable interactions were observed when performance was compared between the first and second halves of the experiment.

In regards to response time, on correct trials there was a significant main effect for difficulty, $F(2,64) = 448.93$, $p < .05$ (see Figure 4.3), but no difference between anxiety groups and no significant group by difficulty interaction. For error trials, there was a marginally significant RT difference between anxiety groups when collapsed across levels of difficulty, $t(32) = 1.71$, $p = .09$. Further, there was a significant difficulty main effect with easy trials being significantly faster than medium trials which were in turn significantly faster than difficult trials, $F(2,64) = 65.34$, $p < .05$. The interaction between anxiety level and difficulty again was not significant.

Response times changed significantly from the first to second half of the experiment with RT decreasing significantly from the first half of the experiment to the second, $F(1,30) = 22.09$, $p < .05$. Furthermore, a significant Half x Difficulty x Anxiety Level interaction was observed, $F(2,60) = 5.65$, $p < .05$. This interaction resulted from a significant decrease in RT for anxious participants on difficult questions in the second half of the experiment as can be seen in Figure 4.4. Although accuracy did improve from the first to the second half of the experiment, this improvement was not significant $F(1,30) = 2.15$, $p = .15$.

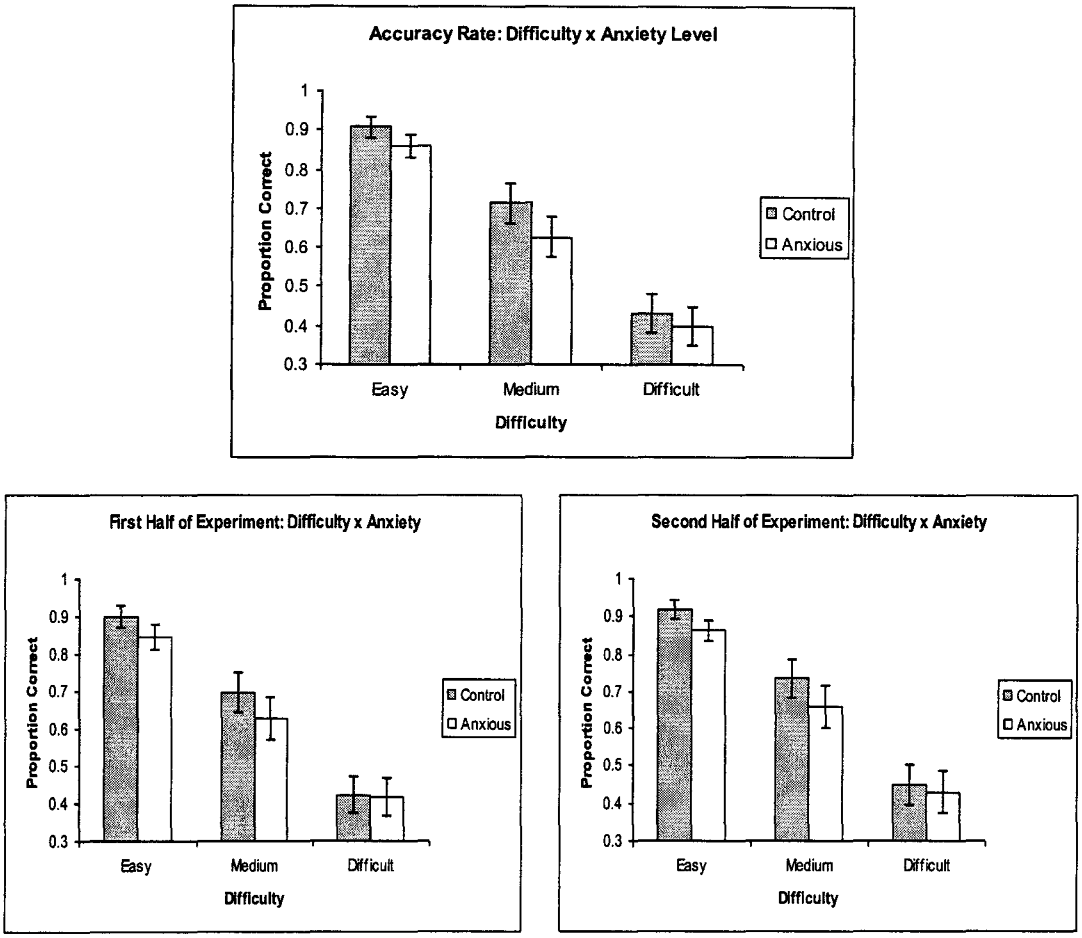


Figure 4.2: Mean accuracy rates as a function of Group (Control, Anxious) and Difficulty Level (Easy, Medium, Difficult). The top figure shows data collapsed across both halves of the experiment while the bottom two panels indicate accuracy rates for the first half (Left panel) and second half (Right panel) of the experiment.

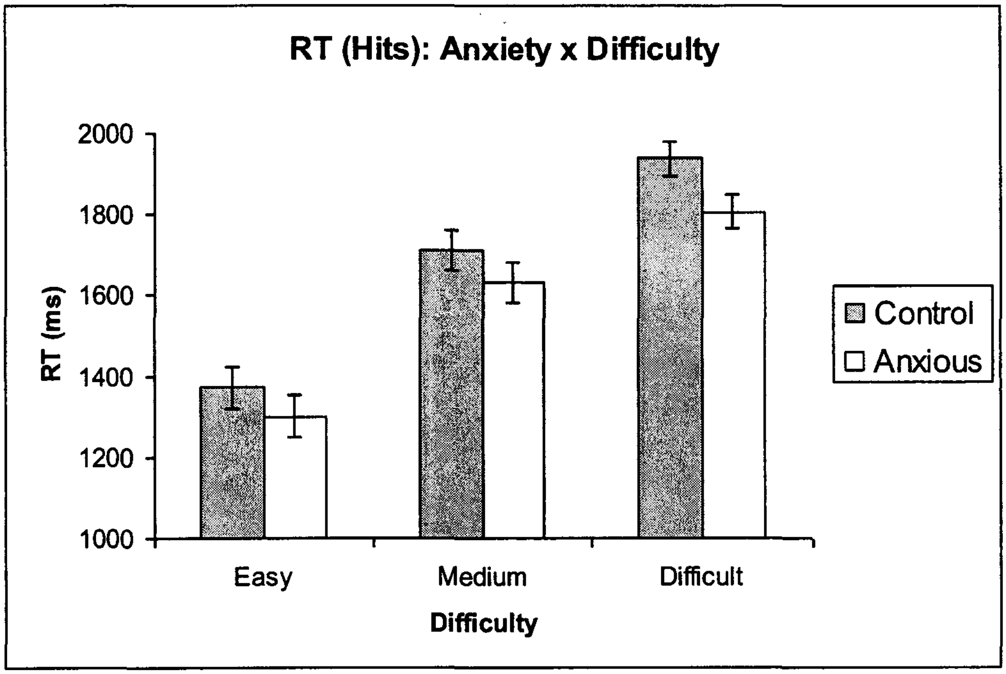
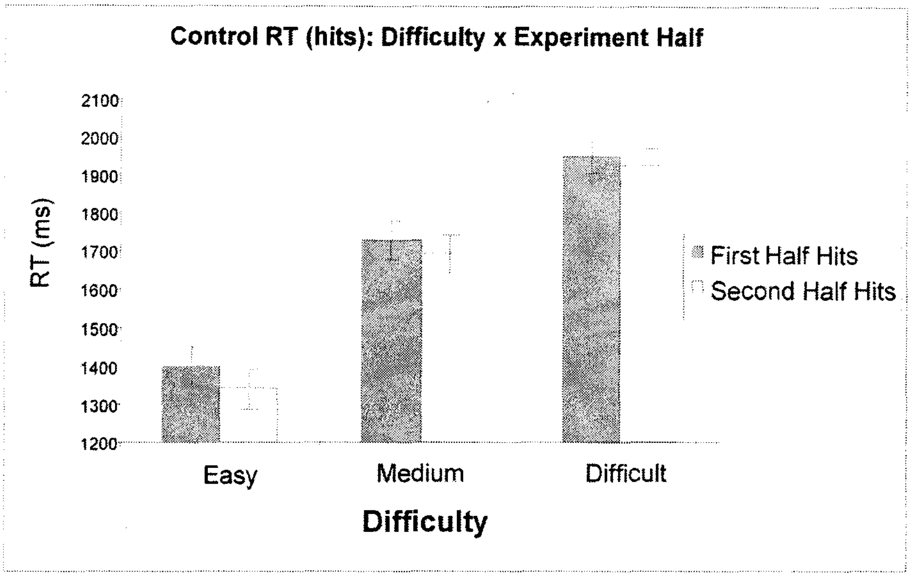


Figure 4.3: Mean response time for correct trials as a function of Group (Control, Anxious) and Difficulty Level (Easy, Medium, Difficult)



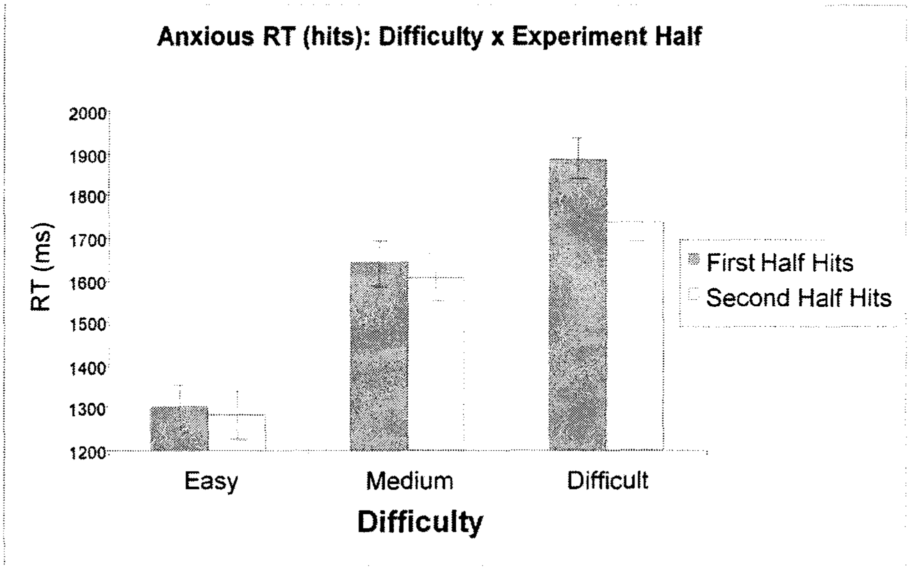


Figure 4.4: Mean response times for math-anxious participants (bottom) and control participants (top) on correct trials as a function of difficulty and experimental half.

