Behavioral and Electrophysiological Investigation of Attention and Executive Functions With and Without Minor Head Injury

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ABSTRACT

The existence of lasting cognitive effects following a minor head injury (MHI) is subject to considerable debate. Frequently persons with MHI complain of difficulties with attention and concentration whereas standard objective measures such as neuropsychological testing and neuroimaging do not reveal any behavioral deficits or underlying structural damage. In Experiment 1, a group of high-functioning students with MHI had difficulty with tasks that required them to divide their attention and allocate attentional resources during a dual-task despite normal performance on most behavioral tasks associated with frontal-lobe function. In Experiment 2, we collected event-related potential (ERP) and electroencephalographic (EEG) coherence measures while participants with head injury and controls performed tasks that increased in difficulty and in demands on cognitive resources. Even though, in this sample, participants with head injury and controls performed similarly on all behavioral measures, those with head injury demonstrated an increased cortical-activation cost associated with increased demands on attentional allocation.

Data from Experiment 2 also revealed theoretically relevant relations between electrophysiological activity and task requirements. Early components of information-processing (N1, P2, N2) were found to be enhanced with increased cognitive demands, suggesting that these components are affected by increased focused attention as demands on attentional abilities increase. Speed of information-processing increased and processing capacity decreased with increased demands on attentional allocation as evidenced by task

effects on P3 ERP component latency and amplitude. Increasing focused attention led to a decrease in EEG coherence between frontal and posterior regions and an increase in local, short connection EEG coherence in posterior brain regions. Divided attention, on the other hand, increased EEG coherence between frontal and parietal sites. In all, tasks requiring divided, relative to focused, attention elicited different patterns of brain activation and these were captured through subtle variation in electrophysiological activity.

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Dedication

I dedicate this thesis to my husband, Andy, whose patience, understanding and encouragement allowed me to find my way through. Thanks for having a little faith in me.

Table of Contents

Introduction 1

Brain Damage Resulting from Minor Head Injury 2

Recovery Following Minor Head Injury 6

Lasting Cognitive Impairment Following MHI: Attention Deficits and Reduced Information-processing Capacity 12

Assessment of Attentional Abilities Following MHI 14

Lasting Cognitive Impairment Following MHI: Executive Function 18

Assessment of Executive Function Following MHI 19

Overview of Experiments 1 and 2 21

Rationale for Experiment 1 22

Tasks Associated with Frontal-Lobe Function 23

Attentional Recruitment: Focused Attention 23

Distractibility and Inhibitory Control 23

Divided Attention, Working Memory and the Central Executive System 23

Tasks Less Dependent on Frontal Lobe Functions 24

Intelligence, Acquired Knowledge and Motor Speed 25

Method 26

Participants 26

Questionnaires 26

Minor Head Injury Screening Questionnaire 26

Brock Health and History Questionnaire 27

Behavioral Paradigms 27

Attentional Recruitment: Focused Attention Tasks 27

Easy Pitch Discrimination Task 27

Difficult Pitch Discrimination Task 28

Easy Duration Discrimination Task 28

Difficult Duration Discrimination Task 29

Table of Contents (continued)

Distractibility and Inhibitory Control Tasks 29
Eriksen Flanking Paradigm 29
Continuous Performance Task 30
Stop Signal Paradigm 31
Selective Stimulus Finding 32
The Cross-Circle Test 32
Divided Attention, Working Memory and Central Executive Tasks 33
Duration Discrimination with Distractor Task 33
Paper and Pencil Dual task 34
Computerized Multiple Performance Task 35
Digit Span Backward 36
Two-Back Task 36
Self-Ordered Pointing Test 36
Culture Fair Intelligence Test 37
Control Tasks 38
Acquired Knowledge 38
Motor Speed 38
Simple Reaction Time 39
Procedure 39
Results 40
Participants 40
Comparison of University Populations 40
MHI Characteristics 41
Attentional Recruitment: Focused Attention Tasks 42
Reaction Time Performance: Task Differences 42
RT Performance: Group Differences 42
Signal-Detection Analysis and Task Performance 43

Table of Contents (continued)

Signal-Detection Analysis and Group Performance ... 44
Summary of Results ... 44
Distractibility and Inhibitory Control Tasks ... 44
Divided Attention, Working Memory and Central Executive Tasks ... 45
Working Memory ... 45
Divided Attention and the Central Executive ... 45
Duration Discrimination with Simultaneous Distractor: Reaction Time Performance ... 45
Duration Discrimination with Simultaneous Distractor: Signal-Detection Analysis and Task Performance ... 46
Duration Discrimination with Simultaneous Distractor: Signal-Detection Analysis and Group Performance ... 46
Summary of Results ... 47
Paper and Pencil Dual Task and Computerized Multiple Task Performance ... 47
Control Tasks ... 48
Discussion ... 49
Conclusions ... 51
Experiment Two ... 53
Event-Related Potentials ... 53
ERPs and MHI ... 55
EEG Coherence ... 59
EEG Coherence between Frontal and Parietal Cortical Regions ... 62
EEG Coherence and MHI ... 65
Rationale for Experiment 2 ... 67
Outline of Experiment 2 ... 68
Hypothesis 1a: ERPs and Task Differences ... 69
Hypothesis 1b: ERPs and Group Differences ... 69
Hypothesis 2a: EEG Coherence and Task Differences ... 69

Table of Contents (continued)

Hypothesis 2b: EEG Coherence and Group Differences 70
Method 71
Participants 71
Psychometric Measures 72
MHI Screening Questionnaire 72
Brock Health and History Questionnaire 72
Culture Fair Intelligence Test 72
Electrophysiological Measures 72
Easy Duration Discrimination 72
Difficult Duration Discrimination 73
Verbal-Working-Memory Distractor Task 73
Sequential-Letter Working-Memory Task 74
Electrophysiological Recording 75
EEG Coherence 76
Procedure 77
Results 78
Participants 78
Head Injury Characteristics 78
Behavioral Results 79
Duration Discrimination Task with and without Working-Memory Distractor Task 79
Statistical Analysis 79
Reaction Time (RT) Performance: Task Differences 79
RT Performance: Group Differences 80
Errors: Task Differences 80
Errors: Group Differences 80
Signal-Detection Analysis and Task Performance 80
Signal-Detection Analysis and Group Performance 82

Table of Contents (continued)

Summary of Behavioral Results 82

Working-Memory Distractor Task 82

Statistical Analysis 82

RT Performance: Task Differences 82

RT Performance: Group Differences 83

Errors: Task Differences 83

Errors: Group Differences 84

Signal-Detection Analysis and Task Performance 84

Signal-Detection Analysis and Group Performance 84

Summary of Results 85

Sequential-Letter Working-Memory Task (n-Back) 85

Statistical Analysis 85

RT Performance: Task Differences 85

RT Performance: Group Differences 85

Errors: False Alarms and Omissions: Task Differences........ 86

Errors: False Alarms and Omissions: Group Differences 86

Summary of Results 86

Electrophysiological Results 87

Event-Related Potentials: Duration Discrimination With and Without Working-Memory Distractor Task........ 87

Statistical Analysis 87

Early ERP Component Amplitude (N1, P2, N2): Task Differences 87

P3 Component Amplitude: Task Differences 88

ERP Component Amplitude: Group Differences 88

Early ERP Component Latency (N1, P2, N2): Task Differences 88

P3 Component Latency: Task Differences 88

ERP Component Latency: Group Differences 89

Discussion of ERP Results 89

Table of Contents (continued)

Event-Related Potentials: Sequential-Letter Working-Memory Task 92
Statistical Analysis 92
Early ERP Component Amplitude (N1, P2, N2): Task Differences 92
Early ERP Component Amplitude: Group Differences 93
P3 Component Amplitude: Task Differences 93
P3 Component Amplitude: Group Differences 93
Early ERP Component Latency (N1, P2, N2): Task Differences 93
Early ERP Component Latency: Group Differences 93
P3 Component Latency: Task Differences.. 94
P3 Component Latency: Group Differences 94
Discussion of ERP Results 94
EEG Coherence: Duration Discrimination With and Without Working-Memory Distractor Task 97
Statistical Analysis 97
Task Differences 97
Group Differences 98
Discussion of EEG Coherence Results 99
EEG Coherence: Sequential-Letter Working-Memory Task 101
Statistical Analysis 101
Task Differences 102
Group Differences 103
Discussion of EEG Coherence Results 103
General Discussion 106
Conclusions and Future Directions 109
References 111
Appendix A: Tables 124
Appendix B: Figures 163

List of Tables

Table 1a: Studies Finding No Lasting Cognitive Effects Following MHI 125

Table 1b: Studies Finding Some Lasting Cognitive Effects Following MHI 126

Table 2: Order of Presentation of Computer and Paper and Pencil Tasks in Experiment 1 . 127

Table 3: Means and Standard Deviations for Culture Fair, Information Subtest and Age: A Comparison of University Populations. 128

Table 4: Causes of MHI in Both University Populations: Experiment 1 129

Table 5: Mean RT Performance and Standard Errors for Each Auditory Oddball Task in Experiment 1 130

Table 6: Mean RT Performance and Standard Errors for MHI and Control Groups at Brock and Waterloo As A Function of Auditory Oddball Task in Experiment 1 131

Table 7: Means and Standard Errors for d' and β for all Oddball Tasks in Experiment 1 132

Table 8: Means and Standard Errors for d' and β for MHI and Control Groups for Each Oddball Task in Experiment 1 133

Table 9: Means and Standard Errors for d', β and RT for Duration Discrimination with and without Distractor Task 135

Table 10: Means and Standard Errors for d' and β for MHI and Control Groups for Duration Discrimination with and without Distractor Task and for the Distractor Task alone 136

Table 11: Means and Standard Errors for the Computerized Multiple Performance Task for MHI and Control Groups at Both Universities 137

Table 12: Number of Individuals Reporting Persistent Difficulties Following Their Head Injury in Experiment 2 137

Table 13: Causes of Head Injury for Both RLOC<20 and RLOC>30 Groups in Experiment 2 138

Table 14: Means and Standard Errors of RT Performance for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2 139

List of Tables (continued)

Table 15: Means and Standard Errors of RT Performance for All Groups for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2 140

Table 16: Means and Standard Errors of Number of Errors Committed for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2 141

Table 17: Means and Standard Errors of Number of Errors Committed for All Groups for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2 142

Table 18: Mean and Standard Errors of d′ for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2........ 143

Table 19: Mean and Standard Errors of β for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2........ 144

Table 20: Means and Standard Errors for RT Performance on the Working-Memory Distractor Task for Each Group in Experiment 2........ 145

Table 21: Means and Standard Errors for Number of Errors Committed on the Distractor Task and Percentage of Correct Responses for Distractor versus Duration Discrimination Tasks in Experiment 2........ 146

Table 22: Means and Standard Errors for Number of Errors Committed for Each Group on the Working-Memory Distractor Task. In Experiment 2........ 147

Table 23: Means and Standard Errors for d′ and β on the Working-Memory Distractor Task in Experiment 2 148

Table 24: Means and Standard Errors for RT As a Function of WM Load During the n-Back Task in Experiment 2........ 149

Table 25: Means and Standard Errors for RT for Each Group As A Function of WM Load During the n-Back Task in Experiment 2........ 150

List of Tables (continued)

Table 26: Means and Standard Errors for False Alarms (FA) and Omissions (OM) as a Function of Working-Memory Load During the n-Back Task in Experiment 2....... 151

Table 27: Means and Standard Errors for FA and OM for Each Group as a Function of WM Load During the n-Back Task in Experiment 2 152

Table 28: Means and Standard Errors for N1, P2, N2 Amplitudes During Single and Dual-Task Conditions of the Duration Discrimination Task in Experiment 2.......... 153

Table 29: Means and Standard Errors for P3 Amplitude During Each Conditions of the Duration Discrimination Task in Experiment 2 154

Table 30: Means and Standard Errors for P3 Latency During Each Condition of the Duration Discrimination Task in Experiment 2 155

Table 31: Means and Standard Errors for Early ERP Component Amplitudes As a Function of Working-Memory Load During the n-Back Task in Experiment 2....... 156

Table 32: Means and Standard Errors for Dorsal F-P Beta Coherence as a Function of Stimulus Difficulty and as a Function of Task Condition During the Duration Discrimination Task in Experiment 2 157

Table 33: Means and Standard Errors for F-C and C-P Beta Coherence as a Function of Stimulus Difficulty and as a Function of Task Condition During the Duration Discrimination Task in Experiment 2 158

Table 34: Means and Standard Errors for F-P Beta Coherence for Each Group in each Hemisphere as a Function of Task Condition and Stimulus Difficulty During the Duration Discrimination Task in Experiment 2 159

Table 35: Means and Standard Errors for F-P Theta Coherence as a Function of WM Load During the n-Back Task in Experiment 2 160

Table 36: Means and Standard Errors for F-C and C-P Theta Coherence as a Function of WM Load During the n-Back Task in Experiment 2 161

Table 37: Means and Standard Errors for F-P Beta Coherence for Each Group as a Function of Hemisphere During the n-Back Task in Experiment 2........ 162

List of Illustrations

Figure 1: Mean RT as a Function of Task and Stimulus Difficulty During Auditory Oddball Tasks in Experiment 1 164

Figure 2: Mean RT for Waterloo MHI and Control Group as a Function of Oddball Task in Experiment 1 165

Figure 3: Mean d' for Task Condition and Stimulus Difficulty During Oddball Tasks in Experiment 1 166

Figure 4: Mean Beta as a Function of Task and Stimulus Difficulty During Oddball Tasks in Experiment 1 167

Figure 5: Mean d' for Each Group as a Function of Duration Discrimination Condition in Experiment 1 168

Figure 6: Mean Beta for Each Group as a Function of Duration Discrimination Condition in Experiment 1 169

Figure 7: Mean Score on CMPT as a Function of Group and University 170

Figure 8: Electrode Placement Employed During Electrophysiological Recording in Experiment 2 and Placement of Electrodes Used in the Average Reference for EEG Coherence 171

Figure 9: Mean RT as a Function of Task and Stimulus Difficulty During Duration Discrimination Tasks in Experiment 1 172

Figure 10: Mean d' as a Function of Stimulus Difficulty and Task Condition During Duration Discrimination Tasks in Experiment 1 173

Figure 11: Mean Beta as a Function of Stimulus Difficulty and Task Condition During Duration Discrimination Tasks in Experiment 2 174

Figure 12: Mean Percentage of Correct Responses as a Function of Stimulus Difficulty for the Duration Discrimination vs. Distractor Tasks 175

Figure 13: Mean RT for Each Group as a Function of WM Load During the n-Back Task in Experiment 2 176

List of Illustrations (continued)

Figure 14: Mean P3 Amplitude as a Function of Stimulus Difficulty and Task Condition During the Duration Discrimination Task in Experiment 2 177

Figure 15a: Averaged ERP Waves for a Single Control Participant in the Easy Duration Discrimination Single versus Dual-Task 178

Figure 15b: Averaged ERP Waves for a Single Control Participant in the Difficult Duration Discrimination Single versus Dual-Task 179

Figure 15c: Averaged ERP Waves for a Single Control Participant in the Easy versus Difficult Stimulus Discrimination in the Single-Task Condition 180

Figure 15d: Averaged ERP Waves for a Single Control Participant in the Easy versus Difficult Stimulus Discrimination in the Dual-Task Condition 181

Figure 16: Mean N1 Amplitude as a Function of WM Load and Electrode Site During the n-Back Task in Experiment 2 182

Figure 17: Mean N2 Amplitude as a Function of WM Load and Electrode Site During the n-Back Task in Experiment 2 183

Figure 18: Mean P3 Amplitude as a Function of WM Load and Electrode Site During the n-Back Task in Experiment 2 184

Figure 19: Averaged ERP Waves for a Single Control Participant in the 0-Back, 1-Back and 2-Back Conditions of the n-Back Task 185

Figure 20: Mean P3 Amplitude for Each Group as a Function of Electrode Site During the n-Back Task 186

Figure 21: Mean F-P Beta Coherence in Left Hemisphere for Each Duration Discrimination Task Condition by Group in Experiment 2 187

Figure 22: Mean F-P Beta Coherence For Each Group by Hemisphere During n-Back Task in Experiment 2 188

INTRODUCTION

Severe trauma to the head often results in very explicit behavioral and cognitive deficits, but until recently it had been thought that any sequelae that might be associated with minor head trauma would be inconsequential (e.g., Levin et al., 1987). Persons with minor head trauma are most often discharged from the hospital after brief observation with neurological signs that are normal (Barth et al., 1983). As well, many incidents of minor head trauma are never reported or are treated on solely an outpatient basis (Segalowitz & Brown, 1991). However, the effects of a minor injury are increasingly being identified as clinically important, persistent, and based on long-term, trauma-related changes in the central nervous system (Swenson, 1997).

The American Congress of Rehabilitation Medicine developed a special interest group to set out a number of criteria that define mild traumatic injury to the brain. According to the Mild Traumatic Brain Injury Committee (1993), the criteria include the following:

1. A physiological disruption of brain function that is traumatically induced and evidenced by one or more of the following:
   (a) loss of consciousness (LOC) not exceeding 30 minutes and initial Glasgow Coma Scale (GCS) rating of 13 to 15 (indicating likeliness of good outcome).
   (b) loss of memory for preceding and post-injury events not exceeding 24 hours.
   (c) altered mental state at the time of injury in the form of being dazed, disoriented or confused, or
   (d) transient or non-transient focal neurological deficit.
2. An injury occurring as a result of the head being struck, or striking an object or as a

result of acceleration-deceleration movement that does not result in direct contact of the head with an object.

3. Symptoms that suggest the existence of a mild traumatic brain injury (MTBI) including:
   (a) physical symptoms, such as nausea, vomiting, dizziness, headache and blurred vision.
   (b) cognitive symptoms, such as difficulties with attention, concentration, memory and executive functioning and
   (c) behavioral symptoms, such as irritability, disinhibition and emotional lability.

Having sustained a minor head injury (MHI) does not necessarily mean that an individual has incurred a brain injury *per se* and there are some who argue that any permanent damage from minor injury is of no consequence and is ultimately reversible with time. However, any force sufficient to cause the brain to accelerate and decelerate within the skull increases the likelihood of neurophysiological damage. The greater the acceleration/decleration forces that attend the impact, the greater the likelihood that some permanent alteration in neurophysiological function has occurred.

Brain Damage Resulting from Minor Head Injury

Often with MHI, there appears to be no structural damage to the skull or brain observable with current imaging techniques. CT scans, MRI, EEG and neurological examinations may all result in findings that are normal (Mild Traumatic Brain Injury Committee, 1993). However, Povlishock and Coburn (1989) claim that minor and moderate head injuries can indeed produce structural changes throughout various areas of the brain and that these structural changes can lead to ensuing neurological or behavioral changes in individuals after minor head trauma. Much evidence comes from animal studies in which experimental animals are subjected to minor or moderate head injury and their brains are then investigated in terms of the cellular response (e.g., Povlishock & Coburn, 1989; Hayes, Lyeth, & Jenkins, 1989). These animal models of head injury have led to the replication of many aspects of human head injury including the type of neural damage produced (primarily axonal damage) and the location of the damage. Structural neuroimaging studies and investigations of metabolic activity in humans who have suffered a MHI have also provided evidence that a MHI may cause some instantaneous and irreversible damage to the brain (Jenkins, Teasdale, Hadley, MacPherson, & Rowan, 1986; Kant, Smith-Seemiller, Isaac, & Duffy, 1997; Parker, 1996).

Diffuse microscopic axonal injury following MHI has been well documented, implying that there must be an organic basis for sequelae following this type of injury (King, 1997). Blumbergs, Scott, Manavis, Wainwright, Simpson and McLean (1994) investigated the brains of 5 individuals who had suffered a minor concussion but had died shortly after due to failure of other systems. By immunostaining for amyloid precursor protein, which accumulates in axonal swellings following traumatic brain injury (TBI), they were able to demonstrate that all cases showed multifocal axonal injury. This type of axonal injury is produced by acceleration of the brain within the skull followed by a rapid deceleration in the opposite or lateral directions (Parker, 1996). This "shear-strain" mechanism results in axonal tearing and neuronal degeneration in various ascending and descending fibre tracts of the brain. As well, the cortical regions that are most often affected by this type of acceleration-deceleration injury are the orbitofrontal and the anterior temporal regions of the cortex because of movement of the brain tissue over the rough, bony protrusions of the skull that support the frontal and temporal lobes (Varney & Menefee, 1993). The posterior portions of the brain typically remain relatively unharmed after minor head trauma. Due to the nature of many MHIs that result from vehicle accidents, falls and sports injuries, the "shear-strain" model of brain damage emphasizing acceleration-deceleration and rotational forces, as well as frontal and temporal lobe damage, is particularly relevant (Barth et al., 1983).

Whereas the nature of the accident may cause diffuse axonal damage, cell destruction as well as neurotransmitter (NT) and receptor disruption may evolve from the initial injury (Parker, 1996). Biochemical and physiological changes in neural tissue following minor cortical impact have been demonstrated. For instance, depolarization of neurons may initiate the release of excitatory NT such as acetylcholine, glutamate and aspartate, which are known to be toxic to neurons in a high concentration thus contributing to long-term changes in brain function (Swenson, 1997). Trauma may also induce the loss of brain autoregulation, causing homeostatic decoupling resulting in high blood flow and low oxygen metabolism both of which have been associated with neuropsychological dysfunction (Parker, 1996).

Structural neuroimaging studies of persons with MHI have demonstrated that identifiable lesions can be seen. Magnetic resonance imaging (MRI) has proved to be a more sensitive measure for detecting injury following head trauma as compared to computerized axial tomography (CT) that is insensitive to damage to underlying brain parenchyma (Swenson, 1997). Jenkins, Teasdale, Hadley, MacPherson and Rowan (1986) conducted a study comparing results of MRI scans and the severity of head injury suffered. Frontotemporal contusions were observed in individuals with no loss of consciousness or brief loss of consciousness. Lesions to the deep white matter were more common in those who were in coma at the time of MRI scanning however they were also seen in some of those who had lost consciousness for a brief period of time. Jenkins et al. (1986) concluded that their study provided evidence for the cerebral hemispheres being susceptible to damage from a closed head injury regardless of its severity.

Kant, Smith-Seemiller, Issac and Duffy (1997) conducted a study to investigate the prevalence of single photon emission computed tomography (SPECT) abnormalities in individuals with persisting symptoms following a MHI. They also compared SPECT scanning with MRI and CT in persons with MHI. SPECT appeared to be more sensitive than MRI or CT in determining the number of cerebral lesions following minor head trauma. Their results showed that over half of persons with MHI who had suffered LOC of less than 20 minutes and were just over 1-year post-injury had abnormal SPECT scans with predominantly frontal and temporal lobe lesions. Thus, in a large number of individuals there was evidence of damage to the brain as indicated by SPECT that could be the basis of their chronic complaint of symptoms post-injury (Kant et al., 1997).

Physiological impairment following a MHI has been investigated with electroencephalography (EEG) and evoked potentials (EPs) as well as with positron emission tomography (PET). Montgomery, Fenton, McClelland, MacFlynn and Rutherford (1991) investigated brain-stem and cortical function following MHI with EEG and EP techniques. They collected EEG and EP data 24 to 48 hours post-injury as well as at 6 weeks post-injury. These researchers found an excess of theta immediately following injury that decreased at 6 weeks post-injury. Auditory brain-stem evoked responses demonstrated significant delays at the time of injury and at 6 weeks post-injury many from the MHI group continued to show abnormal brain-stem responses. Gross, Kling, Henry, Herndon and Lavretsky (1996) investigated brain glucose metabolism as measured by PET in 20 MHI individuals who continued to complain of symptoms 1 to 5 years following their injury. Abnormal local cerebral metabolic rates were most prominent in frontal and temporal cortical and subcortical regions. As well, these abnormal cerebral metabolic rates were significantly correlated with clinical complaints of inconsistent attention and concentration. Both studies provide evidence for continuing brain and behaviour deficits following MHI.

In summary, a significant number of persons who demonstrate symptoms following a MHI may have underlying organic brain damage. Animal research and autopsy studies suggest that diffuse axonal changes as well as biochemical changes following minor head trauma, even with brief or no LOC and when brains appear normal upon gross inspection (Kay, Newman, Cavallo, Ezrachi, & Resnick, 1992). Static imaging of the brain using MRI has revealed lesions of the cortex as well as deep white-matter lesions in persons with LOC of 5 minutes or less. Quantitative EEG, EP as well as PET studies have demonstrated physiological abnormalities in the brains of individuals with MHI. In general it appears that it is possible for a MHI to result in specific and permanent changes to the brain, leaving one to wonder about the course of recovery from such an injury.

Recovery Following Minor Head Injury

The term "minor" head injury might lead to the perception that the injury is one that is negligible in terms of symptoms and is promising in terms of recovery. However, as we have seen from studies on brain damage associated with MHI, it is possible that minor injuries can result in long-term changes to the brain. There are also reports that impaired cognition is not uncommon following trauma to the head even when the injury is minor and does not require inpatient admission to a hospital (Bohnen & Jolles, 1992).

Increasingly, persons are being referred for neuropsychological evaluations following minor head trauma (Binder, 1997). Complaints following MHI range from physical (headache, dizziness, fatigue) to cognitive (attention and concentration, forgetfulness) to emotional (irritability, depression, anxiety) and can, at times, be similar to the problems experienced by individuals who have suffered severe head trauma. Generally, symptoms following MHI consist of subjective, poorly defined complaints. Individuals do not feel they can perform tasks at the same level as before trauma, but these symptoms commonly experienced within the first few weeks after injury generally resolve spontaneously. In an often-cited study by Gronwall and Wrightson (1974), persons who complained of poor concentration, fatigue, irritability, headache and an overall inability to carry out normal work demonstrated a persisting reduction in information-processing rate at 5 to 35 days post-injury. These authors claim that subjective elements of a minor concussion can be accompanied by objective changes in intellectual functioning and that, as intellectual function returns to a normal level, subjective symptoms decrease.

A number of studies have investigated the course of recovery of individuals who have suffered a MHI. Levin et al. (1987) claimed that pre-existing neuropsychiatric disorders and/or prior head injuries might be the basis of persisting cognitive difficulties after a MHI and that if persons with these pre-existing conditions were excluded from testing, they would find minor cognitive deficits that resolve quickly following an uncomplicated MHI. When tested immediately post-injury, the group of individuals with MHI demonstrated disturbances of attention, memory and information-processing efficiency in the first days following their injury. Subsequent testing at 1 and 3 months post-injury indicated that MHI group's cognitive performance had recovered to within the range of the matched control group. Levin et al. (1987) concluded that one uncomplicated MHI was unlikely to produce long-lasting cognitive impairment and chronic disability.