Electrophysiological

With regards to ERN peak amplitudes, correct trials were significantly less negative than error trials (F(1, 29) = 19.53, $p < .05$) which suggests that the task, although new and complex compared to most, yielded findings consistent with previous ERP performance monitoring research. No significant differences in amplitude were observed across the three levels of difficulty or between anxiety groups and no interactions between the variables were significant. Contrary to expectations, level of anxiety and level of difficulty had no influence on performance monitoring as indicated by ERN amplitude. There were also no significant latency shifts across conditions for ERN peak amplitude.

For the high math anxious participants (see Figure 4.5), mean Pe amplitude was significantly more positive for error trials compared to correct trials as indexed by a significant Accuracy main effect, F(1,14) = 5.06, $p < .05$. This same effect was not observed in the control individuals, F(1,16) = 2.25, $p > .05$. Similarly, a significant effect was seen across levels of difficulty for the high math anxious group, F(2,28) = 3.35, $p < .05$, but the same effect was not observed in the control group, F(2,32) = .034, $p > .05$. The amplitude of the Pe was differentially affected by state anxiety levels and degree of difficulty levels.

Looking at the waveforms across experiment half revealed no significant differences for either error trials (ERN) or correct trials (CRN). However with regards to mean Pe amplitude on error trials, there was a significant interaction between Anxiety Level and Experiment Half, F(1,30) = 5.06, $p < .05$, with anxious participants eliciting a significantly higher Pe in the first half of the experiment compared to controls and a marginally lower Pe than control subjects in the second half of the experiment (see Figure 4.6).

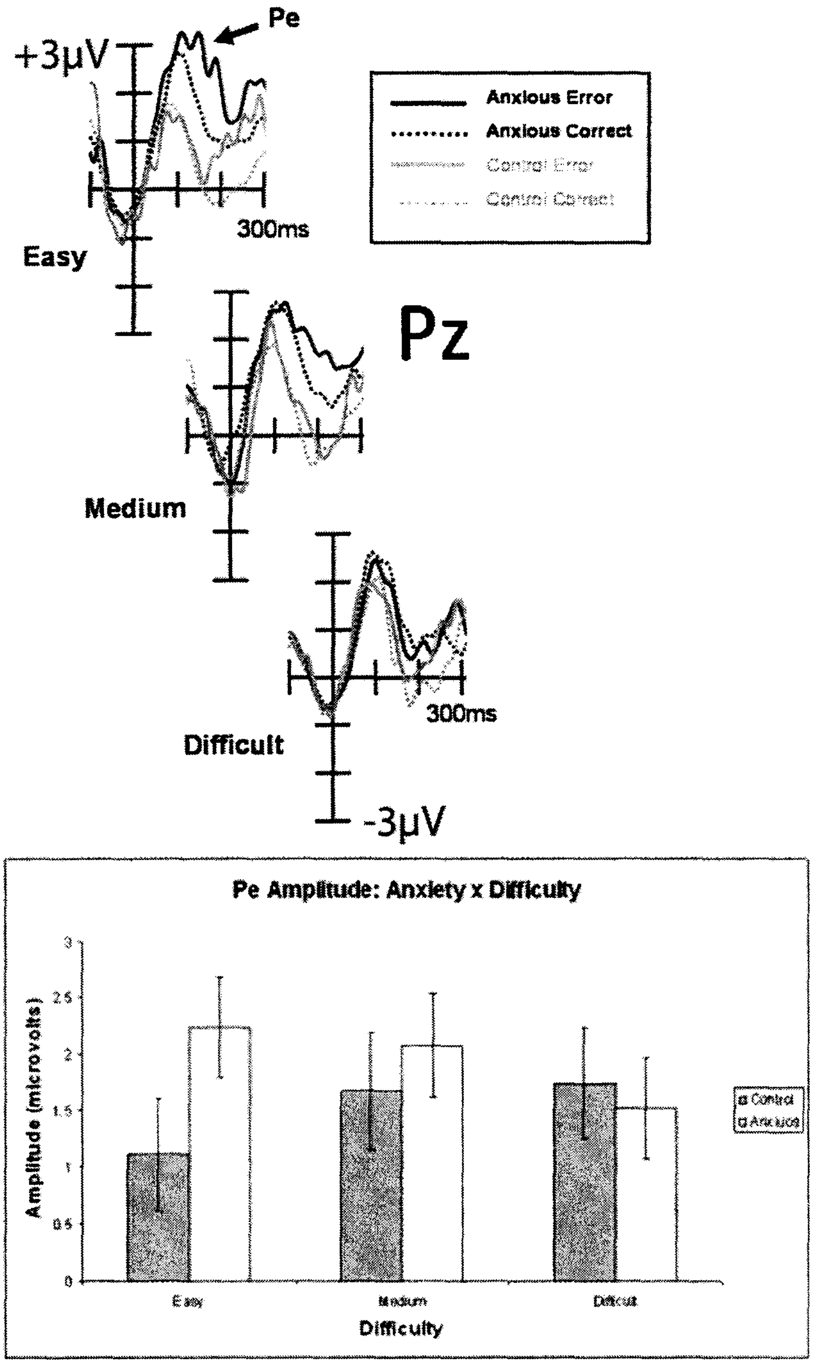


Figure 4.5: Waveform represents mean Pe amplitude for math anxious and control groups as a function of accuracy and difficulty.

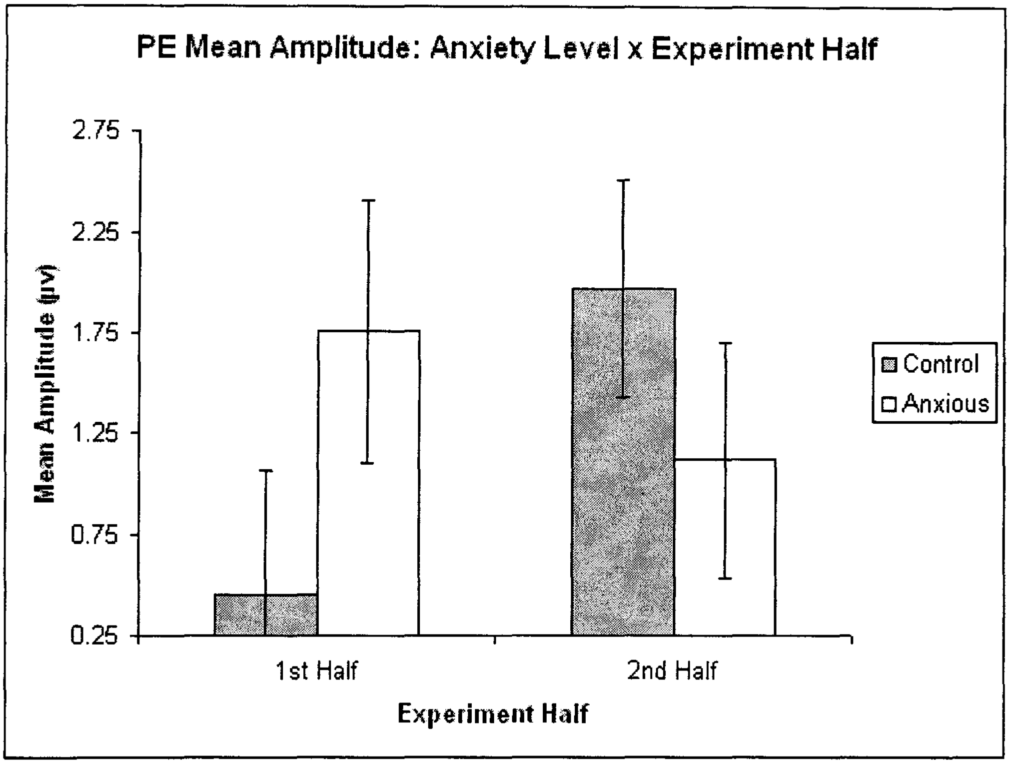


Figure 4.6: Mean amplitude of error positivity (Pe) for control (grey) and math anxious (white) as a function of experiment half.

Discussion

This experiment compared math anxious individuals and controls for differences in performance monitoring and response to errors as they performed a series of arithmetic tasks. Consistent with previous research was the finding that errors produced a large ERN. This finding validates the methodology and further demonstrates that performance monitoring research may benefit from examining tasks that more closely mimic real world performance. In particular, my observations at the Pe (error positivity) are a novel and potentially important contribution to understanding individual differences in the performance monitoring literature.

Interestingly, some of the results of the present study are not consistent with previous findings or experimental hypotheses. In the present study it was hypothesized that math anxious individuals would generate significantly larger ERNs compared to controls. This would have been consistent with obsessive compulsive disorder (OCD), generalized anxiety disorder (GAD), and other special population research However, I found that there was no significant difference between math anxious and control individuals in regards to the amplitude of the ERN. Although inconsistent with the studies mentioned, the result does parallel the findings from Moser et al. (2005) who found that induced fear had no effect on the ERN of state anxious participants. Together, these and my own findings support the notion that specific state anxieties do not influence ERN amplitudes in the same way that generalized trait anxiety does. Possibly the constant heightened state of an individual with GAD or OCD is necessary to generate this monitoring difference reflected in ERN amplitude changes. The constant vigilance involved in both of these disorders could lead to a learned overall performance monitoring strategy different from that of the general population or individuals with specific anxieties. Generalized anxiety disorder involves a day-to-day heightened state of anxiety which may be necessary to produce the changes in ERN amplitude that are observed in trait anxious individuals. State anxieties by definition are context specific and therefore occur relatively infrequently. This might suggest that the observed ERN differences in GAD and OCD are a result of the time exposed to high levels of anxiety. It would be interesting to see if the GAD and OCD findings can be replicated in a long running, multisession experiment where it may be possible to mimic the anxiety exposure seen in individuals with generalized anxiety disorder.

Also contrary to expectation, there were no ERN differences as a function of difficulty level. If error saliency was a driving force behind ERN generation then one would likely predict that errors on easy trials would lead to an increase in ERN amplitude, similar to the finding that errors on high reward trials lead to larger ERNs. That is, if you are asked to find a simple sum of 3 plus 1 and you mistakenly provide "2" as the answer then that would be an obvious and meaningful error and should be reflected in morphology of the ERN. Interestingly in the present study I found no differences, behaviorally or electrophysiologically, between errors made on easy, medium or difficult math problems in either math anxious or control individuals. This is difficult to explain if error saliency is an important modulator of the ERN unless the potential cognitive strategy involved in performing the present task is considered. Anecdotally reported by participants and perhaps obviously, the safest strategy may not be the most efficient.

Since all stimuli were randomly presented the participants had no prior knowledge of the difficulty level of the upcoming stimulus. Once it became apparent to the participants that some of the problems were more difficult than others it became necessary to perform the arithmetic function as it appeared without relying on any kind of previously learned memorizations. That is, knowing that $1 + 1 = 2$ is likely a one step process involving little cognitive effort. Since the correct answer can be summoned from memory easily and quickly, it seems likely that early on in the experimental trials participants relied on pre-learned associations. However, for the more difficult trials (e.g., $180 \div 30$ or $84 \div 21$), retrieving the answer from memory was no longer the most efficient strategy. Therefore, rather than switching between different strategies participants may have opted to use the same strategy for all trials, that is, performing the required mathematical action as opposed to using rote memory. This would lead to all stimuli being treated more equally than would have been expected and therefore any errors would be largely similar in regards to their level of saliency. It is also possible that at as the level of difficulty increases the ACC is being influenced by separate constructs both of which manifest in an increase in ERN amplitude. At an Easy level of difficulty the saliency of the error may be responsible for generating the ERN and although this saliency effect may dissipate as difficulty level increases the cognitive demand necessary to complete this task also increases, potentially confounding the task difficulty comparison. Since both error saliency and cognitive demand have been shown to contribute to ACC activation, the lack of significant ERN amplitude differences as a function of task difficulty may be a direct result of these separate processes.

Although the ERN findings of this study are largely inconsistent with trait anxiety disorders, they are consistent with state anxiety findings. However, the present state anxiety manipulation did lead to marked error positivity (Pe) differences with regards to the difficulty levels. The finding that there was a significantly larger Pe for errors in the anxious group compared to the control group, and that these differences were modulated by task difficulty is suggestive of the Pe playing a different role than that of the ERN in the performance monitoring process. It is in this component that the error saliency may be reflected in this specialized anxiety population. With only the math anxious individuals showing a larger Pe for error trials and the difference being largest in the easy conditions, it appears that the processing reflected in the generation of the Pe component is sensitive to state anxiety levels and therefore may be in part responsible for the generation or maintenance of the anxiety.

Further, the Pe was larger in the first half of the experiment compared to the second half for the math anxious participants. This latter finding points to one of at least two possibilities. First, the math anxious individuals may have experienced higher levels of state anxiety early in the experiment and this heightened level was reflected in the Pe error amplitudes in the first half of the experiment. The dampening down of Pe amplitudes to control group levels and below as the experiment progressed may be indicative of some sort of admission of defeat (i.e., I just cannot get these questions right so I'm going to be less anxious about it) or a loss of personal meaningfulness (i.e., I just do not care anymore if I get them right or wrong) attached to the errors. Secondly, the lowering of Pe amplitudes could be the result of a learning process. That is, the participants may have learned either how to do the problems efficiently or well enough that they felt more confident which led to the decrease in Pe amplitude from the first to the second half of the experiment. If this latter point is the case then the mere exposure of a participant to their anxiety seems to have a therapeutic effect, at least neurologically. It would be interesting to extend this research to examine to what degree, if at all, the reduced Pe amplitudes are permanent. Having participants participate in multiple experiments over a period of days or months would help to determine if exposure is enough to change the neurophysiological response to a state anxiety and if so, how much exposure is necessary.

In summary, the results of this study provide further evidence that state anxiety levels (e.g., math anxiety, phobias) do not modulate the error related negativity in the absence of trait anxiety (e.g., generalized anxiety disorder) making trait anxiety and trait co-morbid factors important considerations for performance monitoring theories and models. However, the processes involved in generating an error positivity seem to be important for error processing in state-anxious populations. The neural activity associated with the Pe seems to be increased in response to specific stressors, task difficulty and, potentially, error saliency. Further examination as to what stressors in which populations can modulate the Pe would be beneficial. Understanding the functional significance of the Pe may also increase the understanding of how state specific anxieties and potentially phobias manifest themselves neurologically. This in turn may lead to advances in the way such anxieties are treated. Finally, I have again shown that the use of more ecologically valid, or at the very least, more complex tasks are justified in the study of performance/error monitoring and the use of such tasks can help to advance our understanding of human cognition.

Chapter 5

General Discussion and Conclusions

The four experiments presented in this thesis represent a body of work designed to examine several variables affecting the performance monitoring system. These ERP investigations examined modulations of the error related negativity (ERN), correct response negativity (CRN) and the error positivity (Pe) resultant from manipulations of (1) stimulus and response uncertainty, (2) participant expectancies, (3) task difficulty, and (4) state anxiety.

I used novel experimental designs that arguably represent the most ecologically valid investigation to date of the aforementioned neural correlates of performance monitoring. As is evident in the list of studies presented in Appendix A, previous ERN investigations have largely used simple tasks that typically generate errors by presenting a task relevant target stimulus amongst other task irrelevant stimuli. For example researchers have used Flanker tasks (Carbonnell & Falkenstein, 2006; deBruijn et al., 2006; Dikman et al., 2000; Gehring et al., 1993); Hajcak et al., 2005; Ladouceur et al., 2006; Luu et al., 2000; Maier et al., 2008; Ridderinkhof et al., 2002; Schrijvers et al., 2009;), Stroop tasks (Christ et al., 2000; Gehring et al., 2000; Hajcak et al., 2003; Liotti et al., 2000; Masaki et al., 2001), Go/No-Go tasks (Bates et al., 2002; Falkenstein et al., 2000; O'Connell et al., 2007; Scheffers et al., 1996; Shalgi et al., 2009; Stahl & Gibbons, 2007; Wiersema et al., 2005), and other laboratory tasks (Antisaccade: Endrass et al., 2007; Gambling: Holroyd et al., 2006; Mental Rotation: Band et al., 2000; Parity

Judgments: Dehaene et al., 1994; Picture Naming: Ganushchak et al., 2008) to study error processing. For my research, an important feature of these tasks is that they use simple designs that work well in the laboratory to provide the controlled conditions necessary for their focused research questions. However, my interest in this thesis has been to test the generalizability of the ERN and Pe by attempting to reproduce standard error-related components in unique tasks and, more importantly, to begin to add aspects of the real world to investigations of the ERN and Pe. The general robustness of the ERN was addressed in Chapter 2 which presented Experiments 1 and 2. These two experiments replicated and extended previous work addressing the role of stimulus uncertainty, response uncertainty, and attentional load on ERN and CRN amplitudes using tasks and stimuli that have not previously been used to study the ERN. Extending performance monitoring investigations to more closely resemble situations we may encounter in the real world was addressed in Chapters 3 and 4 which presented Experiments 3 and 4. Chapter 3 examined errors due to expectation violation in a touch typing task while Chapter 4 examined how state anxiety and task difficulty levels influenced error processing in a mental arithmetic task. In the upcoming sections I will discuss each of the individual experiments in the context of previous literature relevant to the manipulations of interest.