The research of Dikmen, Machamer, Winn and Temkim (1995) showed that there was a relation between the length of time unconscious and the level of cognitive impairment following a MHI. Over 400 individuals were assessed one year post-injury and the results demonstrated that persons with the shortest length of time unconscious demonstrated performance on a comprehensive battery of neuropsychological tests that was comparable to controls. Impairments of attention and memory began to emerge when the severity of the head injury and length of time unconscious increased. Dikmen et al. (1995) claimed that their findings demonstrated that in general there were no long-term neuropsychological impairments associated with MHI.

Binder, Rohling and Larrabee (1997) conducted a meta-analysis of studies that had investigated the persisting effects of minor head trauma suffered by people in adulthood. The meta-analysis focused on studies that included individuals who were at least 3 months post-injury. The results demonstrated a weak association between MHI and persistent neuropsychological difficulties. Binder et al. (1997) concluded that the overall effect of a minor head trauma on neuropsychological performance was undetectable. However, these researchers also noted that detection of subtle neuropsychological problems is likely to be more difficult than detection of an obvious neurological problem.

Even though the results of some studies demonstrate that persons with MHI make a full recovery in the months following minor head trauma, some individuals continue to complain of specific problems post-injury. It has been noted that the return of test scores of individuals with MHI to a level equivalent to control participants' test scores does not necessarily mean full recovery from injury (Gronwall, 1987). Barth, Macciocchi, Giordani, Rimel, Jane and Boll (1983) report that a significant number of individuals with MHI demonstrate reduced adaptive functioning. At 3 months post-injury, persons with MHI who had had difficulty returning to work, were tested on the Halstead-Reitan battery of neuropsychological tests and 33% of those with average or above average intellectual performance demonstrated a mild neuropsychological impairment. In particular, participants demonstrated impaired visuo-motor problem-solving skills and immediate and delayed memory deficits. Kay, Newman, Cavallo, Ezrachi and Resnick (1992) described a study of individuals with MHI seen in the emergency room and assessed symptoms and outcome one week to one year following their injury. Reports of symptoms were very high during the week following trauma. Symptoms declined gradually over time but some symptoms (particularly headache, dizziness, memory problems and decline in socialization) remained at one year following minor head trauma in a substantial minority of individuals. Thus, it appears that although there is a reduction in reported symptoms over the course of recovery, this is not necessarily the case for all symptoms or for all individuals.

The above studies primarily utilized individuals who continued to complain of chronic symptoms following their injury. Symptomatic persons may differ in their prognosis and outcome following head trauma as compared to persons who do not remain symptomatic post-injury and therefore may represent a unique subgroup of individuals. Bohnen, Jolles, Twijnstra, Mellink and Wijnen (1995) investigated whether persons with persistent symptoms following MHI (12 to 34 months post-injury) differed from those individuals who were injured but were symptom-free and from non-concussed controls on various attention and information-processing tasks. Overall, this study demonstrated that no gross differences could be found with regards to attention and information-processing but the subgroup of individuals with persistent symptoms demonstrated a subtle deficit in sustained attention compared to symptom-free individuals and controls.

Alves, Macciocchi and Barth (1993) designed a study to follow a large number of persons with uncomplicated MHI and document the type, frequency and duration of their symptoms following their injury. The majority of persons in this study had been in a motor vehicle accident, were conscious at the time of their admission to hospital (with a GCS of 15), and underwent a one-day stay at the hospital. At discharge, the majority of individuals were symptomatic and a significant proportion continued to demonstrate symptoms at 3, 6 and 12 months post-injury. Headache, dizziness and memory problems were the most common complaints and overall a small but significant number of individuals continued to report symptoms one year following an uncomplicated MHI.

Bohnen, Van Zutphen, Twijnstra, Wijnen, Bongers and Jolles (1994) conducted a study in which persons with MHI were sent questionnaires by mail 1 to 5 years post-injury. These were individuals who were approached simply because they had sustained an injury and not because they were suffering from chronic complaints. The questionnaire consisted of three complaint scales that included everyday complaints that were emotional, vegetative/bodily and cognitive in nature. Rating scores were compared with a group of non-concussed controls. Results demonstrated that the MHI group had higher rating scores on all three complaint scales. Therefore, it appeared that everyday emotional, physical and cognitive complaints were more prevalent and more severe in the MHI group even 1 to 5 years after trauma.

A study of individuals classified as having good recovery from a head injury (regardless of initial severity) was conducted by Stuss et al. (1985). They hypothesized that, if sought, subtle cognitive deficits could be found in well-recovered persons who demonstrated no obvious neurological or neuropsychological deficits at the time of the study. Results demonstrated that there were no significant differences between the individuals with head injury and controls on a variety of measures that included general intelligence, general memory, aphasia and apraxia measures, and measures of frontal-lobe functioning/cognitive flexibility (Wisconson Card Sort, Stroop Task). Significant differences between groups were found on measures of attention and concentration, rapid information-processing, problem-solving and there were some subtle memory deficits. Stuss et al. (1985) concluded that although many individuals seemed to show no objective sequelae associated with injury to the head, cognitive deficits appeared to persist even with good recovery.

In a population of first-year university students, Segalowitz and Lawson (1995) found that those who had suffered a MHI (defined as a blow to the head such that one could not continue the current activity because of dizziness, pain or unconsciousness) were twice as likely to report having attention deficit/ hyperactivity disorder (ADHD). As well, in the university sample having had a head injury was related to having had remedial reading assistance as well as having more difficulty with aspects of social functioning within a school context such as arguing and fighting, daydreaming, and getting started on assignments (Segalowitz & Lawson, 1995). Although the students in this study who had suffered a MHI at some point in their lives had recovered to the point that they could be admitted to university, they continued to complain of difficulties with attention, social monitoring and motivation. Of course, in studies such as these the question of cause and effect remains. It is possible that the difficulties reported by this group of university students who had suffered a MHI were actually pre-existing characteristics that led them to have the injury in the first place. In fact, this is an argument commonly used to dismiss any reported sequelae of MHI.

In summary, some studies demonstrate no significant differences in cognitive functioning between participants with MHI and control participants after a period of recovery. It is possible that this is a result of the nature of the tests being employed and not because there are no differences in cognitive functioning between the two groups. Stuss et al. (1985) claim that standard neuropsychological tests do not create the necessary demands to evoke deficits in many individuals who appear to have recovered from their injury. Other studies have shown that deficits in cognitive processing can persist and that these deficits exist in a MHI group that is overall considered to have good recovery from their injuries.

Lasting Cognitive Impairment Following MHI: Attention Deficits and Reduced Information-processing Capacity

Gross intellectual and memory deficits are not usually found following a MHI. Instead, subtle deficits that selectively impair attention and information-processing often emerge in the context of complex and demanding tasks (Bohnen & Jolles, 1992). We have seen that some of the most common subjective complaints following MHI involve disorders of attention and concentration. Despite a lack of association between general neuropsychological dysfunction and MHI, the meta-analytic review of neuropsychological studies by Binder et al. (1997) demonstrated a small effect size for deficits in the attention domain. Attentional processes such as concentrating attention, sustaining attention, and suppressing attention are thought to be centred in the frontal lobe region (Stuss, Shallice, Alexander, & Picton, 1995). The frontal lobes and, more specifically, the prefrontal cortex (PFC) appear to be integral to the allocation of attentional resources as damage to the PFC has been found to produce disorders of divided attention, problems maintaining attentional focus and high susceptibility to distractions (e.g., Godefroy & Rousseaux, 1996; Grafman, Sirigu, Spector, & Hendler, 1993, Goldman-Rakic, 1993).

A widely accepted explanation of attentional deficits following head injury stems from knowledge put forth both from head-injury theory and from cognitive psychology. In addition to the fact that the frontal lobes are routinely involved in head injury, the type of damage resulting from a head injury, namely diffuse axonal damage, is thought to affect the capacity and speed of information-processing and thus, the ability to allocate attentional resources (e.g., Gronwall, 1989). The term "capacity" is used to refer to the amount of attentional resources one is able to devote to the performance of a particular task with the assumption that there is a limit to the pool of resources available (Schneider, Dumais, & Shiffrin, 1984). Of particular interest in investigating attentional deficits in MHI is the issue of the ability to allocate these limited capacity attentional resources. It has been noted that any physiological or psychological effects (e.g., alcohol/drugs, fatigue, motivation) that result in a reduction of information-processing capacity should primarily affect the ability to allocate attentional resources (Schneider et al., 1984). Thus, if there are limits on the brain's available attentional resources, when there is damage to the brain, there may be even fewer resources available to allocate during information-processing. Clinical observation of individuals recovering from a MHI have indicated that they can be (1) slower than non-injured individuals to process information, (2) distractible, perhaps as a result of reduced capacity to simultaneously monitor relevant and irrelevant information, (3) forgetful, perhaps as a result of reduced ability to concentrate on simultaneous events, and (4) inattentive, as the amount of information to process may exceed their available capacity. These can all be considered attentional deficits related to a reduction in information-processing capacity (Gronwall, 1989) and all may arise as a result of diffuse damage in the frontal lobes.

Assessment of Attentional Abilities Following MH

Those investigating information-processing and attention deficits following MHI have employed a number of measures. These measures have evolved from clinical neuropsychology as well as from experimental psychology. Usually, the subtle deficits demonstrated by persons with MHI are not elicited with standard neuropsychological batteries, which have been developed to detect much more localized brain damage that usually results in specific and isolated cognitive deficits (Gronwall, 1989). As attention cannot be directly observed, a measure of how well a person can attend is usually inferred by how quickly and efficiently they can respond to a task. Reaction time (RT) performance has been a popular method of demonstrating attention difficulties and slowed information-processing following MHI (Gronwall, 1987).

MacFlynn, Montgomery, Fenton and Rutherford (1984) investigated performance of persons with MHI on a 4-choice visual RT task that required them to press a button in response to the spatial location of a light in a display. Individuals were tested 1 day, 6 weeks and 6 months following their injury and results indicated that they performed the task more slowly than controls immediately and 6 weeks post-injury. A serial improvement in RT was noted from 1 day to 6 weeks and from 6 weeks to 6 months post-injury at which point the RT performance of individuals with MHI was significantly faster than control performance. Because controls were only tested once, practice effects likely explain the superior performance of the MHI group at 6 months post-injury. Shum, McFarland, Bain and Humphries (1990) used a 4-choice RT task in which participants had to respond by making a directional judgement based on the visual stimuli presented. Individuals with recent MHI did not demonstrate impairment in responding whereas those with more severe injuries demonstrated impairments in identification of the stimulus, in response selection and in the response execution stages of information-processing. The authors admitted that the simplicity of the RT task might not have captured subtle processing deficits in those with MHI. Cremona-Meteyard and Geffen (1994) employed a more complex visuospatial RT task in which cue information was given that was either neutral or would direct attention to the impending target to occur in the right or left visual field. These directional cues could be either valid or invalid. RTs were expected to be fastest when the targets were presented in the expected location and slowest when they were presented in the unexpected location (Cremona-Meteyard & Geffen, 1994). Two groups of Australian Rules football players were tested within 2 weeks and 1 year of their injuries. Overall, these researchers did not find any differences between the MHI and control groups in terms of simple RTs or number of errors made. Differences were found in terms of benefiting from the presentation of valid cues. At 2 weeks post-injury as well as 1 year post-injury, the MHI group differed from controls in that they did not respond faster to the targets when valid cues were presented, indicating an inability to take action quickly in response to expected events following MHI (Cremona-Meteyard & Geffen, 1994).

Another method of investigating attention has been to look at specific aspects such as the ability to focus attention and withstand distraction. Van Zomeren and Brouwer (1987) used a RT task with a distractor that had to be ignored to test focused attention ability in persons with minor concussion. They found that the addition of a distractor created a large increase in RT for both the control and MHI groups but the effect was stronger in the MHI group. This group needed significantly more time than controls to overcome the effect of the distraction. Stuss, Stethem, Hugenholtz, Picton, Pivik and Richard (1989) also examined the ability of persons with minor concussion to ignore distracting or redundant information during a RT test. Participants were required to focus their attention and suppress any automatic tendency to respond to information intended to be distracting or redundant. Stuss et al. (1989) demonstrated that individuals with minor concussion had more difficulty controlling the unnecessary processing of information.

Another approach to the study of attention has been to use vigilance and continuous- response tasks (Van Zomeren & Brouwer, 1987). Participants are required to respond to relatively infrequent and isolated stimuli. Healthy participants normally show a gradual decline in their ability to detect the target stimulus over time (Buchtel, 1987). Brouwer and van Wolffelaar (1985) predicted that a larger vigilance decrement would be found in recently concussed individuals compared to controls. During a 40-minute auditory task, participants had to identify the presence of a target stimulus that occurred with low probability. Heart-rate variability was also taken as a measure of mental effort associated with performance of the task. Results indicated that there were no significant differences in time-on-task or large increments in heart-rate variability in the MHI group compared to controls. Thus, even though Van Zomeren et al. (1987) have reported that participants make more errors and perform more slowly during vigilance tasks following head trauma their performance over time does not significantly differ compared to controls. Parasuraman, Mutter and Molloy (1991) compared sustained attention performance of individuals with MHI and uninjured controls on a high-probability visual vigilance task that also employed stimulus degradation. Under normal viewing conditions, there were no significant differences in performance between the control and MHI groups. As well, under the degraded viewing condition, there was no evidence for a greater vigilance decrement in the MHI group; however, this group did demonstrate a decreased sensitivity to detection of the degraded stimulus during the vigilance task. These authors concluded that MHI does not lead to a greater rate of performance deterioration but it can lead to lower perceptual sensitivity which could in turn lead to a vigilance decrement.

Bohnen, Jolles, Twijnstra, Mellink and Sulon (1992) compared the vigilance performance of persons with MHI who complained of persisting symptoms following their injury with that of persons with MHI who did not complain of symptoms (asymptomatic) and non-concussed controls. They also tested whether the groups would demonstrate a difference in stress response as measured by increased cortisol levels during vigilance performance. Participants were required to respond to a rare target during a 12.5-minute task. Individuals who complained of post-injury symptoms demonstrated significantly worse performance than individuals without symptoms and control participants. Interestingly, a decrease in vigilance performance was related to an increase in cortisol response during the task and this effect was surprisingly greater for the asymptomatic MHI group compared to the symptomatic MHI group and the controls. Bohnen et al. (1992) suggest that a vulnerability to increased cognitive demands remains in individuals with MHI with good recovery. Even though performance was at the level of controls, there appeared to be a greater physical or stress reaction with increased demands on cognitive resources in those who had apparently recovered from their injury.

Traditional measures of information-processing speed and attention will likely be found to be normal following MHI. Tables 1a and b summarize previous studies that have and have not found long-lasting cognitive impairment following MHI. It would appear that tasks requiring complex attention elicit deficits after MHI, which show up in increased reaction times measured during focused and sustained/vigilant attention conditions.

Lasting Cognitive Impairment Following MHI: Executive Function

In daily activities, we are expected to divide our attention among many things at once. We are also expected to deal with a great deal of relevant and irrelevant information presented quickly. Controlling our attention in situations such as these involves the use of executive functions, i.e., the ability to voluntarily control our cognitive and motor behaviour in order to effectively carry out specific goals. Often, a continuing complaint following MHI is that one can no longer perform two tasks at once. Many individuals complain that they are overwhelmed by rapidly presented information or become easily distracted by irrelevant information. Again, it is the frontal lobes that are thought to be primarily involved in the integration and co-ordination of goal-directed cognitive processes. D'Esposito, Detre, Alsop, Shin, Atlas and Grossman (1995) demonstrated in a functional MRI study that the concurrent performance of two tasks by healthy participants elicited the activation of a region in the prefrontal cortex whereas performance of the tasks alone resulted in activation of posterior regions of the brain. This finding was thought to be reflective of a frontally based "central executive" system responsible for controlling attention and information flow being recruited during the performance of two tasks at once.

Damage to prefrontal regions as a result of head trauma most often manifests in disorders of planning, mental flexibility, difficulty shifting attention between simultaneous tasks and impaired response inhibition (Boller et al., 1995) but assessment of these deficits has proven to be difficult employing standard psychological tests (Varney & Menefee, 1993). Tasks requiring controlled relative to more automatic information-processing are necessary in order to demonstrate the subtle cognitive difficulties of individuals with MHI (Cicerone, 1996).

<u>Assessment of Executive Function Following MHI</u>

Executive function refers to the ability to integrate and co-ordinate several cognitive processes such as goal formulation and planning as well as carrying out the behaviors necessary to accomplish the goals (Stablum, Mogentale & Umilta, 1996). The evaluation of executive functioning and controlled attentional processing has often involved employment of the dual-task paradigm derived from cognitive psychology. Under dual-task conditions, participants are required to distribute and sustain their attention while performing two simultaneous tasks. This usually leads to a decline in performance in the dual task relative to single-task conditions.

Gentilini, Nichelli and Schoenhuber (1989) employed tests of divided and distributed attention to investigate deficits in controlled processing in persons with MHI. Participants in the study completed these attention tasks at one month and three months post-injury. Patient responses on the divided-attention task were significantly slower than controls overall; however, controls and persons with MHI were found to be equally affected by addition of a concurrent task. When persons with MHI were required to distribute their attention in order to respond to the simultaneous appearance of a stimulus across both visual fields, individuals with MHI were found to again be significantly slower than controls at both one and three months post-injury.

Cicerone (1996) investigated the nature of dual-task performance in a group of participants with MHI who complained of deficits following their injury. As with the previous study by Gentilini et al. (1989), both controls and the MHI group were found to perform significantly slower under dual-task demands; however, in this study the MHI group was found to be significantly more affected than the control group by the addition of the relevant distractor condition. Although control participants' performance slowed with the dual-task demands their performances were not as markedly affected as was the performance of the MHI group. There were no significant differences in terms of accuracy between the two groups. Thus, results were interpreted as demonstrating that individuals with MHI suffered more than controls when they were required to process and respond to a secondary task. Although measures of accuracy remained adequate, performance of persons with MHI continued to be compromised by slow information-processing perhaps reflecting a speed-accuracy trade-off (Cicerone, 1996).

Stablum et al. (1996) similarly investigated whether an attentional deficit could be established in a dual-task condition compared to single-task performance in asymptomatic individuals with MHI. The MHI group did not show a greater dual-task cost as compared to the control group, however, the means were in the predicted direction with the MHI group showing slightly slower RTs during the dual task compared to controls. The authors further investigated the effect of LOC on dual-task performance. They divided their participants into a group who had lost consciousness for 20 minutes or less, a group who had not lost consciousness and a control group. When single- and dual-task performance was compared for these groups, the dual task was found to significantly increase the RT performance of the LOC group. Therefore, Stablum et al. (1996) were able to demonstrate that dual-task demands elicited a greater cost for those with MHI who had brief LOC.

In summary, executive functions involve the integration and co-ordination of several processes including forming, planning and carrying out goal-directed behaviours and shifting attention between simultaneous tasks. It appears that complex and demanding information-processing tasks that require either attentional recruitment or controlled attentional allocation are most likely to capture any persistent cognitive deficits associated with MHI.

Overview of Experiments 1 and 2

From the review of literature, we have seen that many of those studying cognitive impairment following MHI have tested symptomatic individuals soon after injury or employed tests that were not likely to be difficult enough to elicit deficits following minor head trauma. Many studies indicate that traditional neuropsychological measures are found to be normal following a MHI and it is not until tasks require complex attention abilities that individuals with MHI demonstrate cognitive deficits. The main question to be addressed in Experiment 1 was whether a group of individuals who reported a MHI, but continued to function well enough to be admitted to university, demonstrated subtle deficits on cognitive tasks requiring complex attentional abilities. By administering complex tasks that require the recruitment of controlled information-processing as opposed to more automatic response tendencies, we might be able to show that those with MHI continue to show deficits even years after their injury. Experiment 2 was designed as an electrophysiological follow-up to Experiment 1 during which we investigated cognitive-resource allocation by collecting event-related potential (ERP) and electroencephalographic (EEG) coherence measures. These measures were intended to provide insight into the cognitive process by allowing us to make inferences from brain activity elicited by various task manipulations. ERP and EEG coherence measures also allowed us to investigate whether electrophysiological differences existed between those with MHI and controls during the performance of particular cognitive tasks requiring controlled information-processing.

Rationale for Experiment 1

We predicted those tasks heavily dependent on frontal-lobe function and controlled processing would be more likely to elicit deficits, even years after a MHI, than tasks more dependent on posterior brain regions. We divided our experimental tasks into those that can be considered to be depend on executive functions and controlled information-processing and those that can be accomplished on the basis of more automatic response tendencies. Thus, our tasks were designed to investigate attentional recruitment, complex information-processing and control of information flow as well as the ability to withstand distraction and ignore irrelevant information. Control tasks were employed to measure cognitive functions that are thought to be preserved following MHI such as acquired knowledge and pure motor speed.

Tasks Associated with Frontal-Lobe Function

Attentional Recruitment: Focused Attention. The first question to be addressed was the degree to which MHI influenced the ability to recruit attention during tasks that required varying degrees of focused attention. Participants with MHI and controls were tested on tasks that were designed to increase in difficulty such that incrementally greater demands were placed on attentional resources. Some tasks would require only the minimal recruitment of attentional resources whereas more demanding tasks would require the recruitment of considerably more resources. ***We hypothesized that if MHI leads to decreased attentional resources, those with MHI would have fewer attentional resources to recruit as the requirements of focused attention increase and their performance will decline relative to controls.***

Distractibility and Inhibitory Control. Attentional difficulties can also take the form of the inability to resist interference from stimuli that would normally be easily ignored or suppressed. This aspect of attention involves inhibitory control over the allocation of attentional resources and one's response tendencies. Our second question was whether MHI would affect the ability to shift attention away from a stimulus and to avoid being distracted by irrelevant stimuli. ***The second hypothesis was that, relative to no injury, MHI leads to reduced attentional resources and those participants with MHI might find themselves unable to ignore or suppress responses to distracting stimuli.***

Divided Attention, Working Memory and the Central Executive System. Dividing attention involves the management of relevant information that is being presented simultaneously while controlling what information is being responded to at any particular time. This process, referred to as the central executive, is thought to co-ordinate the processing of information on-line and is considered to be a component of working memory. Whereas the central executive refers to the ability to allocate attentional resources so that one can prepare for, maintain preparation for and process information, working memory refers to the temporary activation of information so that it can be processed in conjunction with incoming information. Both working memory and the central executive are thought to be highly dependent on attentional capacity so that decreased capacity could lead to deficits in the amount of information that could be actively maintained and co-ordinated at any one time (Baddeley, 1995; Sohlberg & Mateer, 1989). ***The third hypothesis, therefore, was that participants with MHI would have decreased working-memory capacity and/or more difficulty than control participants allocating attention in a systematic way during performance of tasks that required divided attention.***

Tasks Less Dependent on Frontal Lobe Functions

As information becomes well established (crystallized) and as cognitive operations become overlearned and thus, more automatic, reliance on higher level attentional resources is reduced. Standardized measures that rely on well-established knowledge structures are more resistant to the effects of brain damage (Hall & Bornstein, 1991). As control measures, we employed a number of tasks that tapped general cognitive functioning and pure information-processing speed that, because of their relative automaticity, would rely less on frontally based attentional processes. As well, individual differences on these tasks can be used as an index of individual differences in general cognitive ability. As such, they can be used as covariates to control for pre-existing intellectual differences that might affect the more attentionally dependant "frontal" tasks.

Intelligence, Acquired Knowledge and Motor Speed. We did not expect to find any differences in level of general intellectual functioning between the groups, as the population of participants we were testing were all university students who had overcome any intellectual disadvantages to achieve post-secondary education.

Knowledge of previously acquired information was assessed in both MHI and control groups to determine whether facility with learned knowledge differed between the two groups. As studies of individuals with frontal damage have shown, these participants do not usually suffer any loss of previously acquired information and they do not do poorly on formal ability tests. We expected that participants with MHI would not demonstrate differences compared to controls on tasks that measured facility with acquired knowledge.

Evaluation of simple motor-speed performance allowed us to investigate whether those with MHI demonstrated slower processing speed in general. We did not expect to see differences between the MHI and control groups on simple tasks requiring motor speed. We did expect that if speed-of-performance differences existed between groups they would surface on more difficult attentional tasks that required increased attentional resources. ***Thus, the fourth hypothesis was that participants with MHI would not differ from control participants on tests based on overlearned or more automatic aspects of cognitive function.***

METHOD

Participants

Participants were recruited from Brock University and the University of Waterloo. Sixteen students from Brock University (8 female, 8 male) (M=20.0 yrs; SD=0.73; range=19 to 21 yrs) and 16 students from University of Waterloo (8 female, 8 male) (M=22.5 yrs; SD=4.77; range=19 to 33 yrs) reported on a questionnaire given in an Introductory Psychology class that they had experienced a blow to the head that caused them to stop their current activity due to dizziness, pain or unconsciousness. Loss of consciousness, if it had occurred at all, was limited to 20 minutes or less. Thus, our population of injured participants was selected based on self-report of a MHI and was considered to be at a higher risk for MTBI. We had no objective measures of brain injury for these participants (e.g., CT or MRI scans, neuropsychological reports), however, such measures are typically insensitive to the presence of microscopic shearing injuries.

A control group was made up of 16 age-matched students from Brock University (8 females, 8 males) (M=19.6 yrs; SD=1.30; range=19 to 24 yrs) and 16 age-matched students from the University of Waterloo (8 females, 8 males)(M=22.5 yrs; SD=6.21; range = 19 to 39 yrs). Control participants and participants with MHI were additionally matched as closely as possible for their area of major at university. All controls were recruited from an Introductory Psychology class and reported no history of head trauma.

Questionnaires

Minor Head Injury Screening Questionnaire. This questionnaire was given to all participants and contained questions regarding incidence of MHI, age at which the injury occurred, length of time unconscious and whether hospitalization was required. The same questionnaire was used at both universities. This questionnaire was used to select the participants for the study.

Brock Health and History Questionnaire. A questionnaire was given to all participants in order to obtain background information on health history, hospitalizations and use of medication, as well as information on educational background and their use of alcohol and caffeine.

Behavioral Paradigms

Attentional Recruitment: Focused Attention Tasks

Attentional recruitment was investigated with tasks that allowed for incremental increases in the difficulty of task demands. These tasks allowed us to measure focused attention because participants were required to recruit and focus more attentional resources to discriminate the target stimulus as the tasks became more difficult. Tasks were presented in which participants were required to discriminate increasingly difficult distinctions in tone pitch as well as increasingly difficult distinctions in tone duration.

Easy Pitch Discrimination Task. Participants were presented with two different computer-generated tones. They were required to press a computer key to a high-frequency tone (1500 Hz). They were not to respond to the other tone being presented that was a low- frequency (800 Hz), non-target tone. These tones were quite distinct in pitch and therefore were thought to require minimal recruitment of attentional resources in order to distinguish between them. Target tones were presented on 20% of the trials and non-targets were presented on the remaining trials. Both tones were 100 milliseconds (ms) in duration and a total of 200 tones were presented. From this and the following discrimination tasks, a measure of mean RT to the target tones was obtained (with longer

RTs expected for the more difficult discriminations requiring increased focused attention). As well, signal-detection analysis was performed in order to provide a measure of stimulus discrimination (d') and the threshold for making a response (β) (with decreased ability to discriminate the target and increased threshold to respond to the target expected as the difficulty of the stimulus discrimination increased).

Difficult Pitch Discrimination Task. This task was similar to the Easy Pitch Discrimination Task except that to make the task more difficult, target and non-target tones were presented that were very close in pitch, thus requiring recruitment of considerably more attentional resources to distinguish the target tone. In order to determine the threshold level for pitch discrimination for each participant, pilot testing was done prior to administration of this condition to make sure participants could discriminate the tones at a less-than-perfect performance (i.e. 70% of the time). During the Discrimination task, participants were required to make a computer key press to a high target tone that occurred on 20% of the trials and were required to not respond to a low, non-target tone that occurred on the remaining trials.

Easy Duration Discrimination Task. Participants were presented with two different computer-generated tones that differed in duration. They were required to press a computer key to a short, target tone 100 ms in duration and not respond to longer, non-target tone 150 ms in duration. As with the pitch discrimination, in the easy condition these tones were quite distinct in duration and therefore were thought to require minimal recruitment of attentional resources in order to distinguish between them. Target tones were presented on 20% of the trials and non-targets were presented on the remaining trials.

Both target and non-target tones were presented at 400 Hz.

Difficult Duration Discrimination Task. As in the Easy Duration Discrimination Task, this oddball task required participants to distinguish tones that differed in length. To make this task more difficult, the difference in duration between the target and non-target was reduced by 25 ms and therefore requiring an increase in focused attention to distinguish the target tone. Participants responded with a computer key press to a short, 100 ms target tone and were not to respond to a slightly longer, 125 ms non-target tone. Again, both target and non-target tones were presented at 400 Hz with targets presented on 20% of the trials.

Distractibility and Inhibitory Control Tasks

Eriksen Flanking Paradigm (Eriksen & Eriksen, 1974). This task gave us a measure of participants' abilities to have inhibitory control over their automatic response tendencies and abilities to avoid being distracted by irrelevant stimuli. Participants were required to respond with a key press to a target stimulus that was surrounded with four distractor stimuli (e.g., H H S H H; respond to letter S). Thus, participants were required to respond to the center letter (S or H) and avoid being distracted by the surrounding letters. It was expected that the MHI group would demonstrate reduced ability compared to controls to resist interference from the distractors. The five-letter stimuli were presented continuously with an initial presentation being a prime display and the following presentation being a probe display. Both the prime and probe displays were presented for 250 ms. Participants were required to make a response to both of these presentations as quickly as they could. The probe display was presented for 500 ms after a response was made to the prime stimulus. The prime display of the next pair of stimuli was presented

2500 ms after the response to the previous probe trial. Participants started with 48 practice trial and then completed a total of 336 test trials. The administration of the trials was divided into two sessions that were completed at different times during the testing session.

The organization of this task allowed the investigation into how the presentation of the prime affected participant response to the probe stimulus. The prime presentation could have a facilitory effect if it was related to the probe stimulus in some way (e.g., Prime: H H S H H followed by Probe: X X S X X). Also, within each stimulus presentation, the targets and distractors could be identical and this would lead to a facilitation of the target response (e.g., S S S S S or H H H H H). In both cases, the participant would be expected to demonstrate a faster RT to the target stimulus. Participants with MHI and controls were not expected to demonstrate differences in RTs to facilitated targets.

The prime presentation could also interfere with participant performance if the target on the probe trial was the same as the distractor on the prime trial (e.g., Prime: H H S H H followed by Probe: X X H X X). Additionally, within each stimulus presentation, targets and distractors could differ from each other, which would lead to response competition and interference with target responses (e.g., H H S H H or S S H S S). In this case, the participant would be expected to demonstrate longer RTs to the stimulus. The MHI group was expected to demonstrate greater interference effects and longer RTs than controls as a result of the presentation of distracting stimuli.

Continuous Performance Task (CPT) (Gordon, 1983). Participants performed two phases of this task, one that required them to press a computer key whenever the number 9 appeared and to withhold responses to all other numbers that were presented. In the second phase, participants were required to respond with a computer key press to all numbers except the number 9. RT performance during each of these phases of the CPT task was compared with a simple reaction time (SRT) phase in which participants were required to respond as quickly as possible to every number (from 0 to 9) that appeared on the screen. Therefore, this task allowed us to again measure the influence of distracting stimuli and the ability to inhibit automatic response tendencies. RT performance on a SRT task was compared with RT performance on tasks that required suppression of a response to distracting stimuli.

The two inhibitory-control phases of this task each included a total of 240 trials and the numbers were presented for 250 ms at a fixed rate of 1000 ms per presentation, with the number 9 occurring 15% of the time. Mean RTs were calculated by averaging the reaction times of the correct responses in each phase. The number of omissions (failing to press the computer key when supposed to) and false alarms (pressing the computer key when not supposed to) were also calculated. The MHI group was expected to perform more slowly and commit more errors during the components of the CPT task that required inhibitory control.

Stop Signal Paradigm (Logan, Schachar, & Tannock, 1997). One component of the Stop Signal Paradigm required the participant to perform a choice RT task, which required them to press a computer key with the left hand when an arrow pointed left, and right hand when the arrow pointed right, giving us a measure of RT when a decision had to be made. On some trials a stop-signal tone was presented and participants were required to withhold their response to the directional arrow when they heard it, thus giving us a measure of participants' inhibitory control over their responses. The stop signals were presented on 25% of the trials. The timing of the tone was adjusted so the participant was able to inhibit responding on only 50% of trials. After the data were collected, an automatic scoring program calculated, for each participant, the average RT during the choice task when the stop signals were not presented (choice RT), and the average length of time required between presentation of the stimulus and presentation of the stop signal in order for the participant to inhibit a response (average stop signal delay).

Selective Stimulus Finding. This pencil-and-paper task also allowed us to measure distractibility, as it required participants to search for a letter embedded among many, randomly placed irrelevant letters. Participants were given a sheet of paper and were required to go through the page and cross out all of the letter A's that were placed randomly along with many other letters on the page. Participants were given 60 seconds to complete this task and a raw score was derived by counting the number of A's that were crossed out within the time limit.

The Cross-Circle Test. The Cross-Circle test required participants to make drawings of circles and crosses on an 8 ½" x 11" sheet of paper. The figure that was to be drawn was indicated by either the word "circle" or the word "cross" printed above small boxes (3.5 cm x 2.5 cm) on the paper where the drawings were to be made. In Part 1 of the test, participants were required to draw a circle when they saw the word "circle" and a cross when they saw the word "cross". Participants were given 90 seconds to complete this portion of the task and were told to work as quickly as possible without skipping any boxes. In Part 2 of the test, participants were required to switch what they were drawing inside of the boxes such that they were drawing crosses when they saw the word "circle" written above the box and circles when they saw the word "cross" written above the box.

Thus, participants had to overcome the automatic tendency to draw a circle when the word "circle" was presented. Again, 90 seconds was allowed and participants were required to work as quickly as possible. A raw score for each condition was obtained by counting the number of correct drawings that were made within the time limit. The number of errors made was also recorded for each condition. The difference in the number of correct drawings between Parts 1 and 2 of this task provided an index of inhibitory control.

Divided Attention, Working Memory and Central Executive Tasks

Duration Discrimination with Distractor Task. This task allowed us to measure divided attention and the allocation of attentional resources because it required participants to perform two tasks at the same time. The Easy Duration Discrimination task as described above was performed with the non-dominant hand while the participant simultaneously completed a verbal working-memory distractor task. During the distractor task, the participant was presented with a single digit (excluding zero) every 2 seconds. Participants had to monitor the numbers and press the computer mouse button with their dominant hand every time three odd numbers appeared in a row or every time three consecutive ascending or descending numbers appeared. Participants were given a few minutes to practice doing the two tasks at the same time. As in the discrimination tasks described above, a mean RT was calculated for both the duration task and the number task. As well, signal-detection analysis provided a measure of stimulus discrimination (d') and the threshold for making a response (β). A comparison of RT, d' and β performance during the single and the dual-task conditions provided an index of how well participants could divide their attention and allocate their attentional resources.

Paper and Pencil Dual Task (Della Salla, Baddeley, Papagno, & Spinnler, 1995). Divided attention and allocation of attentional resources were also measured during this task, in which participants completed a digit-span task while at the same time completing an eye-hand tracking task. The digit-span task required the participant to repeat back, in the same order of presentation, a series of numbers to the examiner. The examiner first determined the participant's baseline for digit span. The examiner began with 3 digits and then increased the number of digits presented by one digit. The participant's digit span was taken as the maximum length of digits that the participant could repeat back without making an error.

Once the baseline span was determined, lists of digits at the participant's span length were presented continuously for two minutes and the participant repeated them back to the examiner in their order of presentation. The measure obtained from this single-task condition was the proportion of digit lists correctly recalled. A second single-task condition was then given to the participants in which they were required to perform an eye-hand tracking task (crossing out successive square boxes (1 cm x 1 cm) that were linked to form a path) as rapidly as possible within a two-minute time limit. The measure obtained from this single-task condition was the number of boxes that could be crossed out in two minutes.

In the second phase of this test, a dual task was given to the participants. They were presented with a new list of digits at their span length that they repeated back in their order of presentation. At the same time, they were required to perform the eye-hand tracking task. This dual-task condition was presented for two minutes and the measure obtained from this condition was again the proportion of digit lists recalled correctly as well as the number of successive boxes crossed out within the time limit. The difference between single- and dual-task conditions in the proportion of digit lists recalled and the number of successive boxes crossed out served as an index of a participant's ability to adapt to the increased attentional demands of the dual task.

Computerized Multiple Performance Task (Elsmore, 1991). Participants completed a computerized multi-tasking program. Again, this task allowed us to measure divided attention and allocation of attentional resources because participants were required to perform 4 different tasks at the same time. The tasks necessitated (1) recollection and evaluation of items (participants monitored the presentation of single letters and determined whether a letter was present in a series of study letters), (2) the performance of a self-paced task (participants added two 4-digit numbers), (3) monitoring and responding to visual information (participants kept track of an advancing line and pressed a reset button before it reached the end) and (4) monitoring and responding to auditory information (participants discriminated between a high and low tone and responded to the high tone only). These four tasks were performed simultaneously and were presented on the computer screen that was divided into four quadrants, each quadrant presenting a single task. All responses were made by pressing a computer mouse key with the participants' dominant hand. A window in the center of the screen presented the participant's "score" that was a composite of all tasks being performed. The participants were told that their goal was to maximize this score. Points were automatically given for correct performance and they were subtracted for incorrect performance on all tasks. The total score on this task was taken as an index of the participant's ability to adequately allocate their attention under high demand conditions. A higher score would indicate greater facility in the allocation of attention.

Digit Span Backward (Wechsler, 1981). Participants repeated back, in reverse sequence, a series of numbers to the examiner. For example, if the examiner recited "2-5-8", the participant needed to repeat back "8-5-2". Every so often, one number was added to the series of numbers so that it increased in length until participants repeated back two sets in a row incorrectly. Each participant's digit span was subsequently calculated to be the length of digits of which two consecutive series could be correctly repeated and was considered an index of working-memory capacity in that participants were able to successfully maintain temporary activation of information.

Two-Back Task (Petrides, Alvivsatos, Meyer, & Evans, 1993). The Two-Back Task required participants to view a series of numbers presented on a computer screen one at a time. Participants were required to indicate with a computer key press every time the number on the screen was the same as the number that was presented two items earlier. Thus, this task provided us with another index of working memory and the ability to maintain information in an active state. For example, given the numbers 4-4-5-3-5-3, the participant would respond with a computer key press to the second 5 and the second 3. A response was not required when the number was not a repeat of the item that was presented two items earlier. A total of 80 numbers (30% targets) were presented for 500 ms at a rate of one number every 1000 ms. The mean RT was calculated for all correct responses. As well, the total number of correct responses and the number of omissions and false alarms were calculated and provided an index of working- memory ability.

Self-Ordered Pointing Test (Petrides & Milner, 1982). This task provided a measure of visual working memory. Participants viewed a 4 x 4 arrangement of different pictures and were required to point to a different picture in 16 consecutive trials until all of the pictures were selected. Therefore, on trial 1, participants were required to point to a picture and on trial 2, participants were instructed to point to a picture that was different from the one pointed to on trial 1. On the third trial, participants were instructed to point to a picture that was different from the first two selected. This process was continued until participants had made 16 selections. The arrangement of the pictures on the cards was changed from trial to trial and participants had to depend on their working memory in order to keep track of their performance and to avoid selecting the same picture more than once. This task was repeated three times and the raw score was the total number of correct responses across the three trials. As well, the number of errors made over the three trials was calculated. Both measures provided another measure of working-memory ability.

<u>Culture Fair Intelligence Test</u> (Cattell & Cattell, 1960). The Culture Fair Test correlates highly with Spearman's "g" (general intelligence). This test can also be considered a general index of attention and/or fluid intelligence. According to Duncan, Emslie and Williams (1996), evidence suggests that "g" largely reflects frontal-lobe-control functions. Thus, we employed the Culture Fair test in order to determine whether individuals with MHI demonstrate deficits compared to controls on a test of general function. This measure does not have the specificity of the other attentional measures we employed and appears to rely heavily on visuo-spatial skills.

The Culture Fair test was designed to reduce the influence of previous knowledge by presenting four different subtests all containing novel spatial problems for participants to solve. The raw score on this test was obtained by summing the number of correct responses on all four subtests and was considered an index of non-verbal intelligence.

Control Tasks

These tasks presumably rely on overlearned information and automatic response tendencies and therefore no group differences were predicted.

Acquired Knowledge. The Verbal Meaning subtest of the Primary Mental Abilities Test (PMA) for Grades 9 to 12 (Science Research Associates, 1962) was given to assess verbal knowledge. The subtest was composed of 60 items and participants were required to locate a word in the row with the same meaning as the word at the beginning of the row. For example, the word "safe" was presented at the beginning of the row and the rest of the words in the row were "secure", "loyal", "passive", "young" and "deft". Participants were required to choose the word that meant the same as "safe". The raw score was the number of correct meanings selected by the participant and was considered an index of verbal ability.

In a second test of acquired knowledge, the Information subtest of the WAIS-R (Wechsler, 1981) was administered. This subtest included 29 questions that tested a broad range of general knowledge including important dates as well as historical and geographical facts. For example, the participant was asked questions such as "How many weeks are there in a year?" or "What is the Koran?" and they were required to give a verbal response. The raw score was the number of correct answers given by the participant and was considered an index of crystalized intelligence or general world knowledge.

Motor Speed. Participants were given a sheet of paper containing 22 rows of 19 letter A's. They were required to go through one row at a time and cross out as many A's as they could in 60 seconds. The raw score was the total number of A's crossed out within the time limit indicating pure speed of motor performance.

The Paper-and-Pencil Dual task, which required participants to perform a eye-hand tracking task (crossing out square boxes) under the single-task condition, also gave us an indication of participants' motor speed performances. This speed measure was the number of boxes that participants crossed out within the time limit (two minutes).

Simple Reaction Time. This portion of the CPT task briefly described above involved the presentation numbers from 0 to 9 rapidly on the computer screen during which time participants were required to respond with a computer key press to all of the numbers that appeared on the screen. A total of 40 numbers were presented randomly for 250 ms. The delay period between stimulus presentation was variable (2000 to 4000 ms). The mean RT was obtained by calculating the average time to respond to the number stimuli and provided an index of simple motor response to presentation of visual stimuli.

Procedure

The testing session was 3 hours in length during which time all participants performed the behavioral tasks described above. Participants were provided with rest periods throughout the testing session. The order in which the tasks were administered is presented in Table 2.

RESULTS

Participants

A total of 64 participants were tested in this experiment with 32 participants from Brock University and 32 participants from the University of Waterloo. From each university, 16 participants reported having suffered a MHI and 16 reported never having had a MHI. Both the MHI group and the control group at each university were made up of 8 males and 8 females.

At Brock University, 59.3 % of participants were Arts majors, 15.6% were majoring in Sciences, 6.25% were majoring in Math and/or Computer Science, 12.5% were majoring in Physical Education or Recreation and Leisure Studies and 3.12% were majoring in Business. 78.1% of students were in their first year of study and 21.8% were in their second year of study.

At the University of Waterloo, 25% of participants were Arts majors, 9.3% were majoring in Sciences, 56.2% were majoring in Math and/or Computer Science and 9.3% were majoring in Engineering. 50% of students were in their first year of study, 20.5% in their second year, 14.7% in their third year and 14.7% in their fourth year of study.

Comparison of University Populations

The Brock and Waterloo populations were compared on all control measures in order to determine whether the groups differed in overall intellectual functioning. A oneway ANOVA revealed that the Waterloo group scored significantly higher than the Brock group on the Culture Fair Intelligence Test, ($F(1,63)=15.1$, $p<.001$), as well as scoring significantly higher on the Information subtest of the WAIS-R, ($F(1,63)=15.749$, $p<.001$). This difference was not surprising given the differences in admission requirements, year level, and academic programs between the two university populations. In the Waterloo population, over 50% of participants were math and computer science majors. This program has particularly high admission standards. The two university populations did not differ on any of the other psychometric measures of non-frontal functioning such as motor speed or verbal knowledge.

The two university populations were also compared on the basis of age, as the Waterloo group included more participants from the upper years (Year 3 and 4) of study. A oneway ANOVA revealed that the two university groups were significantly different in terms of age of participants, ($F(1,63)=7.7$, $p=.007$). Means and standard deviations for Brock and Waterloo populations scores on the Culture Fair test and the Information subtest as well as means and standard deviations of age are presented in Table 3.

MHI Characteristics

MHI was defined as any blow to the head that caused participants to stop their current activity. If a participants indicated on the MHI questionnaire that they had suffered such an injury, they also completed questions regarding age at which the injury occurred, cause of injury, whether loss of consciousness occurred and if so, the length of time unconscious, whether hospitalization occurred as a result of the injury and whether they had suffered more than one head injury.

The average length of time since injury was 5.4 years for the Brock group (SD=4.36; range=0 to16 years) and 11.8 years for the University of Waterloo group (SD=7.96; range=0 to 25 years). Causes of injury were motor vehicle or bicycle accidents, falling down, sports accidents, a fight or attack and other causes, such as getting hit in the head with a snowball or running into something with their head. Table 4 summarizes the causes of the injuries sustained in both university populations.

Unconsciousness was reported in 12 cases in the Brock group (7 reported less than 1 minute, 4 reported 1-5 minutes and 1 reported 5-30 minutes) and 9 cases in the Waterloo group (3 reported less than 1 minute, 5 reported 1-5 minutes and 1 reported 5-30 minutes). Hospitalizations as a result of the injury occurred in 8 cases in the Brock sample and 9 cases in the Waterloo sample. Seven people in the Brock group and 6 people in the Waterloo group indicated that they had suffered more than one blow to the head but reported that the most severe injury was the one we classified as a MHI.

Attentional Recruitment: Focused Attention Tasks

We predicted that participants with MHI would demonstrate deficits compared to controls on the more difficult attentional recruitment tasks.

Reaction Time (RT) Performance: Task Differences. A repeated measures ANOVA revealed a Task by Stimulus Difficulty interaction for the auditory oddball tasks indicating participants' RT performances on the four tasks were significantly different, with the Easy Pitch Discrimination task eliciting the shortest RTs, the Difficult Pitch Discrimination and the Easy Duration Discrimination task eliciting slightly longer RTs and the Difficult Duration Discrimination task eliciting the longest RTs, ($F(1,55)=75.61$, $p<.001$) (Figure 1). Table 5 summarizes the means and standard errors for each oddball task.

RT Performance: Group Differences. A significant University by MHI by Task interaction was found, ($F(1,55)=5.24$, $p=.026$). By looking at the University groups separately, we found that there was no significant difference in terms of RT performance between the MHI group and controls at Brock University, ($F(1,26)=0.05$, $p=.827$). There was, however, a significant MHI by Task interaction for the Waterloo group, ($F(1,25)=8.50$, $p=.007$) (Figure 2). Factors such as age and general intellectual functioning were entered as covariates during the separate analysis of the university groups and were not found to contribute to the differences in task performance. The MHI group was slower than the control group on the Pitch Discrimination tasks but performed similarly on the Duration Discrimination tasks. Table 6 summarizes the means and standard errors for RT performance for both MHI and control groups at both universities.

Signal-Detection Analysis and Task Performance. Signal-detection analysis was conducted to investigate participants' abilities to discriminate the target stimuli (d′) as well as their thresholds to respond to the stimuli (β). Main effects of Task and Stimulus Difficulty were found for d′ (Task: ($F(1,55)=19.90$, $p<.001$; Stimulus Difficulty: ($F(1,55)=336.00$, $p<.001$)) (Figure 3). Discrimination of target stimuli was better on the Pitch Discrimination tasks than on the Duration Discrimination tasks demonstrating that it was more difficult to identify the target stimuli on the Duration tasks. As well, discrimination of target stimuli on the Easy tasks was higher than on the Difficult tasks.

A Task by Stimulus Difficulty interaction was revealed for β, ($F(1,55)=13.74$, $p<.001$) (Figure 4). Participants were relatively unbiased in responding to target stimuli during the Easy Pitch Discrimination tasks. Criterion to respond to target stimuli increased for the difficult pitch discrimination and the easy duration discrimination whereas participants responded most conservatively to the target stimuli presented during the difficult duration discrimination. These results parallel the RT findings for task and difficulty manipulations. Table 7 summarizes the means and standard errors for d′ and β for all task conditions.

Signal-Detection Analysis and Group Performance. No Group differences emerged for d′ or for β for any of the oddball task conditions. MHI and control groups demonstrated similar ability to detect and respond to target stimuli during all task conditions. Table 8 presents means and standard errors for d′ and β for both groups under each task condition.

We found RT differences for the Waterloo MHI group on the Pitch Discrimination tasks indicating that the MHI group was slower in responding on these tasks than the control group. We did not find any group differences in terms of stimulus discriminability or threshold to respond for the Pitch Discrimination tasks. This could be reflective of a speed-accuracy trade-off such that the Waterloo MHI group reduced their speed of responding in order to keep their ability to detect and respond to target stimuli in check.

Summary of Results. Analysis of RT and signal-detection performance on the four attentional recruitment tasks revealed that incremental increases in demands on attentional recruitment resulted in slower RTs and increased difficulty in detecting and responding to target stimuli for all participants.

We did not find substantial evidence for performance deficits on the more difficult attentional recruitment tasks in participants with MHI compared to controls. We did find evidence of a speed-accuracy trade-off for the Waterloo MHI group such that they performed slower but with the same accuracy as controls on the Pitch Discrimination tasks.

Distractibility and Inhibitory Control Tasks

It was hypothesized that participants with MHI would have more difficulty inhibiting responses to stimuli that were to be ignored and would also be more distractible than controls.

No significant differences were found between groups in the analysis of the Eriksen Flanking Paradigm, the Stop-Signal Paradigm, the CPT or the Selective Stimulus Finding task.

Divided Attention, Working Memory and Central Executive Tasks

It was predicted that participants with MHI would demonstrate decreased working-memory capacity and/or more difficulty than control participants allocating attention in a systematic way during performance of tasks that required divided attention.

Working Memory

We did not find any significant differences between MHI and Control groups on any of the working-memory measures we employed including Digit Span Backward, Two-Back task and the Self-Ordered Pointing Test.

Divided Attention and the Central Executive

Duration Discrimination with Simultaneous Distractor: Reaction Time Performance. A repeated measures ANOVA demonstrated that addition of the simultaneous working- memory distractor task served to significantly increase participants' RTs to the target tones, ($F(1,56)=38.08$, $p<.001$). No group differences were found for RT performance on the Duration Discrimination task with the addition of the second simultaneous task, ($F(1,56)=1.50$, $p=.227$) indicating that the groups performed similarly under this condition. As well, no group differences for RT performance were revealed for the verbal-working-memory distractor task, ($F(1,59)=1.02, p=.317$).

Duration Discrimination with Simultaneous Distractor: Signal-Detection Analysis and Task Performance. The addition of a simultaneous distractor task served to significantly decrease participants' ability to detect the target stimulus tone on the duration discrimination task (reduced d'), ($F(1,56)=76.84$, $p<.001$), as well as significantly increasing participants' criteria to respond to the target tones (β), ($F(1,56)=37.76$, $p<.001$). Table 9 summarizes means and standard errors for d' and β under single- and dual-task conditions as well as means and standard errors for RT performance.

Duration Discrimination with Simultaneous Distractor: Signal-Detection Analysis and Group Performance. A repeated measures ANOVA revealed a MHI by Task interaction for d' with the addition of the simultaneous distractor task (both university groups together), ($F(1,56)=3.93$, $p=.052$). When the Duration Discrimination task was performed simultaneously with the Working-memory Distractor task, the second simultaneous task produced more interference for the MHI group than for the Control group in terms of their ability to discriminate the target tones (Figure 5).

Analysis of the threshold to respond (β) for MHI and Control groups revealed a MHI by Task trend, ($F(1,56)=3.14$, $p=.082$). Although this interaction did not reach significance, the means indicated that the MHI group had a lower threshold to the target tones under the dual-task condition compared to controls (Figure 6).

An analysis of the verbal-working-memory task performance did not reveal any significant group differences in terms of ability to detect the targets or threshold to respond to targets indicating that the MHI and Control groups performed similarly on this portion of the dual task. Table 10 presents the means and standard errors for d' and β for MHI and

Control groups for the Duration Discrimination task with and without Distractor task and for the verbal- working-memory task.

Summary of Results. The addition of a second simultaneous-distractor task served to increase RTs, reduce target discrimination and increase the threshold to respond for all participants in the study. However, we found that the MHI group had particular difficulty discriminating the target stimulus under the dual-task condition. There was also a trend for the MHI group to have a lower threshold to respond to targets on the primary task when a simultaneous task was added. The MHI group did not differ from the control group in their speed of responding to either of the simultaneous tasks, suggesting a speed-accuracy trade-off in which accuracy of performance was sacrificed in order to respond quickly to the target stimuli.

Paper and Pencil Dual Task and Computerized-Multiple-Task Performance. There were no significant group differences on the Paper-and-Pencil Dual task indicating that the MHI and Control groups performed similarly on this task.