Stimulus and Response Uncertainty

Aron, Shohamy, Myers, Gluck, and Poldrack (2004) provided fMRI evidence that the activity in the ACC can be modulated by the presence of uncertainty. In a classification learning task participants were asked to predict one of two possible outcomes on each trial. Outcome probabilities were manipulated across 14 levels from .14 to .94 with .50 representing the highest level of prediction uncertainty. A strong positive correlation was observed between ACC activity and uncertainty. This suggested that the ACC, among other regions, was activated to a greater extent in the presence of a stimulus that led to a high degree of decision uncertainty.

A similar question was asked in a number of related experiments conducted by Pailing and Segalowitz (2004) when they investigated the role of both stimulus and response uncertainty on ERN and CRN amplitudes. Aron et al. (2004) did not look at the difference between correct and incorrect responses whereas Pailing and Segalowitz (2004) were able to analyze both ERNs and CRNs which likely represent ACC activity on both error trials and correct trials.

Pailing and Segalowitz (2004) performed two experiments assessing the role of uncertainty in performance monitoring due to attentional demand and stimulus discriminability manipulations. In the first experiment they hypothesized that there would be uncertainty effects on the ERN and CRN due to differences in attentional demand which they manipulate in two ways. They contrasted two different tasks (flanker task vs. letter discrimination cue task) and hypothesized that the letter discrimination cue task was more demanding than the flanker task. In the flanker task participants made a key press that corresponded to the central letter of a stimulus array (i.e., SSHSS: correct response is H). The letter discrimination cue task involved the selection of a single, previously cued letter from a pair of letters. In addition, they manipulated uncertainty within both of these tasks by comparing single task performance with dual task performance. In both cases the dual task required listening to a stream of numbers and providing a verbal response when three odd numbers were presented in a row. This second task was meant to serve as a distractor and increase the attentional demand placed on the subject as they completed the primary tasks. They made two predictions about uncertainty effects on the ERN and CRN. They expected that the dual task condition would result in ERNs and CRNs that were similar in amplitude due to uncertainty about performance accuracy. Results supported this hypothesis with larger ERNs than CRNs in the single task condition and equal ERN and CRN amplitudes in the dual task condition. The heightened uncertainty led to correct and incorrect trials being processed in similar ways, possibly because they were more difficult to distinguish.

Their second prediction was that the cue task would be more sensitive to attentional demands than the flanker task because of the extra memory load of the cue and would therefore show greater uncertainty effects. This hypothesis was not supported. It was suggested that this result was possibly due to insufficient differences in the attentional manipulation across the tasks. That is, the interaction between the attentional load manipulation and task type was not powerful enough to reveal potential CRN differences between the flanker and the cue tasks. Experiments 1 and 2 presented in Chapter 2 of this thesis were designed in part to re-address this unsupported hypothesis.

Pailing and Segalowitz's (2004) second experiment varied uncertainty levels by varying the perceptual information available in a tone-duration task. Participants were asked to determine if a tone's duration was either long or short in easy (100 ms tone vs

150 ms tone) and difficult (100 ms tone vs 125 ms tone) conditions. While ERN amplitudes were larger than CRN amplitudes in the easy condition, they were approximately equal in the difficult perceptual condition. This suggested that uncertainty generated by making binary decision stimuli more similar in an auditory context leads to correct and incorrect trials being processed similarly by the performance monitoring system.

There is evidence for both overlapping neural activation and distinct neural activation (Crottaz-Herbette & Menon, 2006) during auditory and visual attention tasks. Additionally, different ACC activation patterns between auditory and visual attention tasks have been observed (Kawashima et al., 1999). Pailing and Segalowitz's (2004) stimulus uncertainty manipulation (i.e., uncertainty driven by perceptual properties of the stimulus) used an auditory task, and it is unknown if these results extend to visual uncertainty manipulations. Therefore, a second purpose of Experiments 1 and 2 was to examine the effect of stimulus uncertainty in a visual domain.

The tasks employed by the two initial experiments also served to accomplish a third purpose that is perhaps the most important to this thesis - to extend the neural investigation of performance monitoring literature using more complex tasks. As mentioned earlier in this thesis, the vast majority of research in this field uses tasks which generate errors by asking participants to attend to a task relevant target while ignoring task irrelevant dimensions of the stimulus. Experiment 1 instead asks participants to attend to both dimensions of the stimulus making any committed errors independent of a competing stimulus property. The replication of previous findings using this atypical task would help pave the road for additional investigations using increases in task complexity.

To reiterate, Experiments 1 and 2, by manipulating the visibility of the stimulus properties, allowed me to examine the previously unknown role of visual uncertainty on the ERN and CRN components; to assess the effect of uncertainty due to attentional demand levels on performance monitoring via inter-experiment comparisons; and to validate the use of new, more complex tasks to study performance monitoring by replicating standard performance findings in this novel, somewhat more complex task. I will compare the two experiments starting with a reminder of Experiment 2.

Experiment 2 used a standard global/local task to reveal no simple effect of visual noise on the ERN although there was a significant interaction between noise and congruency. This interaction resulted from a reversal of ERN amplitude from low noise to high noise on congruent error trials compared to ERN amplitude across noise levels for incongruent trials. That is, on incongruent error trials ERN amplitudes decreased as stimulus uncertainty increased as expected. However, on congruent error trials ERN amplitudes increased as stimulus uncertainty levels increased. Pailing and Segalowitz (2004) restricted their analyses to incongruent trials; the pattern of results observed on incongruent trials in Experiment 2 is consistent with their observations. However, the opposite trend elicited on congruent error trials suggests that response uncertainty effects may be strategy dependent. As mentioned in Chapter 2, the most likely strategy employed by participants was to maintain a high attentional state in order to deal with the high noise trials that appeared randomly over 1/3 of the trials. When a low noise trial occurs, a high degree of attentional allocation towards extraction of local stimulus features in noise could lead to the powerful extraction of both stimulus features. Error responses driven by the extracted global feature may be more salient because the error is driven by dominant (global vs local), easily available, but misleading information. In contrast, errors on low-noise congruent trials may be subjectively less salient, with no obvious source of having been misled through overinvestment in the task.

Importantly however, a difference in ERN amplitude patterns observed between experiments supports that the task was driving the observed congruency by noise level interaction. In Experiment 1 participants were asked to make a S*ame/Different* judgment by comparing the two stimulus dimensions. As such, incongruent and congruent trials are processed similarly since both aspects of the stimulus were made task relevant. As can be seen in the left panel of Figure 2.7, the lack of a congruency main effect or congruency by noise interaction suggests this was the case. In contrast to Experiment 1, in Experiment 2 the congruency property of the stimulus becomes a factor in the decision process since only one stimulus dimension is task relevant in the *Identify Local* task. This is supported by the significant congruency by noise interaction seen in the right panel of Figure 2.7. The presence of opposite ERN amplitude patterns for incongruent (i.e., amplitude decreases as noise level increases) and congruent (i.e., amplitude increases as noise level increases) indicates that stimulus uncertainty (i.e., noise level) and response uncertainty (i.e., congruency level) interact and differentially effect the ERN.

Although in both experiments I found no CRN amplitude modulations as a function of stimulus uncertainty levels, my between experiment comparisons revealed significantly higher CRN amplitudes in the more attention demanding task of Experiment

1. This supports the previously unsubstantiated suggestion of Pailing and Segalowitz that the amplitude of the CRN should increase in response to increased levels of uncertainty (e.g., uncertainty about whether an error was made). If the CRN is indicative of correct trials that are subjectively viewed as being errorful then an ERN-like component should be observed on correct trials that are misperceived as errorful. Compared to the *Identify Local* task of Experiment 1, the *Same/Different* task of Experiment 2 was much more demanding as was indicated behaviourally by the increased reaction times and error rates. As a result of this increase in attentional demand, some number of correct trials would have been interpreted as incorrect and the resultant average of these trials with the 'pure' correct trials would result in the observed waveforms. It seems that the null result observed in the Pailing and Segalowitz (2004) study was possibly due to their manipulation not being powerful enough, as they suggested.

Over and above the replication and extension of previous literature, the results from Experiments 1 and 2 supported my contention that different and more complex tasks can be validly used to examine the neural correlates of performance monitoring. Larger ERN and Pe components on error trials compared to correct trials were observed in keeping with the majority of previous research. Furthermore, by replicating some of the results of Pailing and Segalowitz (2004) (i.e., larger CRNs on uncertain trials) and showing support for an attentional demand effect on ERN/CRN amplitudes I have shown the importance and usefulness of an overall increase in task complexity in ERP investigations of the performance monitoring system.

Importantly, these experiments supported the notion that uncertainty influences the performance monitoring system by affecting processing on *both* error and correct trials. Furthermore and importantly, the effect of this uncertainty is task dependent which again suggests that it is important to consider context when investigating performance monitoring as the neural response may change from one situation to another.

Expectation Violations

The majority of existing literature concerning the role of expectation violations on error-related ERP components does not strictly examine the ERN. Rather these studies focus on the fERN (feedback error related negativity) and typically utilize positive or negative feedback which is either consistent or inconsistent with participant expectations (Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003; Holroyd, Larsen, & Cohen, 2004). Using simple gambling tasks, the participants are asked to choose one of a number of potential options (i.e., prizes behind doors). Each of these options has 'hidden' behind it either a win, lose or draw outcome which is revealed (i.e., feedback about response) to the participants upon their selection and the fERN is the average of EEG recordings timelocked to this feedback. However, the probability of these outcomes is manipulated such that participants may come to expect a win or expect a loss. Results typically reveal larger fERNs to feedback that is inconsistent with participant expectations, more so on negative feedback trials, and thereby representative of a 'worse than expected result' (Holroyd & Coles, 2002; Cohen, Elger & Ranganath, 2007).