A univariate ANOVA revealed a University by MHI trend for the Computerized Multiple Performance task (CMPT), ($F(1,58)=2.831$, $p=.098$) (Figure 7). University groups were analysed separately (again factoring out age and general intelligence) and a main effect of MHI for the Waterloo group was found, ($F(1,26)=5.11$, $p=.032$). The MHI group at Waterloo obtained a significantly lower total score on this task than the control group, indicating more difficulty allocating attentional resources to perform four simultaneous tasks. This difference did not exist in the Brock group, ($F(1,28)=0.15$, $p=.698$). Table 11 presents means and standard errors for CMPT performance for MHI and Control groups at both universities.

Control Tasks

There were no significant differences between the MHI and control groups on non-frontal control measures. We did find a significant difference between universities on the Culture Fair Intelligence Test and the Information subtest but these differences did not contribute to any of the MHI effects. Although these differences were interesting, they were not central to our hypotheses surrounding cognitive performance of those with MHI. The fact that the two university populations differed on specific tasks of intellectual functioning was not surprising given the differences in admission requirements, academic programs and the level of university education achieved by the two university populations. Also, the difference between the two university groups on the Culture Fair test in particular may stem from the fact that this test depends heavily on visuo-spatial problem-solving. Over half of the participants tested in the Waterloo sample were math and computer science majors who may be more proficient at processing visuo-spatial information. Other non-frontal measures employed in this study including tests of motor speed (Crossing out A's task and Simple Reaction Time task) and acquired knowledge (Verbal Meaning subtest) did not reveal differences between the MHI and control groups.

DISCUSSION

Experiment 1 was designed to investigate whether well-functioning university students who reported a MHI demonstrated any residual cognitive deficits reflected in behavioral differences (i.e. increased RTs or more errors committed) as compared to a control group who had reported no incidence of head trauma. Participants were subjected to a broad range of tasks selected to tap into various aspects of attention. Although some measures, i.e., Culture Fair Test and the Information subtest, distinguished university groups, most measures did not distinguish the groups on the basis of MHI. This suggests that individuals with MHI do not show evidence of brain injury on these measures. It may be that the injuries reported by our participants were not damaging enough to produce differences between our groups. The MHIs in our sample, for the most part, may not have involved sufficient accelerative force to affect neural function. In fact, only 25% of our participants reported a MVA as the cause of their injury. This is typically the type of injury that involves accelerative/ decelarative forces and results in diffuse axonal injury and frontotemporal contusions. Some of the inconsistencies in the previous literature no doubt have arisen from variability between samples tested and the nature of the MHIs involved.

Although the MHI group did as well as controls on most of the attentionally demanding tasks, they did differ from controls on a divided-attention task that required participants to perform a tone duration discrimination task simultaneously with a working memory distractor task. We also found decreased overall performance of MHI participants (Waterloo group only) on the computerized-multiple-performance task that required allocation of attention to four simultaneous tasks. During the duration-discrimination-with-distractor task, participants with MHI demonstrated a reduced ability to discriminate between targets and non-targets as well as a tendency towards lower threshold to respond to target stimuli. Our findings are in line with the findings of Segalowitz, Bernstein and Lawson (1995) who demonstrated that a group of individuals with MHI had attentional difficulties during some difficult auditory oddball tasks. Segalowitz et al. (1995) found that participants with MHI had stimulus discriminability problems and demonstrated a lower threshold to respond to target stimuli on more difficult attentional tasks.

Although our effects were not large, the dual-task paradigm may be a sensitive paradigm to bring out subtle behavioral differences in performance between the MHI and control groups. Differences in performance between groups on tasks of divided attention and allocation of attentional resources certainly met our expectations for the kind of measures that ought to have discriminated between our groups. Dividing attention involves managing relevant information while simultaneously controlling what information is to be responded to at any particular time. This function is considered to be heavily dependent on the frontal lobes. We cannot, however, use the differences between groups found in our data as support for the hypothesis that a MHI results in fundamental injury to the brain and altered neural function. On the majority of behavioral measures employed in this study, the MHI and control group performed similarly. A post-hoc interpretation of this result is that the MHI group is putting forth increased cognitive effort to achieve performance that is similar to controls. Indeed, there is evidence in the literature to suggest that MHI results in cognitive fatigue, which may stem from these individuals having to allocate additional cognitive effort in order to successfully complete tasks (e.g., Mild Traumatic Brain Injury Committee, 1993; Gronwall, 1989; Stuss et al., 1989). A behavioral study alone cannot determine if participants with MHI are employing processing strategies that are different from controls in order to achieve the same performance outcome. Experiment 2 addresses the question of whether MHI and control groups differ in their allocation of processing resources through the collection of EEG and ERPs that give us an on-line measure of information-processing.

CONCLUSIONS

We have been able to show that well-functioning university students who have reported MHI do very well on most tasks purported to measure various aspects of attention and even performed better than controls on several tasks. There was, however, a measure highly dependent on attentional resources that did distinguish the groups. This task required participants to divide their attentional resources and allocate them in a systematic way in order to complete two tasks at the same time. Reduced capacity to allocate attentional resources systematically may result in impairments during everyday living, particularly in situations in which a great deal of relevant information is presented quickly and simultaneously or when we are expected to divide our attention among several subtasks (Van Zomeren & Brouwer, 1987). MHI may be thought to be of minor consequence and some researchers claim that those suffering a minor head trauma recover to their full potential in the months following their injury. Although not able to convincingly refute this claim on the basis of our current data, we have been able to demonstrate some subtle differences between the groups that might be a consequence of the MHI.

The results of Experiment 1 revealed several issues that lend themselves well to an electrophysiological follow-up study. First and foremost, we were interested in investigating whether participants with MHI might be putting forth increased cognitive effort or employing different information-processing strategies in order to achieve a satisfactory behavioral outcome. Second, we were interested in observing the effects of increasing the demands on cognitive resources on information-processing ability in participants with MHI. Third, because the injuries involved in this first study may have been too mild to affect cognition (i.e., the criterion used was too stringent with respect to mildness), we increased the range with respect to severity of injury to include those with unconsciousness greater than 30 minutes.

EXPERIMENT TWO

The first study was conducted to determine whether well-functioning university students with MHI differed from students who had not suffered a MHI on certain behavioral tasks designed to tap abilities associated with the frontal lobe. The second study was designed to further investigate allocation of cognitive resources, employing an electrophysiological investigation of those tasks that elicited behavioral differences in Experiment 1. This time, cognitive resource allocation was investigated by collecting event-related brain potentials and EEG coherence measures while participants performed various cognitive tasks. The electrophysiological measures employed in Experiment 2 were intended to give us an on-line analysis of cognitive processing and a measure of cortico-cortical communication for each group during the performance of particular tasks. The nature of these measures and how they relate to investigations of minor head trauma are reviewed below.

Event-Related Potentials (ERPs)

Within an epoch of EEG that is time-locked to the presentation of a stimulus, voltage changes occur that are thought to be specifically related to the brain's response to that stimulus. These voltage changes are what comprise the ERP (Coles & Rugg, 1995). ERPs recorded from the scalp represent the synchronous activity of a large population of neurons. In the functional approach to defining ERPs, components are looked at in terms of information-processing operations or cognitive functions thought to be performed by the brain systems producing the activity (Coles & Rugg, 1995). ERPs following the presentation of a stimulus can be separated into a number of different components that are identified by their polarity and the approximate latency of their maximal peak. They are divided into two types of components: those that are exogenous and depend on the physical properties of the stimulus; and those that are endogenous and depend on the interaction between the participant and the stimulus (Coles & Rugg, 1995).

Exogenous components occur early in the cognitive process. They are considered sensory components that occur automatically with latencies up to 100 ms after presentation of a stimulus. For example, the N100 (or N1), a negatively deflecting wave that occurs at 100 ms post-stimulus is thought to reflect detection of an auditory stimulus at primary auditory cortex (Picton & Hillyard, 1988). Although exogenous components are often considered not to be influenced by cognitive manipulations due to their automatic nature, it has been demonstrated that these early sensory components can be modified with varying demands on attention (Coles & Rugg, 1995; Hackley, 1993).

Endogenous ERPs are later-occurring components thought to be related to participant-centered or controlled information-processing and have been shown to change as a function of processing demands such as task relevance or amount of attention required (Kramer & Strayer, 1988); Kramer, Strayer, & Buckley, 1991). In particular, the amplitude and latency of the P300 ERP component (also known as the P3) are considered a sensitive indication of allocation of attentional resources and information-processing efficiency (Hoffman, Simons, & Houck, 1983). The P3 is elicited by rare and unpredictable events or events with high information value. The simplest way of obtaining a P3 is to employ a standard oddball paradigm in which participants must detect a rare target stimulus. In these situations, a P3 wave is thought to be evoked due to the salience the target represents for the participant and the initial attention the participant must allocate to the discrete stimulus. When attention must be divided in order to perform two tasks at once, P3 amplitude is reduced (Isreal, Chesney, Wickens, & Donchin, 1980; Kramer & Strayer, 1988). P3 amplitude is thought to reflect the amount of attentional resources available for allocation because its amplitude can be significantly reduced by presentation of two simultaneous tasks (Hoffman et al., 1983).

The methods of cognitive psychology alone do not permit cognitive information-processing to be observed directly. It is necessary to make inferences based on overt behavioral performance such as RT and accuracy measures (Rugg & Coles, 1995). With the measurement of ERPs, we can achieve insight into the constitution of the cognitive process by making inferences based on brain activity resulting from various experimental task manipulations. As well, researchers are now using electrodes in high-density montages to allow for more discrete spatial sampling of brain electrical activity (Rugg & Coles, 1995). Thus, ERPs provide a valuable measure in assessing the dynamic properties of brain function during information-processing (e.g., Parasuraman, Richer, & Beatty, 1982; Rugg & Coles, 1995).

<u>ERPs and MHI</u>

ERP components have been employed in order to investigate information-processing following traumatic injury to the brain. These measures provide on-line, millisecond analysis of cognitive processing thus providing unique information that standard neuropsychological tests are only able to imply given abnormal performance. With ERPs, brain events before, during and after stimulus presentation can be observed thus allowing the events that lead to abnormal behaviour to be monitored (Campbell & deLugt, 1995).

Most ERP studies following TBI have focused on the endogenous components, likely due to the numerous cognitive deficits that remain following head trauma. The most extensively studied ERP in a variety of clinical populations is the P3. Differences in P3 latency and amplitude have been found in individuals with dementia, depression and schizophrenia (Pfefferbaum, Wenegrat, Ford, Roth, & Kopell, 1984). Children diagnosed with Attention Deficit Disorder (ADD) have been shown to have smaller P3 amplitudes during tests of sustained attention (Klorman, 1991). The study of cognitive ERPs has proven to be effective in interpreting cognitive difficulties in many clinical populations and thus may prove to be a useful aid in investigating cognitive impairment following MHI.

Following moderate or severe TBI, there appears to be an attenuation and prolongation of the P3 peak (Campbell & deLugt, 1995). Deacon-Eliott, Campbell, Suffield and Proulx (1987) conducted a series of studies in which persons with TBI of varying severity were tested on an auditory oddball task requiring the discrimination of tones that varied in pitch. The individuals with TBI had little difficulty performing the task behaviorally and demonstrated nearly perfect performance. Compared to controls, participants with TBI demonstrated attenuated P3 amplitudes that were also prolonged by 50 to 75 ms. Deacon-Eliott et al. (1987) reinvestigated whether the attenuated P3 was due to "cognitive" abnormalities and not merely a result of subtle hearing deficits in the patient group by presenting a visual decision task. Participants were required to indicate the presence of a rare visual target and the visual P3s in the individuals with TBI continued to be reduced with a longer latency. These researchers interpreted their results as an indication that the TBI group required additional time to complete an evaluation of the target stimulus. Attenuated P3 components in TBI patient populations have been interpreted as reflecting an inability to maintain attention to a task (Campbell & deLugt, 1995). Unsal and Segalowitz (1995) investigated whether reductions in P3 amplitude were simply an artifact of greater performance variability in a group of participants with TBI. They utilized single-trial amplitudes, the variability in P3 latency (latency jitter) and EEG power to determine whether differences in P3 amplitudes between TBI and control groups could be attributed to these sources. Results demonstrated that single-trial amplitudes predicted averaged amplitudes and that reduced P3 amplitude was not an artifact of increased latency jitter. Their data suggested that attenuated P3 amplitude was a result of decreased attentional capacity and not inconsistency in information-processing following TBI (Unsal & Segalowitz, 1995).

There have been few electrophysiological studies conducted with persons who have suffered MHI, perhaps because of the fact that less consistent ERP and EEG findings have been shown following MHI as compared to those following more severely injured populations (Ford & Khalil, 1996). The role of the P3 component in assessing dysfunction in the post-concussion period was investigated by Pratap-Chand, Sinniah, and Salem (1988). In this study, individuals who had suffered loss of consciousness (LOC) of less than 30 minutes were tested on an auditory oddball paradigm within 4 days of their injury. The results demonstrated that initial P3 amplitudes and latencies were significantly different compared to matched uninjured controls. Repeated testing 1 to 8 months later revealed improvement to normal levels in P3 amplitudes and latencies in all persons who had suffered a MHI. Pratap-Chand, Sinniah and Salem (1988) concluded that cerebral dysfunction as indexed by abnormal P3 amplitudes and latencies occurs immediately following minor concussion but that this dysfunction is short-lived.

Ford and Khalil (1996) investigated whether consistent patterns of auditory and visual ERP differences could be revealed following MHI. They assessed symptomatic individuals, the majority of whom reported no LOC at the time of their injury although they claimed to have been dazed and had poor recollection of events surrounding their injury. Individuals were tested one year post-injury on auditory and visual oddball tasks that required them to count the number of randomly occurring rare targets. Results demonstrated that the middle ERP components (P2, N2) were augmented while the cognitive P3 component was attenuated during both the auditory and the visual tasks. Ford et al. (1996) concluded that they were able to provide objective evidence of electrophysiological abnormalities following MHI. They speculated that the intriguing finding of middle component (P2, N2) augmentation could be a result of a hyperresponsivity resulting from the type of neuronal damage expected to occur in MHI. Another interpretation of this finding is that the MHI group were allocating compensatory effort, as reflected in augmented middle-latency components, in order to maintain successful performance (Campbell & deLugt, 1995).

Segalowitz et al. (1995) tested well-functioning university students who reported MHI and found that these individuals demonstrated deficits compared to controls on a series of auditory oddball tasks. The MHI group performed more slowly and with less accuracy than controls on focused/sustained attention tasks as well as during a divided-attention dual task. Participants with MHI demonstrated decreased P3 amplitudes during all of the oddball tasks as compared to controls. This result was interpreted as reflecting less overall information-processing capacity in the group of MHI participants. The MHI group did not differ from controls in the latency of their ERP components (N1, P2, N2 and

P3). This was interpreted as the MHI group having no difficulty with information-processing speed. Segalowitz et al. (1995) were able to show that subtle attentional deficits persisted in a group of participants with good recovery from MHI, particularly when they were subjected to demanding attentional tasks.

In summary, employing strict behavioral measures to diagnose deficits following trauma to the head allows one to make inferences about the cognitive processes leading up to the observed behavioral output. However, by looking at exogenous and endogenous ERPs, one can monitor information-processing and allocation of attentional resources in the milliseconds during and following a cognitive event (Deacon-Eliott et al., 1987). ERP studies of information-processing following moderate or severe TBI have revealed an attenuation and prolongation of the P3 component, thought to reflect reduced attentional capacity and processing speed in this population. Of course, this interpretation fits with some behavioral observations of reduced attentional ability and slower responding following TBI. Similarly, differences in ERP components following a MHI have not proven to be reliable or consistent. This may be due to the fact that behavioral evidence of reduced attentional ability is not always observed, as demonstrated in Experiment 1. One study of ERP differences following MHI revealed immediate abnormalities in the late cognitive components that resolved over time (Pratap-Chand et al., 1988) while others have demonstrated ERP component differences a year or more following minor head trauma (Ford & Khalil, 1996; Segalowitz et al., 1995).

EEG Coherence

ERPs can provide information about only a fraction of the neural activity associated with the processing of a stimulus (Rugg & Coles, 1995). As well, the ERP method provides information about the temporal characteristics of information-processing without indication of spatial characteristics. Activity recorded at particular scalp sites may not necessarily be attributed to activity in the brain regions underlying those sites due to volume conduction of the brain. As a result, electrical activity generated in one area can be detected at distant locations (Coles & Rugg, 1995). Therefore, spatial characteristics of cortical activation during the performance of a cognitive task are limited with the ERP method. EEG coherence analysis allows the investigation of communication patterns of activity between cortical regions. EEG coherence reflects a correlation of the EEG signal between two cortical sites over time, which in turn is thought to indicate information linkage between two brain areas. However, EEG coherence also suffers from the same problem of potentially reflecting brain volume conduction.

Thatcher, Krause and Hrybyk (1986) have provided support for EEG coherence reflecting intercommunication between cortical regions and not simply a result of volume conduction of EEG activity through the brain. Researchers had been hesitant to employ EEG coherence measures particularly because the predominating theories of EEG activation favored the view of volume conduction. Thatcher et al. (1986) claimed that if volume conduction was the underlying cause of EEG coherence, then coherence would exhibit a smooth, equal decrement as interelectrode distances increased. These researchers were able to demonstrate a considerable amount of spatial non-homogeneity such that changes in coherence between electrode pairs were not simply due to the distance between electrodes. They also demonstrated differences in magnitude of coherence between regions in the anterior and posterior cortex and regions in the left versus right hemispheres (Thatcher et al., 1986).

The human neocortex is very densely interconnected by both short-range intracortical fibers and long cortico-cortical fibers. Human cognition is thought to involve neocortical "circuitry" that may be distributed over widespread cortical regions (Nunez, 1995). Even simple cognitive tasks require co-ordination of a number of widely distributed, and highly specialized brain systems (Gevins, Leong, Smith, Le, & Du, 1995). Bressler, Coppola and Nakamura (1993) investigated the nature of multi-regional cortical coherence during the performance of a visual pattern-discrimination task by primates. Their task required response to a particular type of visual pattern and inhibition of response to another type of visual pattern. The results demonstrated a large increase in coherence between striate sites and motor sites when a response was required as compared to when a response was to be inhibited. Bressler et al. (1993) interpreted their results as reflecting evidence for synchronization of activity from widespread cortical sites being involved in perceptual-motor integration. Indeed, when we present various cognitive tasks to participants, what we are looking for with scalp EEG coherence is recruitment of certain functional cell assemblies that are defined by synchronized activation of participating neurons (Singer, 1993).

The common hypothesis is that coherence between signals from different brain regions represents functional networks that are recruited in the performance of sensory, cognitive and motor tasks (Gevins et al., 1995). Because of advancements in the field of EEG coherence research (i.e. the use of higher-density montages to enhance spatial detail, the use of more sophisticated referencing measures to sharpen the features of EEG activity, and the employment of specific hypotheses based on task manipulations or differences in participant populations) the measure can now be used to shed light on functional interactions between cortical regions (Gevins et al., 1995).

EEG Coherence between Frontal and Parietal Cortical Regions

In the case of the tasks employed in this study, we were interested in the communication between brain areas in the frontal (prefrontal) and parietal (posterior association) regions and how this frontal-posterior (F-P) long fiber communication might be affected by MHI. The prefrontal cortex (PFC) and its connections with posterior association areas are considered integral to allocating attentional resources and attentional scheduling particularly when one is performing complex cognitive tasks. In contrast, the more posterior regions of the brain (central-parietal and parietal-occipital areas) have been found to be more locally connected (i.e. shorter intrahemispheric connections (Thatcher et al., 1986)). These short connections may be functionally related to local cortical communication required for primary, secondary and tertiary perceptual and cognitive processing whereas the long-distance connections of the frontal regions are involved in integrating and co-ordinating information from various cortical sources (Thatcher et al., 1986). As we have seen, damage to frontal cortical regions and difficulty with allocating attentional resources has been demonstrated following TBI. Thus, disruption of the F-P long fiber cortico-cortical connections may underlie attentional control deficits after TBI.

During the performance of a dual task, the brain must divide its cognitive resources while the central executive (involving the PFC) schedules these divided attentional resources to perform the two tasks at once. Under these conditions, it is suggested that the PFC engages the posterior cortex in order to keep information in an active state. Single-cell recording studies have found prefrontal neurons most active during memory retention periods in delayed-matching-to-sample tasks. Miller, Erickson and Desimone (1996) were able to show that PFC neurons in monkeys demonstrated heightened activity during the delay period after presentation of a sample stimulus. Further, they demonstrated that sample-selective delay activity was maintained in the PFC even when other test stimuli were presented during the delay period. Miller et al. (1996) concluded that their results were indicative of the PFC playing an integral role in working memory. Fuster, Bauer and Jervey (1985) demonstrated that cooling regions of PFC and posterior cortex induced changes in both spontaneous and task-related discharge of cells. Again, monkeys were trained to perform a delayed-matching-to-sample task and the effect of cooling the cortex in these areas led to performance decrements in the monkeys' abilities to complete the task. Fuster et al. (1985) concluded that areas in the PFC and posterior cortex are mediated by cortico-cortical connections and that the functional integrity of this network is important for working memory.

Functional mapping studies of both non-human primates and humans have also demonstrated a functional association between regions in the PFC and posterior cortical areas. Friedman and Goldman-Rakic (1994) demonstrated enhanced local cerebral glucose utilization in the PFC and parietal areas of monkeys during working memory. Interestingly, the metabolic activity was the highest in lower layers of the cortex that is made up of association and callosal neurons. These findings lend support to the idea that PFC and parietal cortex are important parts of a neural network that mediates working memory and attentional allocation. The PFC and parietal cortex areas have also been shown to be particularly active in humans during the performance of working-memory tasks. Using functional magnetic resonance imaging (fMRI), Cohen, Perlstein, Braver, Nystrom, Noll, Jonides and Smith (1997) and Courtney, Ungerleider, Kell and Haxby (1997) demonstrated that distinct areas of the PFC demonstrated activation during working memory. Cohen et al. (1997) also showed that areas of the posterior parietal cortex became active during working memory. They concluded that the PFC and areas of parietal cortex play a primary role in actively maintaining information within working memory. Based on evidence from single-cell recording studies and functional activation studies and what we know about EEG coherence, neuronal synchronization must play a role in communication between posterior association cortex where sensory information is stored, and PFC where relevant information is held and continuously updated and modified.

D'Esposito, Ballard, Aguirre and Zarahn (1998) investigated the role of the PFC in cognitive processes other than working memory. According to the authors, non-working memory processes that could activate the PFC might include stimulus encoding, sustained attention and motor preparation or response. Employing fMRI during both working-memory and non-working-memory tasks, D'Esposito et al. (1998) demonstrated that greater activity was associated with working memory as compared to non-working memory, however, the PFC was also shown to be active during non-working-memory tasks compared to resting baseline. The same PFC region was found to be significantly active during tasks demanding working-memory and non-working-memory tasks.

In summary, many animal and human studies have demonstrated activation of areas in the PFC and areas in the posterior cortex in association with the performance of working-memory tasks. As well, evidence exists that PFC is active during cognitive processes that are not related to working memory (i.e. stimulus encoding or sustained attention to a stimulus). One of the issues to be addressed in this experiment is whether communication between cortical sites in frontal and posterior (F-P) areas during attentional allocation and attention scheduling can be investigated using EEG coherence measures and second, whether this F-P communication might be affected by MHI.

EEG Coherence and MHI

Investigations of scalp EEG have served as an indicator of information-processing abilities in various clinical populations (Morrison-Stewart, Velikonja, Corning, & Williamson, 1996; Papanicolaou, 1987). The different EEG frequencies are thought to be related to different aspects of cortical activation. EEG activity in the theta range (6-7 Hz) occurs prominently in structures of the limbic system (i.e. septum, hippocampus) during states of attentive arousal. Alpha activity (8 to 10 Hz) has been shown to occur during relaxed wakefulness but increased alpha activity has also been demonstrated during tasks requiring attention to internal information-processing (Ray & Cole, 1985). Low amplitude, high frequency EEG oscillations in the beta range (15 to 30 Hz) are thought to denote intense mental activity particularly during complex cognitive processing and has been shown to be prominent in humans and other mammals that are in a state of focused attention (Pockberger, Rappelsberger, & Petsche, 1988; Singer, 1993).

Few studies of EEG activation following MHI have been conducted, and those that have investigated the effects of MHI on EEG have done so during the acute stages following minor head trauma. Watson et al. (1995) found reductions in EEG theta power immediately following a MHI that appeared to improve over approximately 10 days post-injury. They were also able to demonstrate a correlation between persistent organic symptomatology over several weeks following injury and remaining reductions in theta power. Tebano et al. (1988) also investigated EEG frequency variation in persons with

MHI in the days following their injuries and found increases in slow alpha (8 to 10 Hz), decreases in fast alpha (10.5 to 13.5 Hz) and a reduction in the beta frequency in the MHI group compared to controls. It is unknown, however, whether these EEG changes are reflective of alterations in cognitive functioning in individuals following MHI. According to Gevins et al. (1992), advances in EEG recording that combine EEG with information from MRI in order to provide both spatial and time-locked resolution of cognitive processes may provide us with the ability to detect and characterize subtle cognitive difficulties following MHI. EEG coherence may be another method that can allow us to gain some insight into cortico-cortical communication during cognitive processing after minor head trauma.

Thatcher, Walker, Gerson and Geisler (1989) investigated EEG coherence following MHI, but coherence measures were performed on resting EEG only and did not involve changes in information-processing demands through experimental manipulation. Their results demonstrated consistently increased EEG coherence in the frontal and fronto-temporal regions of the brain. Frontal and temporal differences in EEG coherence are consistent with the localization of damage to the brain following MHI. Greater EEG coherence in these areas following injury may reflect a hyperresponsivity of these frontal and temporal brain regions. In summary, electrophysiological recording measures have proven to be informative in terms of highlighting the nature of information-processing differences in clinical populations, particularly following TBI. ERPs allow us to investigate on-line, the nature of cognitive processing and the brain events associated with different aspects of processing information. EEG coherence gives us a measure of cortico-cortical communication between brain regions that are thought to be involved in the performance of a particular cognitive task. Both ERP and EEG coherence analysis may be useful in investigating subtle cognitive-processing deficits following MHI.

Rationale for Experiment 2

Even though Experiment 1 clearly demonstrated that the MHI and control groups performed similarly on most behavioral tasks thought to measure aspects of frontal-lobe functioning, there was still the question of whether participants were employing similar processing strategies in order to achieve the same behavioral outcome. After a head injury, cognitive activities that do not normally demand full capacity may use all available processing resources (Gronwall, 1987). Participants who have suffered a MHI may employ more cognitive resources in order to achieve a satisfactory behavioral outcome. Satz's (1993) brain-reserve-capacity theory claims that following traumatic injury, individuals may have to employ less efficient neuronal circuits and they may not be as neuronally adaptable, particularly under conditions of appropriate cognitive challenge. Therefore, in Experiment 2 we collected electrophysiological measures, employing participants with and without head injury, in order to investigate aspects of the brain events that occur throughout the cognitive process.