Based largely on topographical ERN similarities and similar patterns of ACC activation, the fERN is thought to be an ERN generated in response to feedback.

However these similarities are only suggestive at best as the ACC has been shown to be activated in a variety of tasks assessing different variables. Further, equating the ERN and fERN on the basis of waveform topography and EEG source analysis is potentially problematic since different dipole patterns can result in identical EEG data. Therefore the relationship of the fERN to the ERN is not well established. To the best of my knowledge there are no studies that have examined how expectation violations directly influence the ERN which makes our third experiment an important starting point for this avenue of investigation.

In Experiment 3 I manipulated expert touch typists' expectations in a touch typing task. As was explained in detail in Chapter 3, by presenting the second word of a word pair a letter at a time I was able to support or violate participant expectancies at the final letter position by either presenting a letter that completed or did not complete a word (refer to Table 1 for examples of word pairs and conditions). Behaviourally, I clearly established that there was an expectancy effect as evidenced by significantly lower RTs on the last letter of correctly spelled words compared to incorrectly spelled words and the accompanying increase in error rates observed for the last characters for the incomplete and misspelled stimuli.

Importantly this largely ecologically valid task resulted in standard ERN/Pe waveforms when correct and error trials were examined. Furthermore and most importantly to the expectancy literature, I found a complete lack of ERN amplitude modulations as a result of our expectancy manipulations. Additionally, although the trend was in the predicted direction no statistically significant effects on Pe amplitude were observed.

These findings suggest that the sensitivity of the ERN to expectancy violations may not parallel the fERN expectation violation findings. This suggests that the two are not synonymous and it is important that a demarcation in nomenclature and theory be made in the literature. This is a relatively profound statement and needs to be qualified by taking into account that our task was quite different from typical tasks used in this literature, and the non-replication of previous findings could be a direct result of task differences, although the experiment did replicate standard ERN results. In support of this task's validity, this finding was also somewhat consistent with Luu, Tucker, Derryberry, Reed and Poulsen (2003) suggestion that although the ERN and fERN seem to be produced in the ACC the ERN activates both the dorsal and rostral sections of the ACC while the fERN only activates the dorsal. This too suggests that the ERN and fERN are possibly indicative of two different processes. Finally, consistent with my ERN results Hajcak, Holroyd, Moser and Simons (2005) found no significant fERN modulations as a function of expectancy violations. Although the results of this last study are in direct contradiction with all previous fERN expectation violation literature it does question some of the previous conclusions drawn by Holroyd and others. When put in the context of Experiment 3's results and my subsequent conclusions concerning the dissociation of ERNs and fERNs, the Hajcak et al., (2005) study leaves the door ajar, if not quite open, for future ERN and fERN comparisons to be made in order to further investigate the components' functional similarity.

It is again important to remember that the findings of Experiment 3 were obtained using a task that was extremely different from the norm and even with having replicated typical ERN results the null findings observed may possibly result from the study design. Although this sounds negative it is actually very important to recognize that increasingly complex tasks may result in a change of findings. It is possible that performance monitoring works differently depending on the nature of the task; in fact this is what most researchers are examining to a certain extent with any variable manipulation made. The change in outcomes in Experiment 3 could be the result of the task not tapping into what it was meant to but it could also be that the performance monitoring system is malleable and works in various ways depending on context. Additional investigations should attempt to replicate well established findings from standard performance monitoring experiments while using new more ecologically valid tasks. In the particular case of Experiment 3, future work might develop a simpler task that still generates a violation of stimulus driven expectations as opposed to feedback driven expectation violations. Perhaps manipulating stimulus probabilities in a cuing or priming framework would suffice, providing the behavioural data supports the predicted expectation violation as was evident in Experiment 3.

Task Difficulty

The ERN is thought to be generated in the ACC as suggested from a large number of experiments utilizing a variety of techniques (i.e., fMRI, PET, EEG source analysis). It has also been well established that the ACC is consistently and to a greater extent activated during cognitively demanding tasks and has been shown to be more highly activated during tasks that have a high degree of difficulty (Paus et al., 1998; Botvinick et al., 2001). It has therefore been proposed that task difficulty should have a modulating effect on the ERN but Pailing and Segalowitz (2004) failed to show a consistent ERN or CRN modulation as a function of task difficulty. Tasks with higher error rates did not lead to a significantly larger or smaller ERN when compared to tasks with lower error rates. On the other hand, Tanaka, Masaki, Sakazawa and Yamazaki (2002) showed that ERN amplitude decreased as difficulty level increased. Unfortunately both findings cannot be correct as they are directly at odds. Results from three (Experiment 1: Same/Different judgement; Experiment 2: Identify Local; and Experiment 4: Math task) of our four experiments lead me to support one side of this debate.

According to the behavioural data (i.e., increased RT and increased error rates) obtained across stimulus discriminability manipulations in Experiments 1 and 2, I could propose that task difficulty increased across the three visual noise levels. Experiment 1 showed decreasing ERN amplitudes as difficulty (i.e., stimulus discriminability) increased. Similarly, incongruent trial ERN amplitudes in Experiment 2 decreased as visual noise level increased and ERN amplitudes on congruent trials decreased from low to medium levels of stimulus noise, consistent with Experiment 1 and Tanaka et al., (2002). Even though the results for congruent trials were in an unexpected direction in Experiment 2 (i.e., an increased ERN in the high noise condition compared to the low and medium noise conditions), this supports the hypothesis that the ERN is sensitive to levels of task difficulty. ERN waveforms in Experiment 4, on the other hand, showed little or no modulation across the three difficulty conditions. The lack of support for difficulty's influence on ERN amplitude in Experiment 4's findings may again be a result of the task not being standard. By employing six different response buttons, as opposed to the two or four typically utilized, any difficulty effects may have been masked by response uncertainty or just plain confusion; any right or wrong answer that was included in the grand averaging process may not have been a true indicator of a correct or incorrect response simply because the response system was overwhelmed by the potential options it had to choose from. We do, however, see the Pe modulated as a function of difficulty and anxiety level: anxious individuals (but not controls) elicited smaller Pe amplitudes as difficulty increased .

Taken together the results of these three experiments seem to support the notion that task difficulty influences the performance monitoring system as indicated in the amplitudes of *both* the ERN ad Pe components. Although Experiment 4 directly manipulated levels of task difficulty and portions of Experiments 1 and 2 can partially address this issue, further investigations directly manipulating difficulty across a variety of contexts would help clarify the effects of difficulty level in the monitoring of performance.

Individual Differences (Math Anxiety)

One of the main contributions of this body of work concerns the role that individual differences have on ERN amplitude and the potential interactions between task and personal variables. As discussed in Chapters 1 and 4, studies have observed performance monitoring system modulations as a function of personal characteristics including OCD, high negative affect, ADHD, anorexia nervosa, Parkinson's disease, and, most pertinent to the present study, high levels of trait anxiety. Significantly higher ERN amplitudes are consistently found in individuals with a trait or trait-like disorder involving any overemphasis on negative affect. Interpreted in an error significance framework, these findings are taken to indicate that the more personal significance that is attached to an error the higher the ERN amplitude, which in turn indicates a greater effect on the performance monitoring system.

If the human performance monitoring system is sensitive to the attached significance of an error then a prediction would be that individuals with specific anxieties or who attach a high level of negative affect to specific objects or situations should elicit a correspondingly larger ERN in a situation specific to their anxiety. Moser et al. (2005) did not find support for this contention however. They predicted that larger ERNs would be observed in the presence of a spider for those participants who scored high on a spider fear scale compared to participants who were not afraid of spiders. No significant ERN modulations were observed in regards to the presence or absence of the spider. This was taken as evidence for state anxiety levels having less of an influence on the performance monitoring system in contrast to the trait anxiety findings that are usually observed in the general negative affect literature. However, in the Moser et al. study participants performed a standard flanker task and only the presence of the spider was used to provoke participants' state anxieties. The flanker task itself does very little to influence the participants' anxiety levels. I took this idea a step further by examining how placing a state anxious person in a task that directly stimulates their anxiety influences performance monitoring. Filling the potential gap in the Moser et al. (2005) study by examining math anxious individuals in a math setting, my study represents the first to generate specific anxieties in subjects through the direct performance of an experimental task designed to provoke math anxiety. As a result, I was able to determine if my results were in line with the general literature on negative affect or with the state anxiety findings.

Even when placed in an arithmetic environment (i.e., task) no ERN differences were observed based on participant levels of math anxiety. The lack of significant ERN differences between the anxiety groups is consistent with the Moser et al. (2005) study and not the trait negative affect literature. This suggests that there is not a simple relationship between ERN amplitude and emotional processing because state anxiety level does not affect ERN amplitude. I did however observe interesting Pe modulations as a result of the group and difficulty manipulations. Math anxious individuals, but not controls, showed significantly higher Pe amplitudes on error trials compared to correct trials. Furthermore Pe amplitudes in math anxious individuals significantly decreased as the difficulty of the math questions increased; this is another pattern of Pe amplitudes that was not observed in the controls. These results provide support for the personal significance of errors being manifested in the amplitude of the Pe. Additionally and importantly, the Pe amplitudes of state anxious individuals decreased to control levels over the course of the experiment without a decrease in performance. Since the Pe is associated with affective processing and the subjective difficulty of the task, it seems that state anxious individuals may be able to learn, over a short immersive time period, to control their emotional responses to errors. The length of immersion necessary for this decrease in Pe amplitude to occur would be an interesting avenue of investigation.