Participants with head injury with good recovery may require increased allocation of cognitive resources compared to controls in order to achieve satisfactory behavioral performance on fairly easy cognitive tasks. The results of Experiment 1 further demonstrated that behavioral difficulties can emerge when participants with MHI are faced with more complex cognitive tasks such as doing two things at the same time. In this situation, the advantage that the increased allocation of resources affords the MHI group is reduced, presumably due to limited capacity resources being substantially taxed during a dual task. In Experiment 2, we presented tasks that increased in difficulty and demands on cognitive resources so that we could investigate changes in information-processing as task difficulty increased. Focused and divided attention were investigated by presenting (1) single tasks that increased in difficulty, therefore requiring increased focus or concentration to perform them, and (2) tasks that differed in the demands made on available attentional resources, that is a single task versus a dual task. Working memory (WM) was also investigated in Experiment 2 as it is thought to be a capacity-limited cognitive ability associated with frontal-lobe function. WM was investigated in an additive-factors framework, such that increased demands on memory load were presented.

We also added a second group of participants with moderate head injury in Experiment 2. In addition to the group of participants who had suffered a MHI and reported unconsciousness of 20 minutes or less, we included a group of participants who had suffered a more significant head injury and reported unconsciousness of 30 minutes or more. This group was included in Experiment 2 because we were looking for very subtle differences in functioning between groups. Experiment 1 demonstrated few behavioral differences between our MHI and control groups so we wanted to add a group that would be more likely to demonstrate both behavioral and information-processing differences due to head injury. In this way we intended to investigate characteristics of MHI performance in relation to controls with no history of head trauma and a group of participants with reported moderate head injury.

Outline of Experiment 2

In Experiment 2, cognitive-resource allocation was investigated electrophysiologically while participants performed attention and working-memory tasks.

Differences in information-processing and communication between cortical regions may exist even when there is a lack of behavioral performance differences between groups. By collecting ERP and EEG coherence measures we investigated (1) the brain events associated with the performance of complex cognitive tasks requiring allocation of attentional resources, and (2) whether there were any individual differences in information-processing and/or cortico-cortical communication following a MHI.

Hypothesis 1a: ERPs and Task Differences. For all groups of participants, we predicted that the early ERP components (N1, P2, N2) reflecting mainly automatic responses to stimuli, would not show any differences across tasks. We predicted that the P3 component, however, would demonstrate decreased amplitude and increased latency as a function of increased demands on cognitive resource allocation. P3 amplitude and latency have been shown to vary with psychologically important variables such as task difficulty and allocation of attentional resources (Polich, 1993).

Hypothesis 1b: ERPs and Group Differences. Group differences were predicted in the form of a greater reduction in P3 amplitude and increased P3 latency for the head injury groups as compared to controls as the cognitive tasks increased in difficulty. No group differences were predicted for the early ERP components. Reduced P3 amplitude could reflect a reduction in information-processing capacity in the groups with head injury. Participants are thought to have less efficient controlled processing following head trauma but no difficulties with automatic processing.

Hypothesis 2a: EEG Coherence and Task Differences. Coherence between signals from two brain regions should increase as these regions become involved in cognitive effort (Tucker, Roth, & Bair, 1986). Some PET and fMRI studies also demonstrate increased cortical activity as demands on memory load increase (particularly in the dorsolateral prefrontal cortex, posterior/inferior PFC and posterior parietal cortex (Cohen et al., 1997). We predicted an increase in frontal-parietal (F-P) coherence as demands on cognitive resources increased.

Hypothesis 2b: EEG Coherence and Group Differences. There is little known about EEG coherence in MHI. Thatcher et al.(1989) demonstrated an increase in frontal coherence following MHI. However, we were interested in long-fiber communication and patterns of coherence between frontal and parietal regions following a head injury. We predicted that if electrophysiological differences between our head injury groups and controls existed, that the head injury groups would be more likely to demonstrate a pattern of coherence that indicated reduced efficiency in communication between cortical regions. However, we were unsure as to whether differences in cortico-cortical communication between groups would manifest in increased or decreased EEG coherence between F-P sites.

METHOD

Participants

In this study, participants were recruited from an Introductory Psychology class at Brock University. Students signed up for the study based on whether they (1) had ever suffered a blow to the head causing pain, dizziness or unconsciousness, or (2) had never suffered a blow to the head or unconsciousness (same criteria as Experiment 1). Participants were offered credit toward their research participation requirement for the Introductory Psychology course in exchange for their participation. A third group of students was recruited who reported at least 30 minutes of unconsciousness. This group of students was recruited toward the end of the winter term and offered a monetary stipend ($15) in exchange for participation in this experiment.

All participants who reported a head injury were contacted by telephone and administered the MHI screening questionnaire in order to determine whether the nature of their self-reported injuries made them appropriate for the study. Two groups of participants were selected, one group reporting unconsciousness for 20 minutes or less (11 female, 8 male) (M=20 yrs; SD=1.38; range=18 to 23 yrs) and a second reporting unconsciousness between 30 minutes and 36 hours (11 female, 8 male) (M=22 yrs; SD=3.00; range=18 to 31 yrs). Data were also collected from the head injury groups about the existence of persistent complaints of difficulties (e.g. problems with attention, impulsivity, planning, headaches, sleep disturbances) following their injury (Table 12). A control group of age- and sex-matched, healthy students, with no history of head trauma was also recruited (11 female, 8 male) (M=20 yrs; SD=1.74; range=18 to 26 yrs).

Psychometric Measures

MHI Screening Questionnaire. As in Experiment 1, this questionnaire was given to all participants and contained questions regarding occurrence of MHI, age at which the injury occurred, length of time unconscious and whether hospitalization was required. All participants were screened for pre-existing neurological disorders or learning disabilities. In Experiment 2, additional questions were added to obtain information about symptoms immediately following (i.e. headache, dizziness, nausea and loss of memory) and several months following the head injury (i.e. difficulty with chronic headaches, fatigue, forgetfulness, concentration, depression/anxiety, and appetite).

Brock Health and History Questionnaire. As in Experiment 1, this questionnaire was given to all participants in order to obtain background information on health history, hospitalizations and use of medication, as well as information on handedness, educational background and alcohol and caffeine use.

Culture Fair Intelligence Test (Cattell & Cattell, 1960). This measure was used (as in Experiment 1) to provide a measure of general frontal function and non-verbal intelligence. The test is made up of four different subtests containing novel spatial problems that participants are required to solve. The correct responses on the four subtests are summed in order to obtain a total raw score.

Electrophysiological Measures

Easy Duration Discrimination. This auditory oddball task was the same as in Experiment 1. Computer-generated tones that differed in duration were presented using an IBM-compatible PC computer with InstEP stimulus presentation and EEG acquisition software that recorded all behavioral responses (i.e. RTs and correct/error data). Tones were presented through a separate speaker that was placed approximately 80 cm from the participant. A total of 250 trials were presented and participants were required to respond to the 100 ms target tone (20% of trials) by pressing the space bar on the computer keyboard whereas they were not required to respond to the 150 ms non-target tone (80% of trials). Tones were presented at 400 Hz and a variable ITI of 1300 to 1600 ms. Ten practice trials (alternating 5 short and 5 long tones) were presented before the task began so that participants were able to hear the difference between the tones before they started. Total time required to complete the task was 7 minutes. The maximum time allowed for responding was 1200 ms. Speed and accuracy were equally emphasized in the instructions given to the participants.

Difficult Duration Discrimination. This auditory oddball task was also the same as in Experiment 1. The duration discrimination of computer-generated tones was made more difficult by reducing the length of the non-target tone by 25 ms so that the target and non-target tone duration was closer together. Again, 250 trials were presented and participants were required to respond by pressing the computer spacebar when they heard the target tone (100 ms) and were not to respond when they heard the non-target tone (125 ms). Tones were presented at 400 Hz and an ITI of 1300 to 1600 ms. Time required to complete the task was 7 minutes with a maximum of 1200 ms allowed for response to each trial.

Verbal-Working-Memory Distractor Task. In Experiment 2, this working-memory distractor task was presented simultaneously with both the Easy and the Difficult Duration Discrimination tasks described above. Stimuli for this task were presented with a second computer (286 IBM Compatible PC). In Experiment 1, the distractor task was performed with the Easy Duration Discrimination task only. This paradigm was revised in

Experiment 2 so that information about the effects of distraction could be investigated in a more additive manner. The working-memory-distractor task itself remained the same as in Experiment 1. Participants monitored a list of numbers (2-second ISI) presented at the center of a monochrome computer screen one at a time, and responded by pressing the mouse button with the dominant hand every time they saw 3 consecutive odd, or ascending or descending numbers. Participants continued to respond to the tone discrimination tasks by pressing the computer space bar with the non-dominant hand.

Sequential-Letter Working-Memory Task (n-Back Task) (Cohen et al., 1997). Participants were required to perform four conditions of this task that progressively increased in working-memory-load requirements. In all conditions, 10 letters that varied between upper and lower case were presented one at a time, for 250 ms at the center of the computer screen. Stimulus presentation was again accomplished using InstEP stimulus presentation and EEG acquisition software. A total of 180 trials were presented, which were divided into three blocks of 60 trials that included a 30-second break period between blocks 1 and 2 and blocks 2 and 3. The ITI for this task was held constant at 1750 ms. For each condition, targets appeared on 30% of the trials (18 targets per block) and each of the 10 letters appeared 15 times total (5 times per block).

In the 0-back condition, participants were required to respond by pressing the space bar on the computer keyboard every time the letter "X" appeared on the computer screen. In the 1-back condition, participants were required to respond if the letter that appeared was identical to the one that had been presented immediately before it (regardless of case). In the 2- and 3-back conditions, participants were required to respond if the letter that appeared was identical to the one that had appeared 2 or 3 trials previously (regardless of case).

Electrophysiological Recording

Continuous electroencephalographic (EEG) activity was recorded from 27 scalp sites using a scalp cap embedded with tin electrodes (Electro-Cap International, Inc.) while participants performed the above computer tasks. The recording electrodes made contact with the following scalp sites: Fpz, Fz, Cz, Pz, Oz, Fp1, Fp2, C3, C4, T3, T4 as well as 8 coronal lateral frontal (F1, F2, F3, F4, F5, F6, F7, F8) sites and 8 coronal lateral parietal (P1, P2, P3, P4, P5, P6, T5, T6) sites and were referred to the right ear (Figure 8). Activity from the left ear was recorded on a separate channel and EEG was rereferenced offline to averaged ears for purposes of scoring ERPs. A ground electrode on the scalp cap (located between Fz and Cz) was employed. Electro-oculographic (EOG) activity was recorded from bipolar electrodes placed on the supraorbital ridge and at the outer canthus of the right eye on all participants. Participants were instructed to fix their gaze throughout each task to reduce the number of eye movement artifacts. Statistical eye-movement correction was performed offline prior to ERP averaging or EEG coherence derivation. Electrode impedance was kept below 5 kOhms. The EEG signal was amplified by a Sensorium, Inc. amplifier system at a gain of 10 000 (plus software gain of 4) and filtered with a band pass of .2 to 30 Hz. The amplified signal passed through an analogue-to-digital converter window of ±250 μV (12-bit resolution) and was sampled continuously at 256 samples per second.

Single-trial ERPs from 200 ms pre-stimulus baseline to 1800 ms post-stimulus (relative to the mean amplitude of the 200 ms prestimulus baseline period) were averaged offline for each target response. Data from all scalp electrode sites were scored. Only trials with correct responses were entered into the average. A computer-assisted averaging and peak-picking program was used to average and score the ERP components. Single-trial ERPs were either regression-corrected or not included in the average if voltages were greater than $\pm 100\ \mu V$ or if the regression-correction did not adequately correct for eye-movement contamination. The ERP components were selected as follows: N1 was the first most negative peak (in the easy duration discrimination condition between 82 and 176 ms), P2 was the first most positive peak after the N1 (between 156 to 277 ms in the easy discrimination condition), N2 was the most negative peak after the P2 (between 184 and 375 ms in the easy discrimination condition) and the P3 was the most positive peak after the N2 (between 383 to 625 ms in the easy discrimination condition). The other task conditions produced later ERP component ranges.

EEG Coherence

EEG coherence was also calculated offline for all computer paradigms employed in Experiment 2. Before coherence calculations were obtained, EEG was rereferenced to a balanced average reference of sites that included Fz, Cz, Pz, Oz, F3, F4, F7, F8, C3, C4, T3, T4, P3, P4, T5, T6 (Figure 8). EEG coherence was based on a maximum of 90 one-second epochs of clean EEG activity that were automatically extracted from the raw EEG data offline. The 90 epochs were chosen so that 30 came from each third across the entire condition. Another offline program then calculated Fast Fourier Transform (FFT) values for 1 Hz frequency bins from 1 to 30 Hz. Correlations across the time epochs between each electrode site combination for each frequency bin were calculated and averaged over the 1 Hz bins making up the frequency bands of interest (theta 4.5 to 7.5 Hz; alpha 7.5 to 12.5 Hz and beta 12.5 to 30.5 Hz). Correlations were derived between electrode pairs for each hemisphere separately. Electrode combinations of interest in this study were (1) frontal-parietal pairs including F1P1, F1P3, F1P5, F1T5, F3P1, F3P3, F3P5, F3T5, F5P1, F5P3, F5P5, F5T5, F7P1, F7P3, F7P5, F7T5, F2P2, F2P4, F2P6, F2T6, F4P2, F4P4, F4P6, F4T6, F6P2, F6P4, F6P6, F6T6, F8P2, F8P4, F8P6, F8T6; (2) frontal-central pairs including F1C3, F1T3, F3C3, F3T3, F5C3, F5T3, F7C3, F7T3, F2C4, F2T4, F4C4, F4T4, F6C4, F6T4, F8C4, F8T4 and (3) central-parietal pairs including C3P1, C3P3, C3P5, C3T5, T3P1, T3P3, T3P5, T3T5, C4P2, C4P4, C4P6, C4T6, T4P2, T4P4, T4P6, T4T6.

Procedure

Psychometric and electrophysiological measures were collected in the same session. Administration of these measures required approximately 2.5 hours. All participants completed the tasks in the same order, with the psychometric measures being administered first followed by the electrophysiological measures.

RESULTS

Participants

A total of 57 participants (19 per group) were tested in this experiment with 70.2 % majoring in arts, 14.0% majoring in science, 12.3% majoring in physical education or recreation and leisure studies, 1.8% majoring in math and computer science, and 1.8% majoring in business.

Head Injury Characteristics

The average length of time since injury for the MHI group that reported a loss of consciousness (LOC) of 20 minutes or less (RLOC<20) was 7.3 years (SD=4.29; range=1 to 14 years). The average length of time since injury for the moderate group that reported a loss of consciousness of 30 minutes to 36 hours (RLOC>30) was 6.8 years (SD=5.15; range=1 to 21 years). Causes of injury were motor vehicle or bicycle accidents, falling, sports accidents, a fight or attack and other causes such as the head hitting a wall or debris falling on the head. Table 13 summarizes the causes of the injuries sustained by both the RLOC<20 and the RLOC>30 groups.

Unconsciousness was reported in 11 cases in the RLOC<20 group (5 reported less than 1 minute, 5 reported 1 to 5 minutes and 1 reported 5 to 20 minutes of unconsciousness). Seven participants reported that they suffered a significant blow to the head with no loss of consciousness and 1 participant did not know if she had lost consciousness in this group. Thirteen participants in the RLOC<20 group reported having some medical attention as a result of their injury whereas 6 participants reported they did not receive any medical attention. One participant reported being admitted to the hospital overnight as a result of the injury and 18 participants were not admitted to the hospital.

In the RLOC>30 group, unconsciousness was reported in 18 cases (9 reported 30 min to 1 hour, 6 reported 1 hour to 12 hours and 3 reported 12 hours to 36 hours of unconsciousness). One participant reported no loss of consciousness but was included in the RLOC>30 group based on the nature of the injury and the reported severity of post-injury symptoms (i.e. significant loss of memory, severe insomnia, disruption of motor co-ordination). Seventeen participants in the RLOC>30 group reported having had some medical attention associated with their injury while 10 participants were hospitalized overnight as a result of the injury.

BEHAVIORAL RESULTS

Duration Discrimination Task with and without Working-Memory Distractor Task

Statistical Analysis. A 2 x 2 x 3 repeated measures ANOVA was conducted with the behavioral data from Experiment 2 with Stimulus Difficulty (2 levels, Easy vs. Difficult) and Task (2 levels, Single vs. Dual task) as within-subjects factors and Group (3 levels, Controls, RLOC<20 or RLOC>30) as the between-subjects factor.

Reaction Time (RT) Performance: Task Differences. A main effect of stimulus difficulty indicated that an increase in ease of stimulus discrimination from easy to difficult significantly increased participants' RTs to the target tone ($F(1,53)=22.90$, $p < .001$). In addition, a main effect of task indicated that increasing the demands on attentional allocation during the dual-task condition significantly increased the RTs of the participants, ($F(1,53)=266.22$, $p < .001$). Table 14 presents the means and standard errors for all task conditions. A significant stimulus difficulty by task interaction, ($F(1,53)=43.94$, $p<.001$) was also found for RT that demonstrated that the increase in participants' RTs from the single- to dual-task conditions was greater in the easy condition than it was in the difficult condition (Figure 9).

RT Performance: Group Differences. No group differences emerged for RT on the discrimination tasks with and without distractor. Behaviorally, the RLOC<20, RLOC>30 and the control groups performed similarly in terms of speed of responding to target tones during these tasks. Table 15 summarizes the means and standard errors for each group for each discrimination task.

Errors: Task Differences. An increase in stimulus difficulty significantly increased the mean number of errors committed by all participants, ($F(1,53)=62.99$, $p < .001$). A main effect of Task, ($F(1,53)=22.81$, $p < .001$) was also found for mean number of errors indicating that the addition of the distractor task significantly increased the participants' mean number of errors. No significant interaction between stimulus difficulty and task was found for mean errors. Table 16 summarizes the means and standard errors for the number of errors committed for each task condition.

Errors: Group Differences. There were no significant differences between the groups for the number of errors committed during the performance of the discrimination tasks with and without distractor. Table 17 presents the means and standard errors of number of errors for each group during each task condition.

Signal-Detection Analysis and Task Performance. Signal-detection analysis was conducted to investigate participants' ability to discriminate the target stimuli (d') as well as their threshold to respond to the stimuli (β). Increasing the difficulty of stimulus discrimination significantly decreased participants' ability to discriminate the target stimulus, ($F(1,53)=28.08$, $p < .001$). Increasing demands on attentional allocation by adding the distractor condition also significantly decreased the ability of participants to discriminate the target stimulus, ($F(1,53)=21.33$, $p < .001$). Means and standard errors of d′ for the stimulus- difficulty and task manipulations are presented in Table 18. A significant interaction between stimulus difficulty and task type was also found for d′, ($F(1,53)=14.86$, $p < .001$). Stimulus discrimination was highest during the easy single-task condition and was lowest during the difficult dual-task condition (Figure 10).

A main effect of stimulus difficulty was found for participants' threshold to respond to the target stimulus (β), ($F(1,53)=15.72$, $p < .001$). An increase in stimulus difficulty significantly increased participants' threshold to respond, indicating that they were responding more conservatively during the difficult stimulus-discrimination conditions. As well, a main effect of task for β demonstrated that participants' threshold to respond increased with the addition of the distractor task, ($F(1,53) = 42.18$, $p < .001$). Participants' responses were more conservative during performance of the dual task. Table 19 summarizes the means and standard errors of β for stimulus difficulty and task conditions. A significant interaction was also found between stimulus difficulty and task for β, ($F(1,53)=24.64$, $p < .001$) (Figure 11). Participants were relatively unbiased in their responding to the easy stimulus discrimination under the single-task condition whereas their threshold to respond to the easy target stimuli under the dual-task condition was significantly more conservative. Under the difficult stimulus-discrimination condition, participants' threshold to respond was similarly conservative for the single and dual-task conditions.

Signal-Detection Analysis and Group Performance. No group differences emerged for either of the signal-detection measures (d' or β) indicating that the groups performed similarly in their ability to detect and respond to the target stimuli under all task conditions.

Summary of Behavioral Results. Increasing the difficulty of the stimulus discriminability for the tone-duration task as well as adding a second simultaneous distractor task served to affect participant performance. Increasing stimulus difficulty and increasing demands on attentional allocation led to an increase in participant RTs and the number of errors committed. As well, participant ability to detect the target stimulus decreased with the increase in stimulus difficulty and with the addition of the dual task. Participants' threshold to respond to the targets also increased, indicating that they were responding more conservatively as the tasks became more difficult. No group differences emerged, indicating that the groups performed similarly on all behavioral measures of the duration discrimination with and without distractor task. Similar behavioral performance was found despite complaints of persistent symptoms in both head injury groups.

Working-Memory Distractor Task

Statistical Analysis. A 2 x 3 repeated measures ANOVA was conducted with Stimulus Difficulty as the within-subjects factor (e.g., whether the distractor was performed simultaneously with the easy or the difficult duration discrimination task) and Group (Control, RLOC<20 or RLOC>30) as the between-subjects variable.

RT Performance: Task Differences. There was no significant difference between speed of participants' responses to the distractor task during the easy versus the difficult duration discrimination tasks, ($F(1,48)=0.48$, $p = .492$). Therefore participants were taking approximately the same amount of time to respond to the simultaneous distractor task under both the easy (Mean RT=692 ms) and difficult (Mean RT=707 ms) duration discrimination conditions.

RT Performance: Group Differences. There were no significant group differences for RT performance on the verbal-working-memory task when it was performed simultaneously with the easy and difficult duration discrimination tasks. Table 20 summarizes the means and standard errors for distractor task RT performance for each group.

Errors: Task Differences. Increasing the difficulty of stimulus discrimination for the tone-discrimination task significantly decreased the number of errors made on the simultaneous working-memory distractor task, ($F(1,48)=10.75$, $p = .002$). It is possible that this finding of fewer errors in the more difficult condition might be a result of a bias in responding to one of the tasks over the other when they are being performed simultaneously. Therefore, the percentage of trials that were correctly responded to was compared for the tone-duration discrimination tasks and the working-memory distractor tasks. A significant stimulus difficulty by task interaction was found for the percentage of correct responses, ($F(1,48)=42.56$, $p < .001$) (Figure 12). Under the easy condition, participants made more responses to the tone task whereas under the difficult condition, participants made more responses to the working-memory distractor task. The means and standard errors for number of errors committed and percentage of trials correctly responded to for each condition is presented in Table 21. Although participants continued to respond to both tasks when they were performed simultaneously, they appeared to respond more readily to the tone discrimination task under the easy condition but they favoured the verbal-working-memory distractor task under the difficult tone discrimination condition.

Errors: Group Differences. There were no group differences found for the number of errors committed on the working-memory distractor task, demonstrating that the groups performed similarly in terms of the number of errors made during the performance of this task. Table 22 summarizes the means and standard errors for errors committed for all groups on the working-memory distractor task.

Signal-Detection Analysis and Task Performance. Signal-detection analysis was conducted to determine participants' ability to discriminate the target stimuli (d') during the verbal-working-memory distractor task as well as to determine their threshold to respond to the target stimuli (β). Increasing the difficulty of stimulus discrimination for the tone task significantly increased participants' ability to discriminate the working-memory stimuli under the difficult condition, ($F(1,48)=10.17$, $p=.003$). This finding is again most likely the result of a change in responding in favor of the verbal-working-memory task under the difficult tone discrimination condition. There was no significant difference in terms of participants' threshold to respond to the target stimuli for the distractor task, ($F(1,48)=0.08$, $p = .781$. Participants' responses were similarly conservative under the easy duration discrimination condition as under the difficult duration discrimination condition. Table 23 presents means and standard errors for both signal-detection measures of the working-memory distractor tasks.

Signal-Detection Analysis and Group Performance. There were no significant differences between the groups for either of the signal-detection measures (d' or β), indicating that the groups performed similarly in their ability to detect and respond to the target stimuli during performance of the working-memory distractor task.

Summary of Results. Participants made fewer errors and their ability to detect the target stimulus increased when the difficulty of the dual-task condition increased. Participants' threshold to respond to the target stimuli from the easy to the difficult condition remained the same. Participants appeared to demonstrate a bias in responding to one of the tasks over the other. A comparison of responses to both tasks revealed that participants favoured responding to the tone task under the easy stimulus discrimination condition and favoured responding to the working-memory task under the difficult stimulus discrimination condition. No group differences emerged indicating that the RLOC<20, RLOC>30 and Control groups performed similarly on all behavioral measures of the Working-Memory Distractor task.

Sequential-Letter Working-Memory Task (n-Back Task)

Statistical Analysis. A 4 x 3 repeated measures ANOVA was conducted with the behavioral data from the n-Back task with Working-Memory (WM) Load (4 levels, 0-back, 1-back, 2-back and 3-back) as the within-subjects factor and Group (3 levels, Controls, RLOC<20MHI or RLOC>30) as the between-subjects factor.

RT Performance: Task Differences. A main effect of WM load indicated that the increase in load on working memory significantly increased participants' RTs to the target letter, ($F(3,153)=124.99$, $p<.001$). Table 24 summarizes the means and standard errors for RT performance as a function of WM load.

RT Performance: Group Differences. A WM load by group trend emerged for RT, ($F(6,104.4)=2.10$, $p=.085$: Greenhouse-Geisser corrected) (Figure 13) demonstrating that for the 3 groups, speed of responding was similar in the 0-back condition whereas both the RLOC<20 and RLOC>30 groups responded more slowly than the control group during the 3-back condition. Table 25 presents the means and standard errors for RT performance for each group as a function of WM load.

Errors: False Alarms and Omissions: Task Differences. A significant main effect of WM load was found for incorrect responses to letter stimuli. The mean number of false alarms (FA) significantly increased with increased load on WM, ($F(3,153)=61.35$, $p<.001$). A significant main effect of WM load was also found for omitted responses. The mean number of omissions (OM) significantly increased with increased load on WM, ($F(3,153)=285.50$, $p<.001$). Table 26 summarizes the means and standard errors for FA and OM as a function of WM load.

Errors: False Alarms and Omissions: Group Differences. No significant effect of group was found for number of false alarms and omissions of responses to target stimuli. Means indicated that the three groups made a similar number of errors during the four conditions of this task. Table 27 presents the means and standard errors for FA and OM for each group as a function of WM load.