Further experimentation using similar state anxious populations in situations and/or tasks designed to provoke emotional responses specific to that group of participants will help to broaden our understanding. It will likely also lead us to better understand the problems these individuals experience and in turn may help in the treatment and/or diagnosis process.

Before discussing potential limitations of my experiments I would like to readdress the main theme of this thesis. The experiments have shown that it is not necessary to *only* use simple cognition tasks in the electrophysiological study of human performance monitoring. All four experiments replicated standard ERN/Pe findings. Each revealed a response time-locked negative component (ERN) centred topographically around Cz/FCz that was significantly more negative for errors compared to correct responses. Moreover, there was a positive going wave (Pe) following the ERN which was sensitive to accuracy. This general morphology is consistent with nearly all published ERN/Pe findings indicating that it is effective to use non-standard tasks that increase task complexity and more closely parallel reality. The use of these tasks could possibly lead to advances in our understanding of how the human performance monitoring system works. In keeping with the cognitive ethology notion of Kingstone et al. (2008; see also Smilek et al., 2007), I would encourage the use of tasks and tools that are more ecologically valid in the investigation of performance monitoring. Understanding how neurological functioning responds under highly controlled circumstances and using simplified stimuli is important. However, I argue that we should try and further our understanding in additional ways by examining performance monitoring during a situation that the system may actually encounter outside of a laboratory. The tasks the current four experiments employed were by no means perfectly parallel with real-world situations but they represent a series of steps towards that end.

Potential Limitations

Recognizing the potential shortcomings of an experiment is an important part of the experimental process. Rarely is any experimental endeavor free of potential limitations and since the experiments in this thesis are no exception I will deal with them each in turn.

The comparison of results from Experiments 1 and 2 was a between-subject analysis. Different participants took part in each experiment therefore error due to individual differences may have influenced my results. Although there were no observable differences in participant demographics (i.e., age, gender), it is possible that the smaller CRNs observed in Experiment 2 were a function of individual differences in error processing. This seems unlikely, however, given that other inter-experiment comparisons were consistent with Pailing and Segalowitz (2004), who did use a within subjects design.

Experiment 3 used a task requiring participants to select a single response from 26 total possible responses. This is substantially different from all other cognitive neuroscience investigations of performance monitoring. Although standard ERN and Pe components were generated, it is possible that the sheer number of response options negatively influenced some of the more specific comparisons made, specifically the expectation violation comparisons. Although typing is a highly practiced task and all participants were classified as expert touch typists, there may have been confusion due to the large number of possible responses. If this resulted in a more uniform performance monitoring process across conditions it could explain the null results in the electrophysiological data. With that said it is important to remember that the behavioural data (i.e., RT and accuracy) suggested that the expectancy manipulation was successful and as a result this general confusion idea seems not to be supported behaviourally.

The results of Experiment 4 are largely consistent with previous ERN investigations of state anxiety effects (Moser et al. 2005) but inconsistent with previous trait negative affect literature (Gehring et al. 2000; Hajcak et al., 2003). In line with Moser et al. (2005), I concluded that an increase in state anxiety levels did not have an effect on the ERN; however the Pe, a possible signal of an affective response to errors, was influenced. Two potential limitations may have influenced these seemingly clear cut results. First, I collected no trait negative affect data from participants which may have unknown effects. Since participants were assigned to experimental groups on the basis of their math (state) anxiety levels it is possible that the groups were equal to each other with respect to trait anxiety levels. If this were the case then any potential state anxiety group differences may be masked by the equal levels of trait anxiety. Although possible, this does not seem likely since math anxiety and trait anxiety have been shown to correlate highly with each other (Zettle and Raines, 2000). Therefore, if trait anxiety levels were overpowering the math anxiety effects the results should be more similar to the trait anxiety literature which is not the case. Future investigations should be sure to collect the corresponding trait affective data and use it as a covariate in all analyses to partial out the influence of those levels from any state anxiety effects.

Another potential problem relates to how well our arithmetic task stimulated the participants' fears of math. The aspect missing from the Moser et al. (2005) study was the lack of task specific anxiety since the flanker task itself does little to generate anxiety and as a result task related fear provocation may not have been generated to a high enough level. My arithmetic task was designed to address that potential shortcoming by having participants complete a task that directly stimulated their specific state anxiety. However, it is possible that this study shared the shortcoming of the Moser et al. study. Since there was no collection of data concerning how participant anxiety levels were influenced by the task, it is possible that my task also did not generate appropriate levels of task related state anxiety. As it stands it is difficult for me to provide evidence to refute this possibility but anecdotally math anxious participants did suggest that the task caused a significant increase in their anxiety levels. In any subsequent investigations of this or any state anxiety it will be important to collect data that speaks to the effect of the task on individual anxiety levels.

The Use of Ecologically Valid Tasks

The notion of task complexity and ecological validity has been a theme throughout my discussion. Before concluding I would like to address the global aspect of this body of work that many would consider a limitation but I, and others, consider a benefit. I would like to preface my further discussion of this issue by saying that I am in no way attempting to devalue the experimental tasks and paradigms used in the past to study the neural properties of performance monitoring. These tasks will without question be used in the future to further our understanding of many aspects of human behavior. However, regardless of research field, tools, tasks, and special populations, in the end the goal is almost certainly to generalize experimental findings to the population as a whole. In some cases this generalization readily occurs but in many cases, including many aspects of cognitive psychology and cognitive neuroscience, the generalizability may not be as transparent or as easily accomplished. Recently, Smilek et al. (2007) have noted that the conversion of laboratory derived experimental results to real world implications have missed the mark when they noted that quantitative interpretations of a change blindness experiment were at odds with participants' qualitative reports. Coming from this viewpoint, Kingstone, Smilek, and Eastwood (2008) proposed the notion of cognitive ethology which basically suggests that an increase in ecological validity is important so more mistaken interpretations are not made. As might be expected this notion has generated a great deal of controversy (see Crundall & Underwood, 2008; Sebanz, Knoblick, & Humphreys, 2008; Watt & Quinn, 2008) but controversy and invalidity are two different things.

My approach across the experiments presented is consistent with the cognitive ethology approach. In general I believe that the simple laboratory tasks typically employed in our field represent the best methods to probe for knowledge concerning the underlying mechanisms of cognition and they of course should continue to do so. However, that should not be the end of the investigations. Rather, since much of human cognition is context-specific any research findings generated using the standard time-tested methods should be extended to different contexts, tasks, and situations.

Conclusion

I have asked four major questions across the four experiments presented in this thesis. I examined how a number of variables and tasks (i.e., stimulus and response uncertainty, task difficulty, expectation violation, special populations) influence the morphology of the ERN/Pe complex, an electrophysiological correlate of the human performance monitoring system. Furthermore, experiments 1, 3 and 4 were certainly more complex and arguably more ecologically valid than any investigations to date. This body of work helps to elucidate a number of performance monitoring issues previously identified in the field and, further examines unique questions not previously addressed.

Although - as is typical of most scientific endeavors - the results generate as many questions as they answer, I believe significant contributions have been made:

- Stimulus uncertainty in a visual domain predictably influences the performance monitoring system.
- Response uncertainty may not reliably influence the performance monitoring system.
- Expectation violations do not influence ERN amplitudes to the same extent as they influence the amplitude of the fERN suggesting a possible functional

dissociation between these two components.

- Even when participants are immersed in an anxiety provoking task, state anxiety levels do not influence the performance monitoring system to the same extent as trait anxiety.
- The typical ERN/Pe findings observed in response to four new and unique tasks suggest that more complex and ecologically valid tasks can reliably be used in ERP investigations of performance monitoring.

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Appendix A

This appendix presents a list of the type of tasks used to study the ERN and Pe components in the context of performance monitoring. It is not an exhaustive list but it is an extensive list that should provide a good cross-section of the existing literature. Out of 92 studies, 32 use flanker tasks, 12 use gambling tasks, 17 use go/nogo tasks, and 5 use a Stroop task.

Task Type	**Citation**
Flanker task	Schrijvers, de Bruijn, Maas, Vancoillie, Hulstijn & Sabbe (2009) Boksem, Tops, Kostermans & De Cremer (2008) Brazil, de Buijn, Bulten, von Borries, van Lankveld, Buitelaar & Verkes (2009) Carbonnell & Falkenstein (2006) Carp, Quandt, Sklar & Compton (2009) de Bruijn, Sabbe, Hulstijn, Ruigt & Verkes (2006) Dikman & Allen (2000) Falkenstein, Hoormann & Hohnsbein (2001) Franken, Strien, Franzek & Wetering (2007) Gehring, Goss, Coles, Meyer & Donchin (1993) Hajcak & Foti (2008) Hajcak, Moser, Yeung & Simons (2005) Ladouceur, Dahl, Birmaher, Axelson & Ryan (2006) Luu & Collins (2000) Luu, Flaisch & Tucker (2000) Maier, Steinhauser & Hubner (2008) Mathewson, Dywan & Segalowitz (2005) Murphy, Richard, Masaki & Segalowitz (2006) Nieuwenhuis, Ridderinkhof & Talsma (2002) Pailing, Segalowitz, Dywan & Davies (2002) Potts, George, Martin & Barratt (2006) Ridderinkhof, Vlugt, Bramlage, Spaan, Elton, Snel & Band (2002) Ruchsow, Herrnberger, Wiesend, Gron, Spitzer & Kiefer (2004) Santesso, Segalowitz & Schmidt (2005) Stemmer, Segalowitz, Dywan & Melmed (2007) Stemmer, Segalowitz, Witzke & Schönle (2003) Tops, Boksem, Wester, Lorist & Meijman (2006) Van Schie, Mars, Coles & Bekkering (2004)
Flanker task, Auditory Discrimination"	Pailing & Segalowitz (2004)
Flanker task, Gambling	Donkers, Nieuwenhuis & Boxtel (2005)

Task Type	Citation
Flanker task, Go/No-go task	Ruchsow, Spitzer, Gron, Groth & Kiefer (2005) Santesso & Segalowitz (2008)
Go/No-go task	Bates, Kiehl, Laurens & Liddle (2002) Bates, Patel & Liddle (2005) Easdon, Izenberg, Armilio, Yu & Alain (2005) Ganuschschak & Schiller (2008) Johannes, Wieringa, Nager, Muller-Vahl, Dengler & Munte (2002) O'Connell, Dockree, Bellgrove, Kelly, Hester, Garava, Robertson & Foxe (2007) Ruchsow, Herrnberger, Beschoner, Gron, Spitzer & Kiefer (2006) Scheffers, Coles, Bernstein, Gehring & Donchin (1996) Schiller (2006) Shalgi, Barkan & Deouell (2009) Stahl & Gibbons (2007) Vidal, Hasbroucq, Grapperon & Bonnet (2000) Vocat, Pourtois & Vuilleumier (2008) Wiersema, van der Meere & Roeyers (2005)
Go/No-go task and speeded response	Falkenstein, Hoormann, Christ & Hohnsbein (2000)
Gambling task	Toyomaki & Murohashi (2005) Yeung, Holroyd & Cohen (2005) Fukushima & Hiraki (2009) Goyer, Woldorff & Huettel (2008) Hewig, Trippe, Hecht, Coles, Holroyd & Miltner (2008) Holroyd, Hajack & Larsen (2006) Itagaki & Katayama (2008) Martin & Potts (2009) Nieuwenhuis, Yeung, Holroyd, Schurger & Cohen (2004) Yu & Zhou (2009) Yu & Zhoua (2006)
Stroop Task	Gehring, Himle & Nisenson (2000) Hajcak, McDonald & Simons (2003) West (2004) Masaki, Tanaka, Takasawa & Yamazaki (2001)
Stroop task, Simon task	Christ, Falkenstein, Heuer & Hohnsbein (2000)
Antisaccade task	Endrass, Reuter & Kathmann (2007) Nieuwenhuis, Ridderinkhof, Blow, Band & Kok (2001)
Auditory decision task	Vlamings, Jonkman, Hoeksma, van Engeland & Kemner (2008)
Balloon Analogue Risk	Fein & Chang (2008)

Task Type	**Citation**
Task	
Continuous Performance Test (AX-CPT)	Carter, Braver, Barch, Botvinick, Noll & Cohen (1998)
Discrimination task	Burgio-Murphy, Klorman, Shaywitz, Fletcher, Marchione, Holahan, Stuebing, Thatcher & Shaywitz (2007) Compton, Carp, Chaddock, Quandt & Ratliff (2007)
Four choice letter task	Pailing & Segalowitz (2004)
Guessing task	Moser & Simons (2009)
Mental rotation task	Band & Kok (2000)
Parity and accuracy judgment	Cavanagh & Allen (2008)
Parity judgment; Semantic classification	Dehaene, Posner & Tucker (1994)
Picture naming task	Mathalon, Bennett, Askari, Gray, Rosenbloom & Ford (2003) Ganushchak & Schiller (2008) Ganushchak & Schiller (2009)
Probabilistic learning task	Eppinger, Kray, Mock & Mecklinger (2008)
RT forced choice	Hogan, Vargha-Khadem, Kirkham & Baldeweg (2005)
RT task speeded	Bernstein, Scheffers & Coles (1995)
RT task with willed errors	Stemmer, Witzke & Schönle (2001)
Simon Task	Boksem, Meijman & Lorist (2006) Masaki, Falkenstein, Sturmer, Pinkpank & Sommer (2007)
SLIP Task	Möller, Jansma, Rodriguez-Fornells & Münte (2007)
Task-switching	Tieges, Ridderinkhof, Snel & Kok (2004)
Time estimation task	Miltner, Braun & Coles (1997)
Trial and error learning	Holroyd, Larsen & Cohen (2004)
Visual and auditory spatial S-R compatibility tasks	Leuthold & Sommer (1999)
Visual categorization; Priming task	Henry, Bartholow & Lust (2008)
Visual search task	Scheffers, Humphrey, Stanny, Kramer & Coles (1999)
Word completion task	Heldmann, Markgraf, Rodriguez-Fornells & Münte (2008)

Appendix B

Instruction Sheet for Experiment 1

You will see, flashed on the screen very quickly, large arrows made up of smaller arrows. Your task here is to determine if they are pointing in the same or different directions by pressing one of two buttons: 1 or 2 on number pad. The button you have to press and whether you are responding to the large or small arrows will be revealed at the start of each block. Sometimes you will press “2” for the same direction; sometimes you will press “1” for the same direction. It is important to remember which is which for each block. At the end of each block an instruction screen will appear. It is here that you will be told which button to press for same or different directions. There are also different levels of confusion presented. That is some of the arrows will be very easy to see while some will be very difficult to see. I want you to be as accurate as possible but also as fast as possible. You have a total of approximately 1.5 seconds to respond to each picture before a new one appears. If you miss one just continue, no big deal. However, one thing to remember is that the fewer mistakes that you make the quicker the experiment will be over but don’t worry there is a maximum number of trials per block. The bell can be used to alert us to your need. Breaks will occur throughout the experiment so you can rest your eyes.

Instruction Sheet for Experiment 2

You will see, flashed on the screen very quickly, large arrows made up of smaller arrows. Your task here is to determine if the little arrows are pointing to the left or to the right by pressing one of two buttons: (left) or 2 (right) on number pad. There are also different levels of confusion presented. That is some of the arrows will be very easy to see while some will be very difficult to see. I want you to be as accurate as possible but also as fast as possible. You have a total of approximately 1.5 seconds to respond to each picture before a new one appears. If you miss one just continue, no big deal. However, one thing to remember is that the fewer mistakes that you make the quicker the experiment will be over but don't worry there is a maximum number of trials per block. The bell can be used to alert us to your need. Breaks will occur throughout the experiment so you can rest your eyes.

Appendix C

Instruction Sheet for Experiment 3

"What you will see on the screen are a bunch of letters one at a time. Some of the time when these strings of letters are put together they will make pairs of words."

"The task in both the practice trials and the experimental trials is to type what you see on the screen as fast as possible but also as accurately as possible. The letters will be flashed quickly so you have to pay attention and there will be very little time between letters so you also have to type quick. If you miss a letter or make a mistake just carry on like normal"

"For the most part you will be seeing mostly letters, all uppercase but you don't need to use caps or shift key, but you will also be seeing "_", the underscore, please treat this as a space and press the space bar in response to it. The underscore seperates one word from the other and marks the end of a wordpair. Please press the spacebar to each one."

"There will be a break every so often and you can take as much time as you like but when you press the spacebar to continue be ready to type again"

Appendix D

Instruction Sheet For Experiment 4

"What you will see on the screen are a series of addition, subtraction, or division questions. The answers to all of these questions will always be either: 1, 2, 3, 4, 5, or 6. If the answer is 1, you will press 'z'; for 2 press 'x'; 3 press 'c'; if the answer is 4, press ','; 5 please press '.', and if it is it 6 please press '/'. Before we proceed to the experiment we will make sure that you are familiar with the response keys."

"Your task is to type the correct answer to the math question that appears on the screen. Responses are to be made as accurately as possible and also as quickly as possible. The questions will be flashed on the screen quickly so you have to pay attention. You need to respond to the question before the asterisk appears on the screen preparing you for the next question. Corrections cannot be made once you have responded so if you miss a question or make a mistake just carry on like normal and proceed to the next question."

"There will be a break every so often and you can take as much time as you'd like. When you are ready to begin the next block, press the key corresponding to the instructions to continue."

"Do you have any questions at this time? If you have any questions or need any assistance during the experiment, please ring this bell and I will come in."

"Now, can you please summarize these instructions for me before we begin with the experiment"

GOOD LUCK!!

Appendix E

Initials: **Participant #:**

Please rate your level of anxiety for the nine situations below using the 5-point scale provided. Please carefully circle your answer.