Summary of Results. Increasing the load on working memory served to significantly slow down participant responses to the letter target. There was a trend for the head injury groups to respond more slowly than controls in the condition that placed the greatest demand on working-memory load (3-back condition). There were no group differences in the number of errors made during the performance of this task. Increasing the load on WM was found to increase the number of false-alarm responses as well as increasing the number of omissions similarly for all three groups. The large number of omitted responses to the target letters in the 3-back condition (41%) suggested that participants found this condition very difficult and thus were responding at or just above chance level. The 3-back condition was subsequently removed from the electrophysiological analyses of the n-Back task.

ELECTROPHYSIOLOGICAL RESULTS

Event-Related Potentials: Duration Discrimination With and Without Simultaneous Working-Memory Distractor Task

Statistical Analysis. A 2 x 2 x 4 x 3 repeated measures ANOVA was conducted with Stimulus Difficulty, Task and Site (Fz, Cz, Pz and Oz) as within-subjects factors and Group as the between-subjects factor for each ERP component (N1, P2, N2, P3).

Early ERP Component Amplitude (N1, P2, N2): Task Differences. We hypothesized that the amplitude of the early ERP components (N1, P2) would not show any differences with increased cognitive demands whereas late-component P3 amplitude would decrease with greater demands placed on cognitive resource allocation. We also hypothesized that no group differences would be apparent in the early ERP components but that we would see a greater reduction in P3 amplitude for the head injury groups as the tasks got more difficult.

A significant main effect of Task was found for the N1, ($F(1,48)=7.99$, $p=.007$), P2, ($F(1,50)=4.76$, $p=.034$), and N2, ($F(1,47)=14.20$, $p<.001$), amplitudes across all scalp sites. N1 amplitude was greater in the dual-task condition. Similarly, P2 and N2 amplitudes increased in the dual-task condition. Table 28 presents the means and standard errors for N1, P2 and N2 amplitudes for each task condition.

P3 Component Amplitude: Task Differences. A significant stimulus difficulty by task interaction was found for P3 amplitude, ($F(1,47)=4.996$, $p=.030$), averaged across scalp sites (Figure 14). P3 amplitude decreased from the single- to dual-task condition under the easy-stimulus manipulation whereas there was virtually no change in the P3 amplitude from the single to dual-task condition under the difficult-stimulus manipulation. Table 29 presents the means and standard errors for P3 amplitude. Figures 15a, 15b, 15c and 15d present the averaged ERP waveforms for a single control participant for each condition during the duration discrimination task.

ERP Component Amplitude: Group Differences. No group differences emerged for either the early ERP components or the late ERP components indicating that the task manipulations employed affected the information-processing abilities of the groups similarly.

Early ERP Component Latency (N1, P2, N2): Task Differences. We hypothesized that the early ERP components (N1, P2) would not demonstrate latency differences as a function of increased cognitive demands but that late component P3 latency would increase with greater demands placed on cognitive resource allocation. No group differences in latency were expected for the early ERP components but we expected a greater increase in P3 latency for the head injury groups as the tasks got more difficult. There were no significant effects of Stimulus Difficulty or Task Condition on either the N1 or P2 latencies.

P3 Component Latency: Task Differences. A significant main effect of stimulus difficulty was found for P3 latency, ($F(1,47)=25.93$, $p<.001$), increasing from the easy to the difficult stimulus-discrimination conditions. A significant main effect of task was also found for P3 latency, ($F(1,47)=19.73$, $p<.001$), increasing with the addition of the dual task. No significant interactions emerged. Table 30 summarizes the means and standard errors for P3 latency for both the stimulus-discrimination manipulation and the task manipulation.

ERP Component Latency: Group Differences. There were no significant group differences for either the early or late ERP component latencies.

Discussion of ERP Results

The analysis of ERP components associated with performance of the duration discrimination with and without distractor task allowed us to investigate changes in information-processing as a result of increased demands on attentional recruitment and allocation of attentional resources. We were also interested in how the processing of information during the performance of complex cognitive tasks might be affected by head injury. Differences in information-processing could exist between groups even when there was a lack of behavioral differences between the groups.

The early ERP components are thought to reflect automatic, externally driven sensory responses to stimuli. These automatic processes appear to be affected when task demands are increased, in this case, by adding a second simultaneous task, which is contrary to what we hypothesized. We predicted that the automatic ERP components would not be affected by our manipulation of task demands. We did find that increased task demands did not affect the speed of early automatic responses (N1, P2, N2 latencies). Thus, the automatic components of information-processing do not slow down as the demands of the task become more difficult. Under the dual-task condition however, N1, P2 and N2 amplitudes increased, indicating an augmentation of automatic processes at the early stages of information-processing.

There is support in the literature that the ERPs thought to be automatic in nature can actually be affected by the demands placed on attention. Traditionally, N1 is enhanced when participants are required to attend to a particular target stimulus and ignore other stimuli that are presented (Picton & Hillyard, 1988). Fitzgerald and Picton (1983) report increased amplitude of the N2 component as a target stimulus becomes more difficult to discriminate from a standard stimulus. In our study, the heightened concentration required to perform two tasks at once may have led to the enhancement of these early components as the detection of the target stimulus became a challenge to the system. The later P3 component reflecting the more cognitive aspects of information-processing, was shown to be affected by increased demands on attentional recruitment as well as increased demands on attentional allocation. Attentional-allocation capacity as reflected by P3 amplitude was shown to decrease as increased concentration and division of attentional resources were required. As well, speed of information-processing was shown to increase with increased concentration and attentional requirements. This finding is consistent with the literature that demonstrates reduced P3 amplitude with simultaneous presentation of tasks and increased P3 latency with increased task complexity (Hoffman et al., 1983; Picton & Hillyard, 1988).

Interestingly, a comparable decrease in P3 amplitude from single- to dual-task performance in the difficult-stimulus-discrimination condition did not emerge; however, similar results have been reported in the literature. Isreal, Chesney, Wickens and Donchin (1980) demonstrated that participants exhibited attenuated P3 amplitudes during simultaneous performance of two tasks and an increase in difficulty of the primary task did not serve to further alter the P3 amplitude to the second task. In our study, the lack of a significant decrease in P3 amplitude from the difficult single to dual condition may reflect the fact that the difficult-stimulus-discrimination condition alone was sufficient to reduce attentional allocation capacity and the addition of the simultaneous distractor task did not serve to reduce available cognitive resources beyond the demands of the stimulus-discrimination task. Our findings might also be a reflection of participants increasing their attentional capacity during the most difficult condition, perhaps through increased concentration or increased arousal.

An investigation of automatic and controlled processing in children with attention deficit hyperactivity disorder (ADHD) demonstrated enhanced early cognitive components (Robaey, Breton, Dugas, & Renault, 1992). In these children, who present with impaired attentional abilities, the P2 and N2 ERP components were found to be enhanced compared to control children. The later P3 component was found to be reduced in the ADHD population. Robaey et al. (1992) interpreted their results as demonstrating an enhancement in automatic processes as the later, more controlled processes were inadequate during attention-demanding tasks. Although it is difficult to make comparisons between suspected physiological- attentional limitations (ADHD population) and experimental manipulations of attentional capacity, ours is a similar pattern to that of Robaey et al. (1992). Our results of enhanced early- processing components and a decrease in P3 amplitude from the single- to dual-task situation in the easy-stimulus-discrimination condition may reflect augmentation of early components as a decrease in available attentional resources makes controlled processing alone inadequate during the performance of two simultaneous tasks.

We had predicted that group differences would emerge in the P3 amplitude and latency with increased demands on attentional resources. The lack of significant group differences in both ERP component amplitude and latencies indicates that head injury with good recovery does not produce information-processing differences during tasks requiring increased concentration and attentional allocation. The specific aspects of information-processing that were elicited by the task manipulations employed in this study did not appear to be compromised in our head injury groups.

Event-Related Potentials: Sequential-Letter Working-Memory Task (n-Back Task)

Statistical Analysis. A 3 x 4 x 3 repeated measures ANOVA was conducted with WM Load (0-back, 1-back, 2-back) and Site (Fz, Cz, Pz, Oz) as within-subjects factors and Group as the between-subjects factor for each ERP component (N1, P2, N2, P3).

Early ERP Component Amplitude (N1, P2, and N2): Task Differences. Again, we predicted that the increased demands on cognitive resources (increased load on working memory) would serve to decrease the amplitude of the later, cognitive ERP component (P3) whereas the early ERP components would remain unaffected by this manipulation. We also predicted that the head injury groups would demonstrate a greater reduction in P3 amplitude with increased demands on attentional resources.

A significant WM load by site interaction was found for N1 amplitude, ($F(3.2,155.2)=2.67$, $p=.046$) (Figure 16). N1 amplitude increased with the increased load on working memory at the frontal electrode sites.

A significant WM load by site interaction was also found for N2 amplitude, ($F(3.4,160.6)=4.09$, $p=.006$) (Figure 17). N2 amplitude significantly decreased with the increase on working-memory load at the frontal electrode sites. Table 31 presents the means and standard errors for ERP amplitude of the early components during each condition of the n-Back task.

Early ERP Component Amplitude (N1, P2, N2): Group Differences. There were no significant group differences for the early ERP component amplitudes.

P3 Component Amplitude: Task Differences. A significant WM Load by Site interaction emerged for P3 amplitude, ($F(6,300)=11.87$, $p<.001$) (Figure 18). P3 amplitude significantly decreased with an increase on working-memory load at the central/posterior electrode sites. Figure 19 presents the averaged ERP waves for a single control participant for each condition of the n-Back task.

P3 Component Amplitude: Group Differences. A significant Site by Group interaction was found for P3 amplitude, ($F(3.4,84.3)=2.99$, $p=.03$) (Figure 20). The RLOC>30 group demonstrated higher P3 amplitudes at the frontal electrode sites and lower P3 amplitudes at posterior electrode sites compared to the Control and RLOC<20 groups.

Early ERP Component Latency (N1, P2, N2): Task Differences. There were no significant effects of WM Load on the early (N1, P2, N2) ERP latencies.

Early ERP Component Latency: Group Differences. There were no significant group differences for the early ERP component latencies.

P3 Component Latency: Task Differences. A significant WM Load by Site interaction emerged for P3 latency, ($F(3.8,191)=2.49$, $p=.047$). P3 latency was fastest in the 2-back condition at the frontal electrode sites. This finding was contrary to our predictions and is difficult to interpret.

P3 Component Latency: Group Differences. There were no significant group differences for P3 latency.

Discussion of ERP Results

In analyzing the ERP components associated with performance of the n-Back task we were interested in the effect of increased working-memory load on information-processing and how increasing the load on working memory might affect information-processing following head injury. We had predicted that the early ERP components would not show differences with increased memory load. The results of the n-Back task demonstrated that the early ERP components were affected by our manipulation of task demands. As working-memory load increased, we found a significant increase in N1 amplitude at frontal electrode sites that may reflect an augmentation of automatic sensory processes during early information-processing. The heightened concentration required to perform the n-Back tasks as memory load demands increased may lead to the enhancement of the early N1 component as target detection becomes more challenging. Although we found an N1 component enhancement, we also found that the latency of the early ERP components did not increase with working-memory load indicating that the early aspects of information-processing did not slow down with increased load.

We found that N2 amplitude at frontal electrode sites significantly decreased as the load on working memory increased. This reduction in N2 amplitude with increased task demands may reflect reduced resources for automatic stimulus discrimination and categorization of target stimuli when working-memory load increases. As well, the increased complexity of required processing during the working-memory task may result in a reduced N2 component. The reduction in amplitude of the N2 component with increased memory load may also reflect decreased confidence in the detection of the target stimuli. A negative wave with a peak latency between 100 to 200 ms has been shown to decrease in amplitude and increase in latency as participants report reduced confidence in their ability to detect a target (Picton & Hillyard, 1988).

P3 amplitude was found to significantly decrease with increased working-memory load at central/posterior electrode sites whereas a linear increase in P3 latency with increased memory load was not found. Although speed of information-processing was not linearly affected by increased load on working memory, information-processing capacity appeared to decrease as the n-Back task became more difficult. The behavioral results revealed that indeed participants made significantly more errors in responding with increased memory load. Houlihan, Stelmack and Campbell (1998) report similar findings in a slightly different working-memory paradigm. Participants were required to retain 1, 3 or 5 consonants in memory and then indicate whether a single target letter had been among the initially presented consonants. Decreased P3 amplitude to target letters was found with increased memory-set requirements that they interpreted as being indicative of the effects of task difficulty or increased demands on information transmission (Houlihan et al., 1998). Similarly, our results indicate that with increased load on working memory, information-processing efficiency decreases.

We predicted that group differences would emerge as greater P3 amplitude reductions in the head injury groups with increased memory load. Overall, specific aspects of information-processing associated with n-Back task performance did not appear to be compromised in our head injury groups who demonstrated good recovery from their injury. The group with longer LOC (RLOC>30) did demonstrate some ERP differences compared to controls and those with shorter LOC. The RLOC>30 group was found to demonstrate higher P3 amplitude at frontal sites and lower P3 amplitude at posterior sites compared to the Control and RLOC<20 groups during the working-memory task as a whole. Similar differences in the scalp distribution of the P3 wave have been found in older adults compared to young adults. The P3 component becomes more frontal in scalp distribution in the older adults.

Friedman, Kazmerski and Cycowicz (1998) demonstrated that the P3 to novel stimuli habituates (decreases in amplitude) in young adults at frontal electrode sites over time whereas elderly adults do not demonstrate this frontal P3 amplitude decrease. These differences are thought to reflect different brain regions being recruited to perform the oddball task. The pattern of P3 scalp distribution in older adults is thought to be consistent with changes in frontal-lobe function with age (Friedman et al., 1998). Behaviorally, older adults demonstrate more false alarms to non-target stimuli indicating that they are less able to inhibit their responses. This elevation in false-alarm rate has been shown to be related to two distinct P3 foci (frontal and posterior) in older adults in comparison to young adults who show a highly focused, parietally maximal P3 to target stimuli and fewer false alarms (Friedman, 1995). Thus an inability to effectively allocate attention and inhibit responses to non-targets may manifest in a hyperfrontality with aging. Although our RLOC<30 group did not make more errors than the other groups during the n-Back tasks, a frontally oriented P3 was found that was similar to that reported in older adults, indicating a different pattern of neural activation during task performance. Because behavioral performance differences did not emerge between groups, the functional significance of the site interaction may be that those with head injury are showing more effortful processing during performance of the working-memory task to perform at the same level as other groups, i.e. this group requires allocation of more resources.

EEG Coherence: Duration Discrimination With and Without Simultaneous Working-Memory Distractor Task

Statistical Analysis. For all EEG coherence analyses, a 2 x 2 x 2 x 4 x 4 x 3 repeated measures ANOVA was conducted with Stimulus Difficulty (2 levels; Easy and Difficult), Task (2 levels; Single and Dual), Hemisphere (2 levels; Left and Right) and Frontal Site (4 levels; F1/2, F3/4, F5/6, F7/8) and Posterior Site (4 levels; P1/2, P3/4, P5/6, T5/6) as within-subjects factors and Group as the between-subjects factor for each frequency bandwidth (Theta, Alpha, and Beta).

Task Differences. We hypothesized that EEG coherence would increase between the long cortico-cortical fibers in the frontal and posterior regions as the demands on cognitive resources increased.

A significant main effect of stimulus difficulty, ($F(1,48)=5.30$, $p=.026$) for dorsal frontal-parietal (F-P) EEG coherence within the beta band was found as a result of a significant decrease in F-P beta coherence from the easy to the difficult discrimination condition. As well, a significant main effect of task, ($F(1,48)=10.97$, $p=.002$) was found as a result of a significant increase in F-P beta coherence from the single- to the dual-task condition. Table 32 summarizes the means and standard errors for beta F-P coherence during both stimulus- difficulty and task manipulations. There was no significant interaction between Stimulus Difficulty and Task. No significant task effects emerged in the analysis of F-P coherence for the theta or alpha frequency bands.

We also looked at the EEG coherence between areas thought to be connected by short-fiber connections to determine whether the task effects (increased beta coherence with the dual task and decreased beta coherence with difficult stimulus discrimination) were indeed unique to the long-fiber connections as we had predicted and that our F-P effects were not just a result of increased or decreased coherence across the entire brain because of volume conduction. An analysis of frontal-central (F-C) connections demonstrated that there was no effect of stimulus-discrimination difficulty ($p=.175$) or task condition ($p=.060$) on EEG coherence within the beta band. Analysis of central-parietal (C-P) short connections demonstrated no effect of task condition, ($p=.609$), but there was a significant main effect of stimulus-discrimination difficulty, ($F(1,48)=15.14$, $p<.001$), showing that C-P beta coherence increased with greater stimulus difficulty indicating greater local coherence with increased focused attention. Table 33 summarizes the means and standard errors for F-C and C-P beta coherence during both stimulus difficulty and task manipulations.

Group Differences. A Group x Task x Hemisphere interaction, ($F(2,43)=3.541$, $p = .038$) (Figure 21) was found for frontal-parietal (F-P) EEG coherence within the beta band. Overall, coherence values were higher in the left hemisphere than in the right, (Left = .450; Right = .383). This higher coherence in the left hemisphere likely reflects the fact that the working-memory task was verbal in nature. Frontal-parietal coherence in the left hemisphere did not increase among controls from the single to the dual task but it did increase from single to dual task for those in both of the head injury groups. Difficulty of the stimulus discrimination did not elicit a group interaction, ($F(2,43)=0.11$, $p = .892$). F-P coherence decreased from the easy to the difficult discrimination similarly for all three groups. Means and standard errors for F-P beta coherence for each group and each condition are presented in Table 34. No significant group effects emerged in the analysis of F-P coherence for the theta or alpha frequency bands.

Discussion of EEG Coherence Results

The analysis of EEG coherence in this study was conducted to determine whether differences in communication between cortical regions, particularly F-P communication, is associated with increased demands on attentional resources and whether individual differences in cortico-cortical communication could be demonstrated following head injury. The different task manipulations we employed during the Duration Discrimination with and without Distractor task (easy versus difficult discrimination; single versus dual task) led to different EEG coherence findings. Our results suggest that different brain processes are involved when the brain must divide its cognitive resources than when the brain is required to focus attentional resources. Increasing demands on divided attention served to increase beta coherence between F-P sites. Increased mental activity has been shown to relate to increased frequency and regularity of low-amplitude beta waves (Lazarev, 1998; Ray & Cole, 1985). The increase in beta coherence during the dual-task condition in our experiment may be indicative of increased mental activation and recruitment of reciprocal connections between the frontal and parietal regions to keep information in an active state. The increase in F-P coherence from the single to dual task is consistent with the findings of Cohen et al. (1997) who demonstrated that areas in the PFC and posterior cortex become active when participants are required to actively maintain information within working memory.

Conversely, increasing focused attention (making the stimulus discrimination more difficult) served to decrease F-P coherence. Lazarev (1998) reports a similar finding of reduced cortical excitation in the beta-frequency band with focused voluntary attention during tasks that required participants to match rhymes or do mental multiplication. Our results also demonstrate that areas in central and parietal cortex increase in beta coherence with greater discrimination demands. Thus, focused attention may involve recruitment of more short-range, localized connections in the posterior regions resulting in a decrease in coherence involving the long fiber connections.

Analysis of EEG coherence demonstrated a difference between groups for F-P beta coherence in the left hemisphere during the Dual-task condition. F-P communication was increased in the head injury groups within the beta-frequency band compared to control participants. F-P communication did not differ between groups as a result of stimulus discrimination difficulty. Behaviorally, both the task manipulation (single versus dual task) and the stimulus- difficulty manipulation (easy versus difficult) affected performance of all participants by increasing RTs and the number of errors committed. These findings, combined with the EEG coherence findings, suggest that although a dual-task situation and stimulus difficulty both challenge performance, head injury affects cortical communication in situations in which participants are required to allocate their attentional resources.

Increases in long-fiber-connection EEG coherence have been found following MHI (Thatcher, Biver, McAlaster, & Salazar, 1998). During resting EEG, short-connection coherence was found to be reduced and long-connection coherence increased in persons with MHI compared to controls. These findings were interpreted as reflecting the sparing of long cortical connections, with the short-distance connections being more susceptible to damage following MHI (Thatcher et al., 1998). We did not find evidence of short-connection coherence being reduced following MHI but we were able to demonstrate an increase in long-connection coherence. This increased coherence compared to controls may reflect an increased cortical activation "cost" in order for our head injury groups to have behavioral performance similar to controls. This interpretation fits with Satz's theory of brain reserve capacity. Satz (1993) describes a number of PET studies in which participants who performed well on cognitive tests used less metabolic activity than participants who did not perform as well. This finding is interpreted as those with lower performance employing less efficient neuronal circuits and thus requiring higher metabolic output (Satz, 1993). Although our head injury groups did not demonstrate lower behavioral performance, they may be demonstrating reduced neuronal efficiency and therefore requiring increased EEG coherence to achieve satisfactory behavioral outcome when cognitive resources are taxed.

The finding of greater overall coherence in the left hemisphere is not surprising given the verbal nature of a component of the dual task. A left-hemisphere shift in regional activation during verbally mediated tasks has been reported previously (e.g., Lazarev, 1998).

EEG Coherence: Sequential-Letter Working-Memory Task (n-Back Task)

Statistical Analysis. The frontal electrode sites included in the analyses for the n-Back task were those situated over the PFC as it was in this region that (Cohen et al., 1997) found an increase in cortical activation with increased working-memory load. Therefore, for all EEG coherence analyses a 3 x 2 x 3 x 4 x 3 repeated measures ANOVA was conducted with WM Load (3 levels; 0-back, 1-back, 2-back), Hemisphere (2 levels; Left, Right) Frontal Site (3 levels; F3/4, F5/6, F7/8) and Posterior Site (4 levels; P1/2, P3/4, P5/6, T5/6) as within-subjects factors and Group as the between-subjects factor for each frequency bandwidth (Theta, Alpha, and Beta).

Task Differences. Again, we predicted that F-P EEG coherence would increase as we increased the demands on cognitive resources.

A significant main effect of WM load, ($F(1.9,81.8)=5.274$, $p=.008$, Greenhouse-Geisser corrected), was found within the theta frequency band (3.5 to 7.5 Hz) indicating that theta coherence between frontal and posterior electrode sites increased as the load on working memory increased. Table 35 summarizes the means and standard errors for F-P theta coherence as a function of working-memory load. No significant task effects emerged in the analysis of F-P coherence for the alpha or beta frequency bands.

In order to determine whether the effect of WM load was limited to F-P long connections, we looked at the effect of WM load on the short F-C and C-P connections. The results demonstrated that F-C theta coherence was not affected by increasing the load on working memory ($p=.195$). We did find a significant increase in C-P theta coherence with increased WM load, ($F(2,100)=5.59$, $p=.005$), which again may indicate a recruitment of local, short-range connections with increased focused attention required to perform the n-Back task as task demands increased. Table 36 summarizes the means and standard errors for F-C theta and C-P coherence as a function of working-memory load.

Group Differences. A significant Hemisphere by Group interaction was found for beta coherence, ($F(2,43)=3.36$, $p=.045$) (Figure 22), indicating that, although left-hemisphere F-P coherence was greater than right-hemisphere F-P coherence for all groups (likely because of the verbal nature of the task), those with head injury demonstrated greater right-hemisphere coherence, especially the RLOC>30 group. There was a trend ($p=.09$) for the head injury groups to show higher F-P beta coherence than controls overall (Mean beta coherence = .34 (controls), .40 (RLOC< 20), .42 (RLOC>30)). Table 37 summarizes the means and standard errors of F-P beta coherence for each Group as a function of hemisphere. There were no significant group effects for EEG coherence within the theta or alpha frequency bands.

Discussion of EEG Coherence Results

Increasing demands on working memory serve to alter participants' behavioral performance and also leads to electrophysiological changes. In this study, an increase in load on working memory led to significant increases in response time to the target stimuli as well as significant increases in the number of performance errors demonstrating that our task was indeed placing increased demands on working-memory load at each level. Electrophysiologically, increases in WM load led to significant increases in F-P coherence within the theta frequency band. It appears that as the load on working memory increases, an increase in synchronous activity between frontal and parietal electrode sites emerges and that this increased F-P activity can be dissociated from activity from shorter distance F-C connections. This finding is consistent with results from Sarnthein, Petsche, Rappelsberger, Shaw and von Stein (1998), who found increases in theta coherence during a 4-second retention period during which a string of keyboard characters had to be remembered. Sarnthein et al. (1998) interpreted their findings as a reflection of working memory being mediated by low frequency (4-7 Hz) interactions between areas in the prefrontal cortex and posterior association areas. Our findings are also consistent with those of Cohen et al. (1997) who found that the PFC along with posterior parietal regions demonstrated an increase in activity with increased levels of working-memory load.

We were interested in whether individual differences in F-P communication could be observed with increased demands on working-memory load following head injury. F-P beta coherence was higher for the head injury groups in both the Left and the Right hemispheres compared to the Control group during performance of the n-Back task. Again, we have demonstrated that long-distance cortical coherence increases following head injury, consistent with Thatcher et al. (1998). During performance of the working-memory tasks, F-P beta coherence was higher in the left hemisphere for the head injury groups compared to controls and it was also higher in the right hemisphere (especially the RLOC>30 group), perhaps reflecting a recruitment of additional neural resources from both hemispheres in order to complete the WM task with satisfactory performance. These results are consistent with our previous findings of increased F-P communication in the head injury groups during performance of a dual task and again they fit with Satz's brain-reserve-capacity theory that postulates greater neuronal activation as a result of greater neural inefficiency following head injury. Given our findings of a frontally oriented scalp distribution of the P3 component during working-memory performance in the RLOC>30 group, our coherence results may reflect increased recruitment of resources particularly from frontal regions in this group. Overall, we have been able to demonstrate an increased cortical activation cost associated with head injury in that higher EEG coherence in the head injury groups is required to perform with behaviorally equivalence to the control group.

GENERAL DISCUSSION

One of the main issues addressed in this thesis was how attentional allocation and recruitment of attentional resources is affected by increasing the demands or complexity of the cognitive task. We were also interested in how a MHI might affect one's ability to deal with increased demands on attentional control and recruitment was well as performance on other information-processing tasks that are associated with frontal-lobe abilities.

Regardless of MHI, increasing the difficulty of the task produced a number of behavioral and electrophysiological differences. Increased RTs, greater numbers of errors committed, reduced ability to detect a target stimulus and increased threshold to respond to a target were all manifestations of increased cognitive demand on behavioral performance. Electrophysiologically, we demonstrated that the early components of information-processing, including early attention to, detection and processing of a stimulus became enhanced, perhaps as a result of increased focused attention as demands on attentional abilities increased. Speed of information-processing was shown to increase and information-processing capacity to decrease as a result of increased demands on attentional allocation. Our behavioral and ERP findings are consistent with those reported in the literature (Fitzgerald & Picton, 1983; Hoffman et al., 1983; Isreal et al., 1980; Picton & Hillyard, 1988).