Low Anxiety **High Anxiety**

1 2 3 4 5

1. Having to use the tables in the back of a math book.	1 2 3 4 5
2. Thinking about an upcoming math test 1 day before.	1 2 3 4 5
3. Watching a teacher work an algebraic equation on the blackboard.	1 2 3 4 5
4. Taking an examination in a math course.	1 2 3 4 5
5. Being given a homework assignment of many difficult problems that is due the next class meeting.	1 2 3 4 5
6. Listening to a lecture in math class...	1 2 3 4 5
7. Listening to another student explain a math formula.	1 2 3 4 5
8. Being given a “pop” quiz in math class.	1 2 3 4 5
9. Starting a new chapter in a math book.	1 2 3 4 5

Appendix F

Experiment 1

Accuracy: Congruency (C) x Noise (N)

Source	SS	df	MS	F
C	.018	1	.018	2.76
Error (C)	.075	11	.007	
N	.091	2	.045	23.52
Error (N)	.042	22	.0019	
C x N	.019	2	.0098	5.72
Error (C x N)	.038	22	.0017	

Response Time: Congruency (C) x Noise (N)

Source	SS	df	MS	F
C	71064.5	1	71604.5	63.86
Error (C)	12241.17	11	1112.83	
N	2624.69	2	1312.35	4.21
Error (N)	6860.31	22	311.83	
C x N	2051.08	2	1025.54	10.41
Error (C x N)	2169.25	22	98.60	

ERN (Peak Minimum): Accuracy (A) x Congruency (C) x Noise (N)

Source	SS	df	MS	F
A	107.31	1	107.31	24.15
Error (A)	48.88	11	4.44	
C	3.61	1	3.61	0.71
Error (C)	56.29	11	5.12	
N	30.87	2	15.43	4.89
Error (N)	69.43	22	3.16	
A x C	13.45	1	13.45	1.16
Error (A x C)	127.14	11	11.56	
A x N	17.75	2	8.88	3.08
Error (A x N)	63.30	22	2.88	
C x N	13.30	2	6.65	1.16
Error (C x N)	59.92	22	2.72	
A x C x N	5.22	2	2.60	0.52
Error (A x C x N)	111.17	22	5.05	

Experiment 2

Accuracy: Congruency (C) x Noise (N)

Source	SS	df	MS	F
C	.020	1	.020	1.03
Error (C)	.219	11	.0199	
N	.0124	2	.0062	13.91
Error (N)	.0098	22	.0004	
C x N	.0042	2	.0021	4.29
Error (C x N)	.0108	22	.0005	

Response Time: Congruency (C) x Noise (N)

Source	SS	df	MS	F
C	903.13	1	903.13	7.03
Error (C)	1413.71	11	128.52	
N	5926.19	2	2963.10	22.34
Error (N)	2918.14	22	132.64	
C x N	238.08	2	119.04	1.61
Error (C x N)	1623.58	22	73.80	

ERN (Peak Minimum): Accuracy (A) x Congruency (C) x Noise (N)

Source	SS	df	MS	F
A	520.31	1	520.31	25.32
Error (A)	226.02	11	20.55	
C	2.60	1	2.60	.15
Error (C)	188.06	11	17.10	
N	8.73	2	4.37	.46
Error (N)	210.87	22	9.59	
A x C	1.62	1	1.62	.15
Error (A x C)	121.72	11	11.07	
A x N	2.65	2	1.32	.14
Error (A x N)	213.56	22	9.71	
C x N	75.20	2	37.60	4.09
Error (C x N)	202.17	22	9.19	
A x C x N	74.42	2	37.21	4.28
Error (A x C x N)	191.09	22	8.69	

Comparing Experiments 1 and 2

Accuracy: Congruency (C) x Noise (N) x Experiment (E)

Source	SS	df	MS	F
Between				
E	.25	1	.25	4.59
Error	1.20	22	.06	
Within				
C	.00	1	.00	.75
C x E	.00	1	.00	.93
Error	.11	22	.00	
N	.08	2	.04	33.32
N x E	.01	2	.00	4.16
Error	.05	44	.00	
C x N	.00	2	.00	3.76
C x N x E	.00	2	.00	.27
Error	.04	44	.00	

Response Time: Congruency (C) x Noise (N) x Experiment (E)

Source	SS	df	MS	F
Between				
E	1499400.25	1	1488400.25	59.19
Error	557326.64	22	25333.03	
Within				
C	24025.00	1	24.25.00	30.35
C x E	31152.25	1	31152.25	39.35
Error	17417.08	22	791.69	
N	13418.76	2	6709.38	18.62
N x E	21.29	2	10.65	.03
Error	15852.28	44	360.28	
C x N	2002.63	2	1001.31	9.64
C x N x E	872.38	2	436.19	4.20
Error	4568.67	44	103.83	

Pe (Mean Amplitude): Accuracy (A) x Noise (N) x Experiment (E)

Source	SS	df	MS	F
Between				
E	5.90	1	5.90	.16
Error	863.60	23	37.54	
Within				
A	144.59	1	144.59	14.09
A x E	1.68	1	1.68	.16
Error	235.95	23	10.26	
N	1.49	2	.75	
N x E	25.92	2	12.96	3.22
Error	184.95	46	4.02	
A x N	7.04	2	3.52	.94
A x N x E	16.93	2	8.46	2.25
Error	172.95	46	3.76	

Experiment 3

Accuracy: Relatedness (R) x Letter Position (LP) x WordType (WT)

Source	SS	df	MS	F
R	.12	1	.12	11.09
Error	.19	18	.01	
LP	.04	2	.02	1.26
Error	.52	36	.01	
WT	.52	2	.26	36.43
Error	.26	36	.01	
R x LP	.00	2	.00	.52
Error	.08	36	.00	
R x WT	.05	2	.02	3.62
Error	.23	36	.00	
LP x WT	.33	4	.08	10.04
Error	.60	72	.01	
R x LP x WT	.01	4	.00	.78
Error	.33	72	.00	

Response Time: Relatedness (R) x Letter Position (LP) x WordType (WT)

Source	SS	df	MS	F
R	87737.26	1	87737.26	21.33
Error	78160.26	19	4113.70	
LP	420563.54	2	210281.77	72.71
Error	109896.17	38	2892.00	
WT	121801.48	2	60900.74	56.65
Error	40853.65	38	2892.00	
R x LP	9844.84	2	4927.42	10.26
Error	18232.26	38	479.80	
R x WT	52309.80	2	26154.90	8.56
Error	116160.03	38	3056.84	
LP x WT	271429.63	4	67857.41	46.58
Error	110727.42	76	1456.94	
R x LP x WT	19483.52	4	4870.88	6.88
Error	53771.76	76	707.52	

ERN (Peak Minimum): Accuracy (A) x Wordtype (WT)

Source	SS	df	MS	F
WT	.02	1	.02	.00
Error	61.31	11	5.57	
A	28.60	1	28.60	4.23
Error	74.44	11	6.77	
WT x A	8.81	1	8.81	2.33
Error	41.58	11	3.78	

Pe (Mean Amplitude): Accuracy (A) x WordType (WT)

Source	SS	df	MS	F
WT	.25	1	.25	.05
Error	57.86	11	5.26	
A	34.27	1	34.27	7.34
Error	51.38	11	4.67	
WT x A	.52	1	.52	.10
Error	57.10	11	5.2	

Experiment 4

Accuracy: Anxiety (A) x Difficulty (D) x Half (H)

Source	SS	df	MS	F
Between				
A	.1	1	.1	.59
Error (A)	5.08	30	.17	
Within				
H	.01	1	.01	2.15
H x A	.00	1	.00	.02
Error	.15	30	.005	
D	6.58	2	3.29	223.4
D x A	.03	2	.02	1.11
Error	.88	60	.02	
H x D	.00	2	.00	.09
H x D x A	.00	2	.00	.34
Error	.18	60	.00	

Response Time: Anxiety (A) x Difficulty (D) x Half (H)

Source	SS	df	MS	F
Between				
A	211189.83	1	211189.83	1.08
Error (A)	5884678.59	30	196155.95	
Within				
H	174721.12	1	174721.12	22.09
H x A	25192.00	1	25192.00	3.18
Error	237331.89	30	7911.06	
D	10706823.26	2	5353411.63	361.83
D x A	3246.02	2	1623.01	.11
Error	887717.20	60	14795.30	
H x D	43036.37	2	21518.19	4.67
H x D x A	52093.13	2	26046.56	5.65
Error	276614.32	60	4610.24	

ERN (Minimum Amplitude): Anxiety (A) x Difficulty (D) x Accuracy (Acc)

Source	SS	df	MS	F
Between				
A	1.05	1	1.05	.27
Error	113.67	29	3.92	
Within				
D	6.73	2	3.37	2.29
D x A	4.08	2	2.04	1.38
Error	85.44	58	1.47	
Acc	34.13	1	34.13	19.52
Acc x A	.48	1	.48	.28
Error	50.69	29	1.75	
D x Acc	3.53	2	1.76	1.21
D x Acc x A	6.51	2	3.25	2.24
Error	84.47	58	1.46	

Pe Error Trials (Mean Amplitude): Anxiety (A) x Difficulty (D) x Half (H)

Source	SS	df	MS	F
Between				
A	2.13	1	2.13	.09
Error	716.69	30	23.89	
Within				
D	39.27	2	19.63	1.79
D x A	7.43	2	3.71	.34
Error	657.69	60	10.96	
H	9.2	1	9.2	.92
H x A	50.60	1	50.60	5.06
Error	299.92	30	10.00	
D x H	.65	2	.33	.05
D x H x A	14.33	2	7.17	1.01
Error	426.55	60	7.11	

Pe (Mean Amplitude) (Anxious Participants): Accuracy (A) x Difficulty (D)

Source	SS	df	MS	F
A	14.52	1	14.52	5.06
Error	40.18	14	2.87	
D	19.56	2	9.78	3.34
Error	81.91	28	2.93	
A x D	8.5	2	4.25	1.14
Error	104.27	28	3.72	

Pe (Mean Amplitude) (Control Participants): Accuracy (A) x Difficulty (D)

Source	SS	df	MS	F
A	12.08	1	12.08	2.25
Error	85.92	16	5.37	
D	.43	2	.21	.03
Error	198.32	32	6.20	
A x D	9.77	2	4.88	1.40
Error	111.46	32	3.48	