This thesis extends our knowledge of electrophysiological changes associated with increased cognitive demands, as EEG coherence changes were found following different task manipulations. Increasing the difficulty of the stimulus discrimination and thus requiring increased attentional recruitment, resulted in reduced EEG beta coherence between long-fiber connections between frontal and parietal regions, while the short connections between central and parietal cortex increased in coherence. Increasing demands on divided attention as well as having to employ working memory served to increase EEG coherence between frontal and parietal regions although short-fiber connections were not affected. Thus, different brain processes appear to be involved when the brain must divide its cognitive resources compared to when it is required to focus attentional resources. Increasing focused attention may involve increased recruitment of more posterior, local connections resulting in decreased coherence involving long-fiber F-P connections (Thatcher et al., 1986). Increasing demands on divided attention may involve increased recruitment of the long-fiber reciprocal connections between frontal and parietal regions to keep information in an active state both in terms of dual-task performance (central executive) and during working-memory tasks (Cohen et al., 1997; Friedman & Goldman-Rakic, 1994).

Differences in EEG coherence patterns between the head injury and control groups demonstrated that the head injury groups required increased "cross-talk" between frontal and posterior cortical sites during the performance of dual-task and working-memory tasks. Although Experiment 2 failed to replicate the behavioral differences between groups that were demonstrated in Experiment 1 (reduced ability to discriminate targets from non-targets and a lower threshold to respond to target stimuli during the performance of a dual task), we were able to demonstrate definite electrophysiological differences. Despite the report of some persistent symptoms such as attention problems, planning problems, chronic headaches and sleep disturbances, the head injury groups demonstrated behavioral performance equivalent to controls. This lack of behavioral performance differences, however, was accompanied by increased EEG beta coherence between frontal and parietal sites during dual-task performance and during working-memory task performance. Thus, the head injury groups may be demonstrating an increased cortical-activation cost associated with demands on attentional allocation and working memory.

Increased F-P coherence following head injury could be a result of subtle differences in neuronal efficiency such that the head injury groups require greater neural activation to perform at the level of control participants (Satz, 1993). The pattern of hyperfrontality observed in the P3 scalp distribution for the RLOC>30 group during working-memory performance indicates that this group may be recruiting different brain regions than the other groups during task performance. Normally, frontal deactivation occurs with adaptation to a task. The P3 component decreases in amplitude at frontal electrode sites over time (Friedman et al., 1998). A pattern of P3 hyperfrontality is observed in older adults who also demonstrate difficulty with effective allocation of attention and inhibition of responses (Friedman, 1998; Friedman, 1995). Both increased cortical activation and recruitment of more frontal regions in task performance may be indicative of compensatory mechanisms for injured brains that just aren't working as efficiently and require increased recruitment in order to perform well.

One of the major issues in investigating the long-lasting effects of MHI is that of cause and effect; that is, do those who have suffered a MHI have predisposing personality characteristics or deficient judgment skills that lead to risk-taking behaviour and subsequent head trauma (Binder, 1997; Stuss et al., 1985)? Although this is a difficult issue to sort out, it is unlikely that our group differences are attributable to premorbid differences between the groups, especially because there were no behavioral differences demonstrated between the groups. All participants in both experiments had chosen to attend university and had been able to perform well enough to be admitted. As well, no differences between groups were found in terms of general intelligence level, and measures of crystallized intelligence are good indicators of premorbid intellectual functioning. The use of self-report to select participants for our experiments also raises the issue of unreliable reporting of MHI occurrence. If our participants were unreliable in reporting MHI, then their responses would be essentially random with respect to our experimental manipulations and we would likely not find a difference between groups even if one existed (Type II error). Because our analyses revealed differences associated with group membership, the variance associated with self-reporting was not enough to mask the effects and our results are not artifactual.

CONCLUSIONS AND FUTURE DIRECTIONS

This investigation has shown that subtle, long-lasting differences in cortical communication and information-processing can be observed following reported head injury. Even though participants show no performance decrements compared to controls, the cortical-activation cost to their systems appears to be greater in order to achieve this performance. As Gevins et al. (1992) suggest, it may be the advanced EEG recording techniques and higher-density electrode montages that provide us with the ability to detect and characterize subtle cognitive differences following MHI. These methods may provide us with higher resolution with which to investigate brain activity associated with particular cognitive functions. Further investigation of EEG coherence differences following experimental task manipulation should be conducted to validate the measure in the MHI population. Studies of resting EEG coherence have already been conducted (Thatcher et al., 1998; Thatcher et al., 1989). It would be informative to investigate EEG coherence in a population of individuals with MHI who complain of cognitive difficulties post-injury. This population may demonstrate performance differences compared to controls that we did not see in our experiment and therefore behavioral differences could be related to changes in EEG coherence. As well, it would be interesting to investigate other types of individual differences such as the effects of decreased arousal or the effects of aging on cortico-cortical communication during task performance.

Regardless of group, increased demands on attention and information-processing serve to produce deficits (slowing, more errors and reduced attentional capacity) in task performance. As well, communication patterns between long- and short-fiber connections in frontal and parietal regions were different with increased task demands. The brain processes involved when the brain must divide its cognitive resources do not appear to be the same as when the brain is required to focus its attentional resources on a single task. Continued investigation of cross-cortical communication in uninjured brains during tasks thought to recruit neural networks can only serve to increase our knowledge of how the brain processes information.

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APPENDIX A

Tables

Table 1a: Studies Finding No Lasting Cognitive Effects Following MHI

	Author(s)	Participants	N	Measure Employed
Information-processing	MacFlynn, Montgomery, Fenton & Rutherford; 1984	MHI; admitted to hospital; PTA < 24 hrs	45	4-choice visual reaction-time task
	Shum, McFarland, Bain, Humphreys; 1990	MHI; admitted to hospital; GCS 14-15	7	4-choice visual spatial RT task
Sustained Attention	Brouwer, VanWolffelaar; 1985	moderate to severe concussion	8	40-minute auditory low-event rate vigilance task
Executive Functioning	Stablum, Mogentale, Umilta; 1996	MHI; if LOC, <20 min; GCS 13-15; hospitalized <24 hrs	26	Dual-task paradigm. Single task: respond to position of stimulus (R or L); Dual task: respond to position of stimulus and identify whether stimuli are the same or different.

Table 1b: Studies Finding Some Lasting Cognitive Effects Following MHI

	Author(s)	Participants	N	Measure Employed
Information-processing	Cremona-Meteyard & Geffen; 1994	MHI; not hospitalized; change in consciousness <20 and >2 min.; PTA < 24 hrs	9	Covert orienting of attention, cued visuospatial attention task
Focused Attention	Stuss, Stethem, Hugenholtz, Picton, Pivik & Richard; 1989	Minor concussion; not hospitalized	22	Multiple choice reaction time task containing redundant information
Sustained Attention	Parasuraman, Mutter & Molloy; 1991	MHI; hospitalized; LOC < 20 min; GCS 13-15	10	High-event rate visual vigilance task with degraded stimuli
	Bohnen, Jolles, Twijnstra, Mellink & Sulon; 1992	Symptomatic MHI with persistent symptoms versus asymptomatic MHI	11 11	Low-event rate visual vigilance task Measurement of salivary cortisol level
Executive Functioning	Gentilini, Nichelli & Schoenhuber; 1989	MHI; hospitalized < 3 days; LOC < 20 min.; GCS 13-15	48	Divided attention. Respond to visual stimuli while counting backwards by 2s from 100 to 0. Distributed attention. Respond to simultaneous appearance of stimuli across both visual fields.
	Cicerone; 1996	MHI; LOC < 30 min; PTA < 24 hrs; persistent symptoms	15	Dual-task paradigm. 2 & 7 selective attention task (crossing out 2s and 7s) performed simultaneously with non-relevant distraction (ignore segment of a radio talk show) and with relevant distraction (mental arithmetic presented on tape).
	Stablum, Mogentale & Umilta; 1996	MHI; all had LOC < 20 min	9	Dual-task paradigm. Respond to position of visual stimulus (R or L) and identify whether stimuli are the same or different.

Table 2: Order of Presentation of Computer and Paper and Pencil Tasks in Experiment 1.

Computer Tasks: Phase One	Easy and Difficult Pitch and Duration Discriminations; Easy Duration Discrimination with Distractor; Eriksen Flanker Task (Part 1); Two-Back Task
Paper and Pencil Tasks: Phase One	Health and History Questionnaire; Culture Fair Intelligence Test; Paper and Pencil Dual task; Digits Backward
Computer Tasks: Phase Two	Eriksen Flanker Task (Part 2), Simple Reaction Time Task; CPT Respond and Withold Tasks; Computerized Multiple Performance Task; Stop Signal Paradigm
Paper and Pencil Tasks: Phase Two	Verbal Meaning Subtest; Information Subtest; Self-Ordered Pointing Task; Cross-Circle Test; Crossing-out A's (Motor Speed and Selective Stimulus Finding)

Table 3: Means and Standard Deviations for Culture Fair, Information Subtest and Age: A Comparison of University Populations

	N	Mean	SD
Culture Fair Intelligence Test			
Brock	32	34.0	3.80
Waterloo	32	37.9	4.17
Information Subtest			
Brock	32	15.2	4.66
Waterloo	32	19.5	4.00
Age			
Brock	32	19.8	1.05
Waterloo	32	22.6	5.45

Table 4: Causes of MHI in Both University Populations: Experiment 1

Cause of MHI	University	Frequency	Percentage of Cases
Motor Vehicle/ Bicycle Accident	Brock	3	18.8
	Waterloo	1	6.3
Falling Down	Brock	3	18.8
	Waterloo	6	37.5
Sports Accident	Brock	6	37.5
	Waterloo	4	25.0
Fight/Attack	Brock	1	6.3
	Waterloo	0	0
Other	Brock	2	12.6
	Waterloo	5	31.3

Table 5: Mean RT Performance and Standard Errors for Each Auditory Oddball Task in Experiment 1

Task	Mean RT (ms)	Standard Error
Easy Pitch Discrimination	393	11.5
Difficult Pitch Discrimination	589	13.5
Easy Duration Discrimination	611	11.4
Difficult Duration Discrimination	678	10.6

Table 6: Mean RT Performance and Standard Errors for MHI and Control Groups at Brock and Waterloo As A Function of Auditory Oddball Task in Experiment 1

Task	**Group**	**Mean RT (ms)**	**Standard Error**
Easy Pitch Discrimination	Brock MHI	386	20.9
	Brock Controls	384	20.9
	Waterloo MHI	433	26.2
	Waterloo Controls	371	27.1
Difficult Pitch Discrimination	Brock MHI	593	28.2
	Brock Controls	587	28.2
	Waterloo MHI	611	27.8
	Waterloo Controls	567	28.8
Easy Duration Discrimination	Brock MHI	601	22.6
	Brock Controls	592	22.6
	Waterloo MHI	631	23.8
	Waterloo Controls	619	24.7
Difficult Duration Discrimination	Brock MHI	675	24.3
	Brock Controls	685	24.3
	Waterloo MHI	661	18.5
	Waterloo Controls	690	19.2

Table 7: Means and Standard Errors for d' and β for all Oddball Tasks in Experiment 1

Task	Signal-Detection Measure	Mean	Standard Error
Easy Pitch Discrimination	D′	4.50	0.06
	β	1.11	0.08
Difficult Pitch Discrimination	D′	2.65	0.16
	β	2.10	0.36
Easy Duration Discrimination	D′	3.85	0.10
	β	2.46	0.29
Difficult Duration Discrimination	D′	2.33	0.11
	β	6.19	0.55

Table 8: Means and Standard Errors for d′ and β for MHI and Control Groups for Each Oddball Task in Experiment 1

Task	**Group**	**Signal-Detection Measure**	**Mean**	**Standard Error**
Easy Pitch Discrimination	MHI	d′	4.52	0.08
		β	1.02	0.11
	Control	d′	4.48	0.08
		β	1.20	0.11
Difficult Pitch Discrimination	MHI	d′	2.64	0.23
		β	1.97	0.51
	Control	d′	2.66	0.23
		β	2.23	0.52
Easy Duration Discrimination	MHI	d′	4.02	0.13
		β	2.51	0.41
	Control	d′	3.67	0.14
		β	2.41	0.42
Difficult Duration Discrimination	MHI	d′	2.34	0.15
		β	6.72	0.76
	Control	d′	2.32	0.15
		β	5.66	0.78

Table 9: Means and Standard Errors for d′, β and RT for Duration Discrimination with and without Distractor Task

Task	d′ Mean	d′ Standard Error	β Mean	β Standard Error	RT Mean (ms)	RT Standard Error
Duration Discrimination	3.85	0.10	2.46	0.29	611	11.4
Duration Discrimination with Distractor	2.74	0.13	6.03	0.52	689	10.6

Table 10: Means and Standard Errors for d′ and β for MHI and Control Groups for Duration Discrimination with and without Distractor Task and for the Distractor Task alone

Task	**Group**	**Signal-Detection Measure**	**Mean**	**Standard Error**
Duration Discrimination	MHI	d′	4.02	0.13
		β	2.51	0.41
	Control	d′	3.67	0.14
		β	2.41	0.42
Duration Discrimination with Distractor	MHI	d′	2.66	0.18
		β	5.04	0.73
	Control	d′	2.83	0.18
		β	7.03	0.73
Verbal-Working-Memory Distractor Task	MHI	d′	2.48	0.14
		β	5.68	0.64
	Control	d′	2.20	0.14
		β	6.13	0.65

Table 11: Means and Standard Errors for the Computerized Multiple Performance Task for MHI and Control Groups at Both Universities

	Mean Total Score	Standard Error
CMPT		
Brock MHI	426.39	28.35
Brock Controls	410.48	28.35
Waterloo MHI	443.80	20.09
Waterloo Controls	506.24	18.78

Table 12: Number of Individuals Reporting Persistent Difficulties Following Their Head Injury in Experiment 2.

Group	Number of Cases	Percent of Total
Controls	0	0
RLOC<20	8	42%
RLOC>30	14	74%

Table 13: Causes of Head Injury for both RLOC<20 and RLOC>30 Groups in Experiment 2

Cause of Head Injury	Group	Frequency	Percentage of Cases
Motor Vehicle/ Bicycle Accident	RLOC<20	3	15.8
	RLOC>30	8	42.1
Falling Down	RLOC<20	4	21.1
	RLOC>30	5	26.3
Sports Accident	RLOC<20	9	47.4
	RLOC>30	5	26.3
Fight/Attack	RLOC<20	1	5.3
	RLOC>30	1	5.3
Other	RLOC<20	2	10.5
	RLOC>30	0	0

Table 14: Means and Standard Errors of RT Performance for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2

Task Condition	Mean RT (ms)	Standard Error
Easy Duration Discrimination: Single	600	8.76
Easy Duration Discrimination: Dual	761	11.90
Difficult Duration Discrimination: Single	672	12.27
Difficult Duration Discrimination: Dual	765	14.14

Table 15: Means and Standard Errors of RT Performance for All Groups for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2

Task Condition	**Group**	**Mean RT (ms)**	**Standard Error**
Easy Duration Discrimination: Single	RLOC<20	613	15.04
	RLOC>30	585	15.45
	Controls	605	15.04
Easy Duration Discrimination: Dual	RLOC<20	770	20.43
	RLOC>30	753	20.99
	Controls	758	20.43
Difficult Duration Discrimination: Single	RLOC<20	687	21.06
	RLOC>30	649	21.63
	Controls	679	21.06
Difficult Duration Discrimination: Dual	RLOC<20	770	24.28
	RLOC>30	767	24.94
	Controls	758	24.28

Table 16: Means and Standard Errors of Number of Errors Committed for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2

Task Condition	Mean # Errors	Standard Error
Easy Duration Discrimination: Single	18.6	2.33
Easy Duration Discrimination: Dual	25.2	1.85
Difficult Duration Discrimination: Single	29.5	2.53
Difficult Duration Discrimination: Dual	34.9	2.14

Table 17: Means and Standard Errors of Number of Errors Committed for All Groups for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2

Task Condition	**Group**	**Mean # Errors**	**Standard Error**
Easy Duration Discrimination: Singie	RLOC<20	18.8	4.00
	RLOC>30	19.2	4.11
	Controls	17.8	4.00
Easy Duration Discrimination: Dual	RLOC<20	24.0	3.17
	RLOC>30	27.2	3.26
	Controls	24.6	3.17
Difficult Duration Discrimination: Single	RLOC<20	24.4	4.34
	RLOC>30	35.5	4.46
	Controls	28.7	4.34
Difficult Duration Discrimination: Dual	RLOC<20	35.2	3.68
	RLOC>30	37.5	3.78
	Controls	32.1	3.68

Table 18: Mean and Standard Errors of d' for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2

Task Condition	Mean	Standard Error
Easy Duration Discrimination: Single	3.21	0.12
Easy. Duration Discrimination: Dual	2.38	0.10
Difficult Duration Discrimination: Single	2.29	0.11
Difficult Duration Discrimination: Dual	1.88	0.09

Table 19: Mean and Standard Errors of β for All Conditions of the Duration Discrimination Task With and Without Distractor in Experiment 2

Task Condition	Mean	Standard Error
Easy Duration Discrimination: Single	2.31	0.35
Easy Duration Discrimination: Dual	6.92	0.50
Difficult Duration Discrimination: Single	5.78	0.62
Difficult Duration Discrimination: Dual	6.92	0.56

Table 20: Means and Standard Errors for RT Performance on the Working-Memory Distractor Task for Each Group in Experiment 2

Task Condition	**Group**	**Mean RT (ms)**	**Standard Error**
Working-Memory Distractor: Easy Condition	RLOC<20	712	29.77
	RLOC>30	664	30.69
	Controls	700	28.93
Working-Memory Distractor: Difficult Condition	RLOC<20	702	38.08
	RLOC>30	721	39.25
	Controls	696	37.00

Table 21: Means and Standard Errors for Number of Errors Committed on the Distractor Task and Percentage of Correct Responses for Distractor versus Duration Discrimination Tasks in Experiment 2

Task Condition	**Mean # Errors**	**Standard Error**	**Mean % Correct Responses**	**Standard Error**
Working-Memory Distractor: Easy Condition	14.4	1.18	53.7	2.22
Working-Memory Distractor: Difficult Condition	11.7	0.98	60.4	2.73
Easy Duration Discrim. With Distract	---	---	66.9	2.20
Difficult Duration Discrim. With Distract	---	---	53.0	1.99

Table 22: Means and Standard Errors for Number of Errors Committed for Each Group on the Working-Memory Distractor Task. In Experiment 2

Task Condition	**Group**	**Mean # Errors**	**Standard Error**
Working-Memory Distractor: Easy Condition	RLOC<20	15.9	2.04
	RLOC>30	14.6	2.10
	Controls	12.8	1.98
Working-Memory Distractor: Difficult Condition	RLOC<20	12.6	1.70
	RLOC>30	12.4	1.75
	Controls	10.2	1.65

Table 23: Means and Standard Errors for d′ and β on the Working-Memory Distractor Task in Experiment 2

Task Condition	**Mean d′**	**Standard Error**	**Mean β**	**Standard Error**
Working-Memory Distractor: Easy Condition	2.09	0.10	8.43	0.63
Working-Memory Distractor: Difficult Condition	2.35	0.10	8.30	0.56

Table 24: Means and Standard Errors for RT As a Function of WM Load During the n-Back Task in Experiment 2

Task Condition	Mean RT (ms)	Standard Error
0-Back	442	9.67
1-Back	548	17.03
2-Back	622	17.54
3-Back	714	22.73

Table 25: Means and Standard Errors for RT for Each Group As A Function of WM Load During the n-Back Task in Experiment 2

Task Condition	**Group**	**Mean RT (ms)**	**Standard Error**
O-Back	RLOC<20	451	16.28
.	RLOC>30	439	17.21
	Controls	435	16.72
1-Back	RLOC<20	582	28.67
	RLOC>30	535	30.31
	Controls	527	29.46
2-Back	RLOC<20	656	29.55
	RLOC>30	620	31.24
	Controls	588	30.36
3-Back	RLOC<20	738	38.29
	RLOC>30	755	40.48
	Controls	649	39.33

Table 26: Means and Standard Errors for False Alarms (FA) and Omissions (OM) as a Function of Working-Memory Load During the n-Back Task in Experiment 2

Task Condition	Mean FA	Standard Error	Mean OM	Standard Error
0-Back	0.54	0.10	0.19	0.06
1-Back	0.55	0.12	1.63	0.31
2-Back	1.12	0.21	7.08	0.79
3-Back	4.76	0.47	22.33	1.15

Table 27: Means and Standard Errors for FA and OM for Each Group as a Function of WM Load During the n-Back Task in Experiment 2

Task Condition	Group	Mean FA	Standard Error	Mean OM	Standard Error
O-Back	RLOC<20	0.42	0.17	0.21	0.10
	RLOC>30	0.71	0.18	0.29	0.11
	Controls	0.50	0.18	0.06	0.10
1-Back	RLOC<20	0.58	0.20	1.26	0.52
	RLOC>30	0.47	0.21	1.35	0.55
	Controls	0.61	0.20	2.28	0.54
2-Back	RLOC<20	1.21	0.35	7.05	1.32
	RLOC>30	0.53	0.37	6.12	1.40
	Controls	1.61	0.36	8.06	1.36
3-Back	RLOC<20	5.53	0.79	22.42	1.94
	RLOC>30	3.53	0.84	22.12	2.05
	Controls	5.22	0.82	22.44	1.99

Table 28: Means and Standard Errors for N1, P2, N2 Amplitudes During Single and Dual-Task Conditions of the Duration Discrimination Task in Experiment 2

Task Condition	Mean N1 Amplitude	Standard Error	Mean P2 Amplitude	Standard Error	Mean N2 Amplitude	Standard Error
Singie-Task	-5.52	0.26	1.27	0.26	-4.90	0.32
Dual-Task	-6.12	0.35	1.88	0.35	-5.83	0.31

Table 29: Means and Standard Errors for P3 Amplitude During Each Conditions of the Duration Discrimination Task in Experiment 2

Task Condition	**Mean P3 Amplitude**	**Standard Error**
Easy Duration Discrimination	6.64	0.54
Easy Duration Discrimination with Distractor	5.11	0.50
Difficult Duration Discrimination	5.46	0.43
Difficult Duration Discrimination With Distractor	5.49	0.43

Table 30: Means and Standard Errors for P3 Latency During Each Condition of the Duration Discrimination Task in Experiment 2

Task Condition	Mean P3 Latency (ms)	Standard Error
Easy Discrimination	539	7.52
Difficult Discrimination	597	11.21
Single-Task	545	7.45
Dual-Task	591	10.81

Table 31: Means and Standard Errors for Early ERP Component Amplitudes As a Function of Working-Memory Load During the n-Back Task in Experiment 2

Task Condition	Mean N1 Amplitude	Standard Error	Mean P2 Amplitude	Standard Error	Mean N2 Amplitude	Standard Error
0-Back	-1.25	0.22	5.75	0.40	-0.67	0.33
1-Back	-1.66	0.16	5.09	0.34	-0.011	0.34
2-Back	-1.70	0.17	5.36	0.36	0.69	0.40

Table 32: Means and Standard Errors for Dorsal F-P Beta Coherence as a Function of Stimulus Difficulty and as a Function of Task Condition During the Duration Discrimination Task in Experiment 2

Task Condition	**Mean F-P Beta**	**Standard Error**
Easy Stimulus Discrimination	.511	0.02
Difficult Stimulus Discrimination	.489	0.02
Single-Task	.482	0.02
Dual-Task	.518	0.02

Table 33: Means and Standard Errors for F-C and C-P Beta Coherence as a Function of Stimulus Difficulty and as a Function of Task Condition During the Duration Discrimination Task in Experiment 2

Task Condition	Mean F-C Beta	Standard Error	Mean C-P Beta	Standard Error
Easy Stimulus Discrimination	.496	0.02	.508	0.01
Difficult Stimulus Discrimination	.510	0.02	.545	0.01
Single-Task	.492	0.02	.524	0.02
Dual-Task	.514	0.02	.529	0.01

Table 34: Means and Standard Errors for F-P Beta Coherence for Each Group in each Hemisphere as a Function of Task Condition and Stimulus Difficulty During the Duration Discrimination Task in Experiment 2

Task Condition	Group	Mean F-P Beta for Lhem	Standard Error	Mean F-P Beta for RHem	Standard Error
Easy Stimulus Discrimination	RLOC<20	.451	0.03	.368	0.03
	RLOC>30	.461	0.03	.418	0.03
	Controls	.447	0.03	.384	0.03
Difficult Stimulus Discrimination	RLOC<20	.444	0.03	.357	0.03
	RLOC>30	.470	0.04	.418	0.03
	Controls	.429	0.03	.355	0.03
Single-Task	RLOC<20	.425	0.03	.333	0.03
	RLOC>30	.435	0.03	.390	0.03
	Controls	.443	0.03	.356	0.03
Dual-Task	RLOC<20	.470	0.03	.392	0.03
	RLOC>30	.496	0.03	.446	0.03
	Controls	.433	0.03	.383	0.03

Table 35: Means and Standard Errors for F-P Theta Coherence as a Function of WM Load During the n-Back Task in Experiment 2

Task Condition	Mean F-P Theta	Standard Error
0-Back	.537	0.02
1-Back	.560	0.02
2-Back	.595	0.02

Table 36: Means and Standard Errors for F-C and C-P Theta Coherence as a Function of WM Load During the n-Back Task in Experiment 2

Task Condition	Mean F-C Theta	Standard Error	Mean C-P Theta	Standard Error
0-Back	.724	.008	.729	.010
1-Back	.732	.010	.744	.010
2-Back	.747	.014	.762	.013

Table 37: Means and Standard Errors for F-P Beta Coherence for Each Group as a Function of Hemisphere During the n-Back Task in Experiment 2

Group	Mean F-P Beta for LHem	Standard Error	Mean F-P Beta for RHem	Standard Error
RLOC<20	.448	0.03	.353	0.03
RLOC>30	.439	0.03	.398	0.03
Controls	.379	0.03	.291	0.03

APPENDIX B

Figures

Figure 1: Mean RT as a Function of Task and Stimulus Difficulty During Auditory Oddball Tasks in Experiment 1

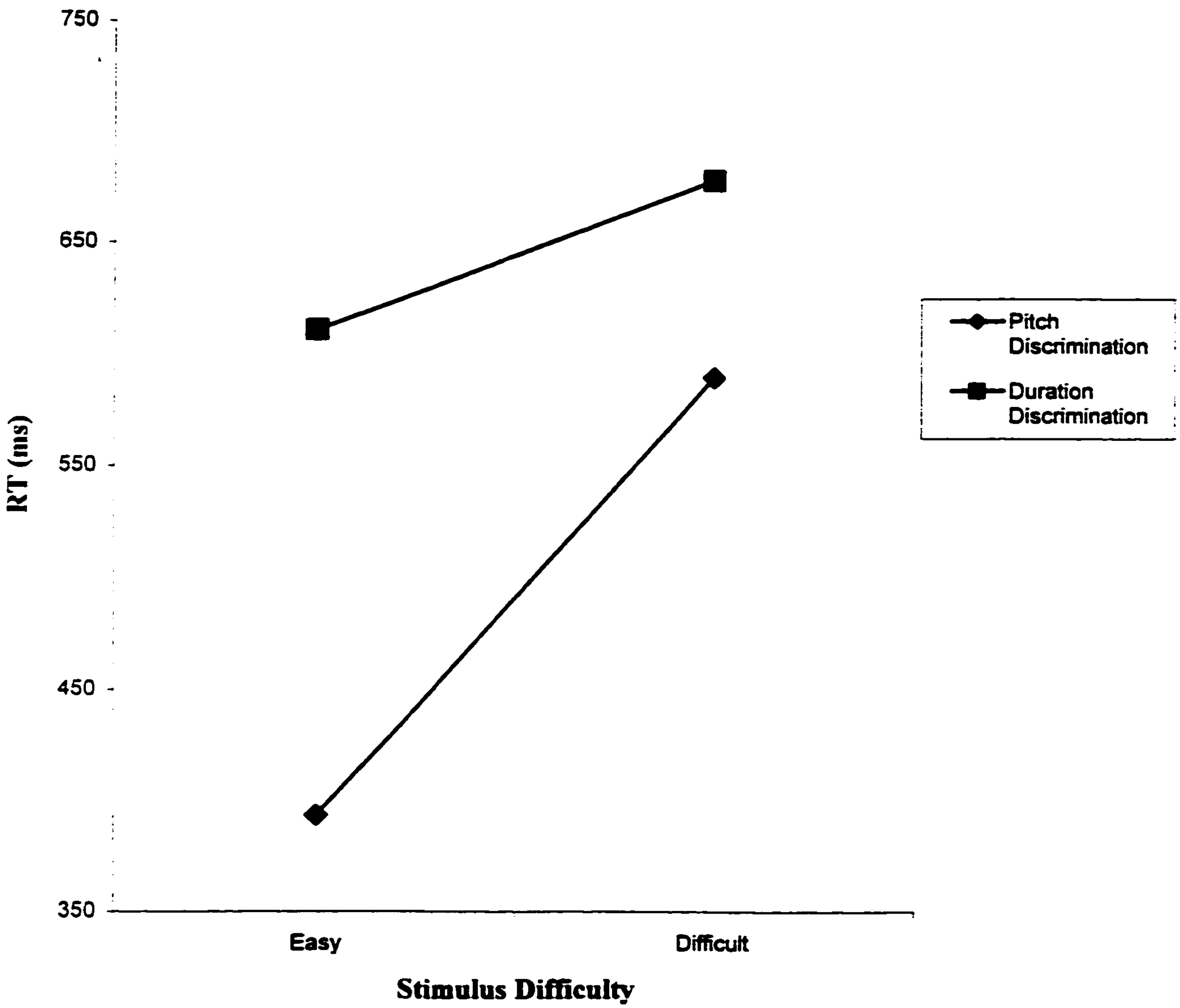

Figure 2: Mean RT for Waterloo MHI and Control Group as a Function of Oddball Task in Experiment 1

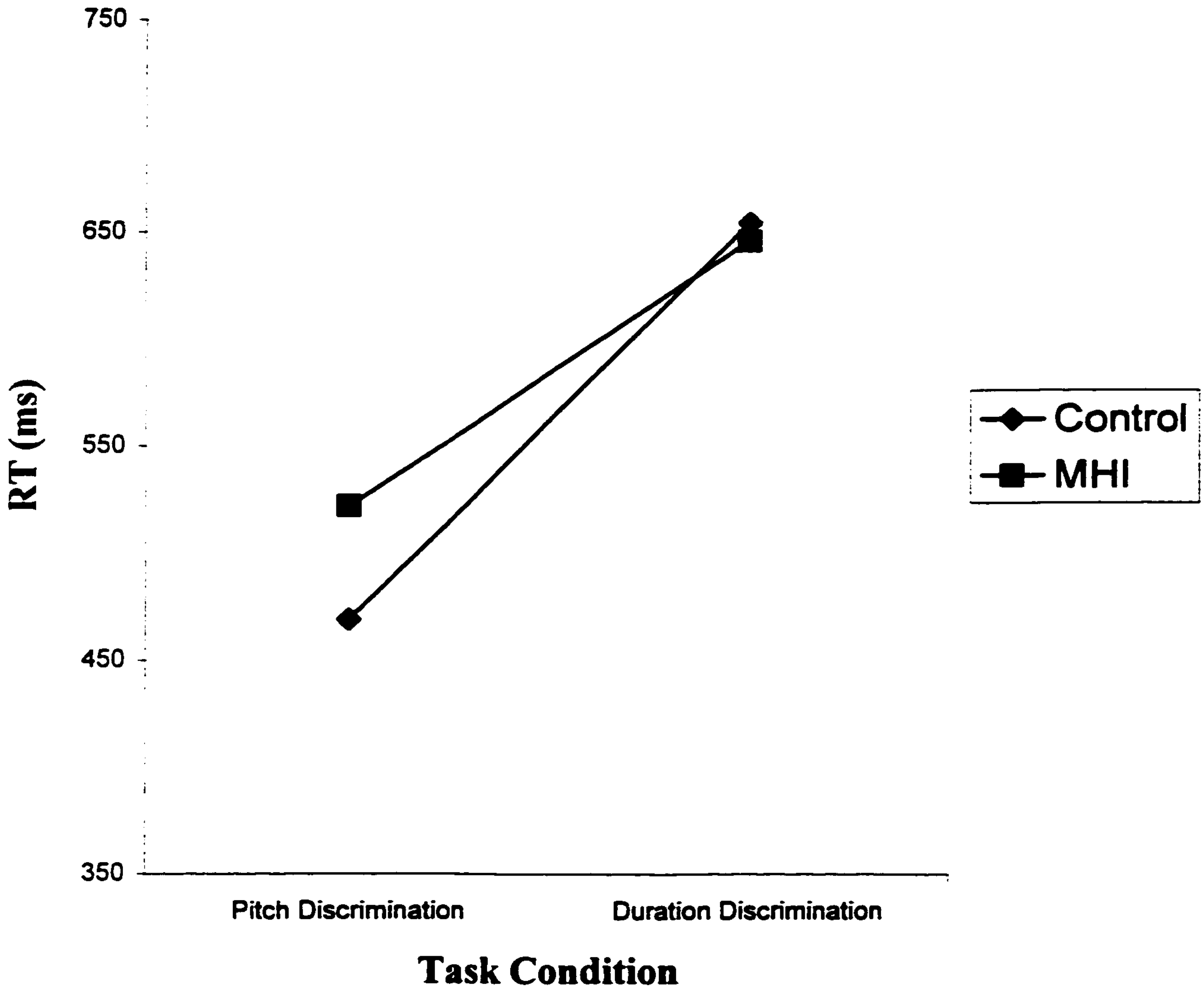

Figure 3: Mean d' for Task Condition and Stimulus Difficulty During Oddball Tasks in Experiment 1

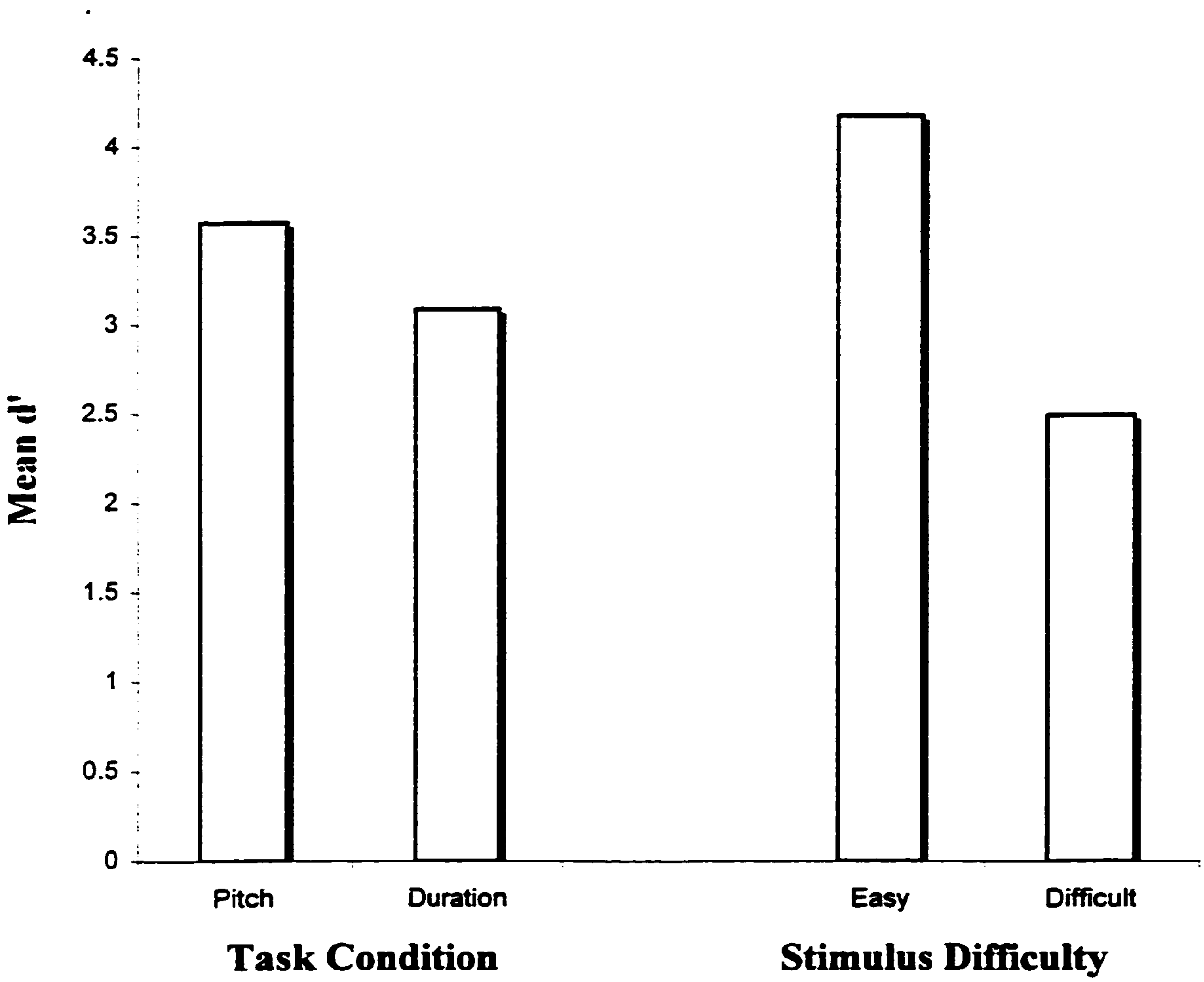

Figure 4: Mean Beta as a Function of Task and Stimulus Difficulty During Oddball Tasks in Experiment 1

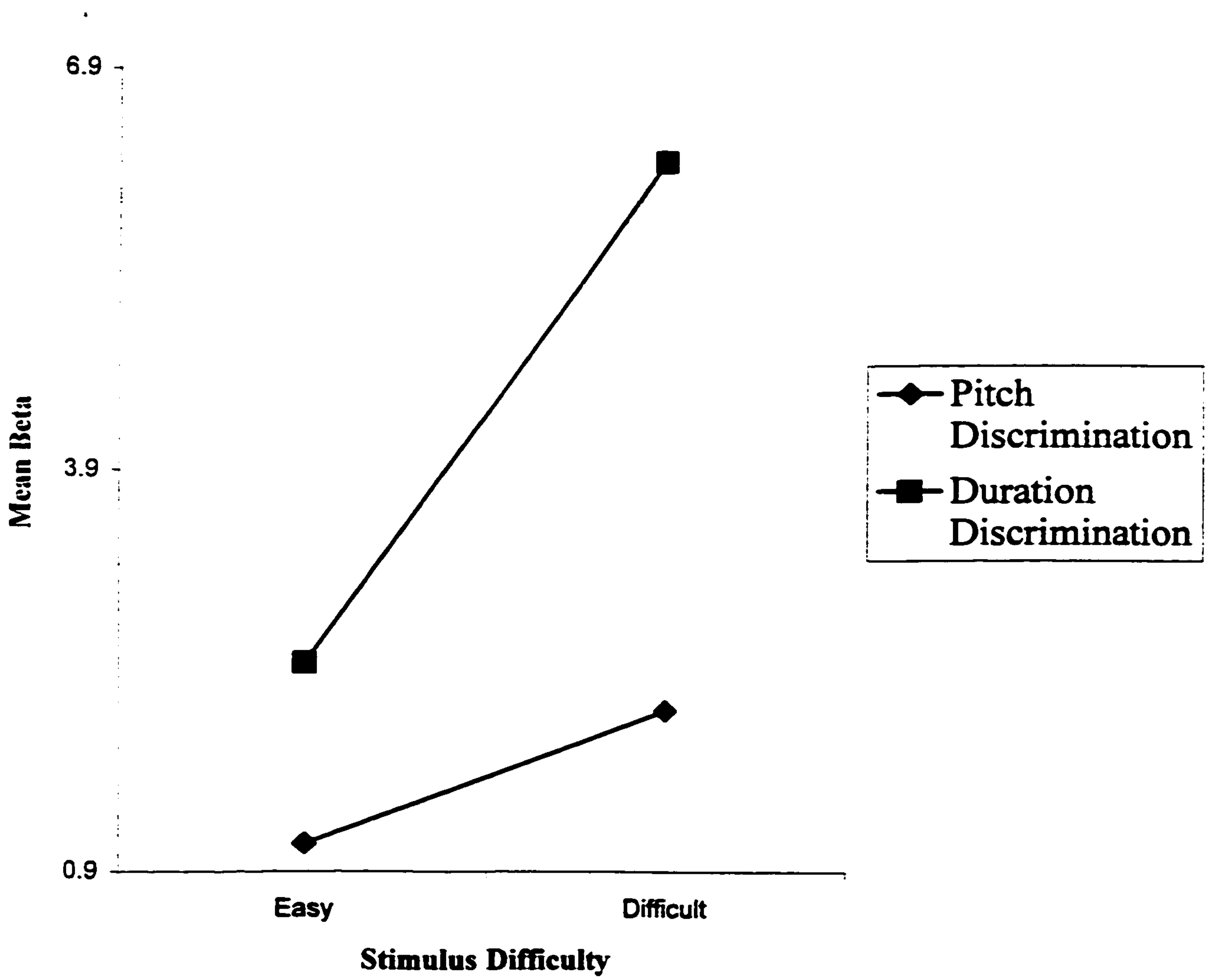

Figure 5: Mean d' for Each Group as a Function of Duration Discrimination Condition in Experiment 1

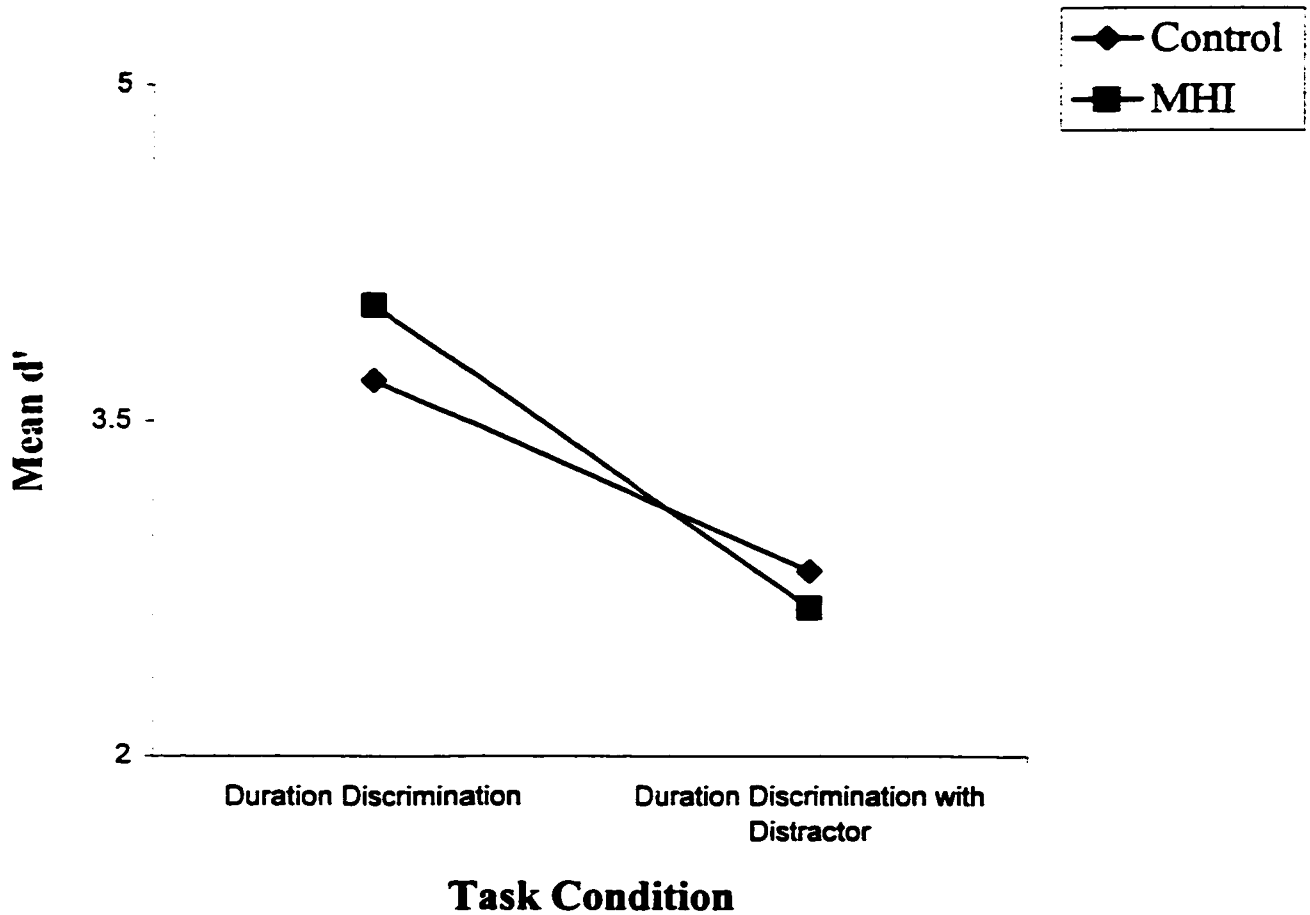

Figure 6: Mean Beta for Each Group as a Function of Duration Discrimination Condition in Experiment 1

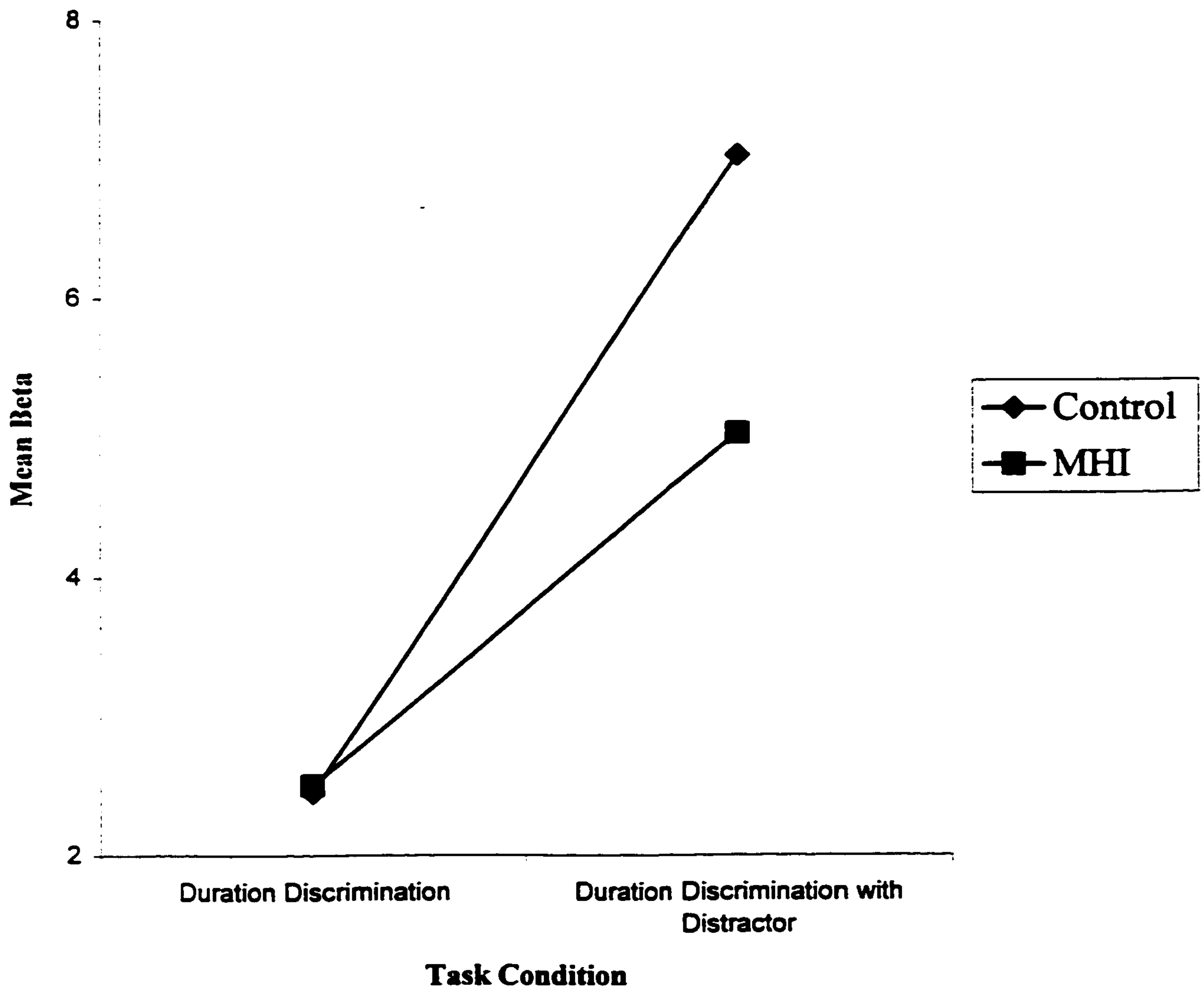

Figure 7: Mean Score on CMPT as a Function of Group and University

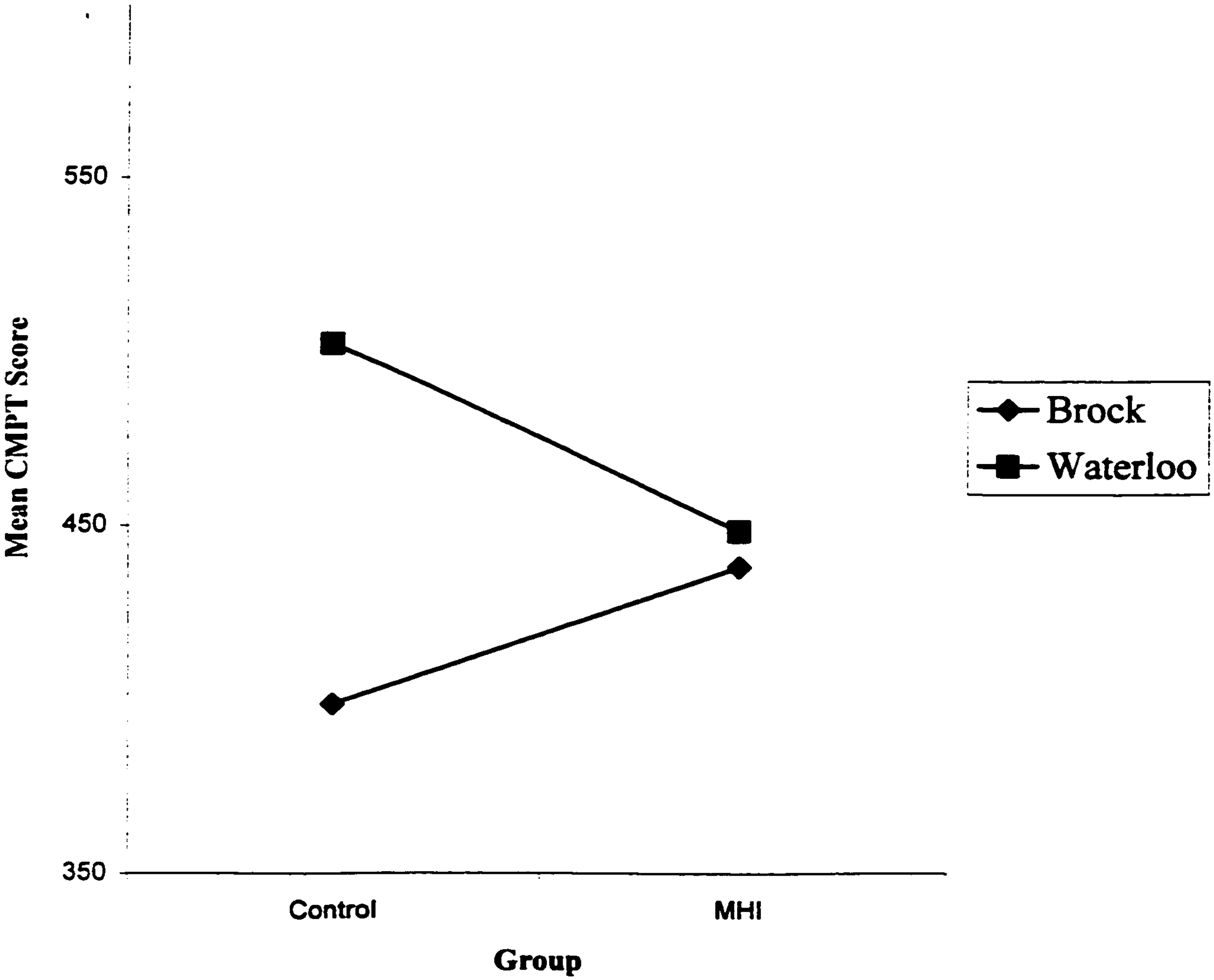

Figure 8: Electrode Placement Employed During Electrophysiological Recording in Experiment Two and Placement of Electrodes Used in the Average Reference for EEG Coherence.

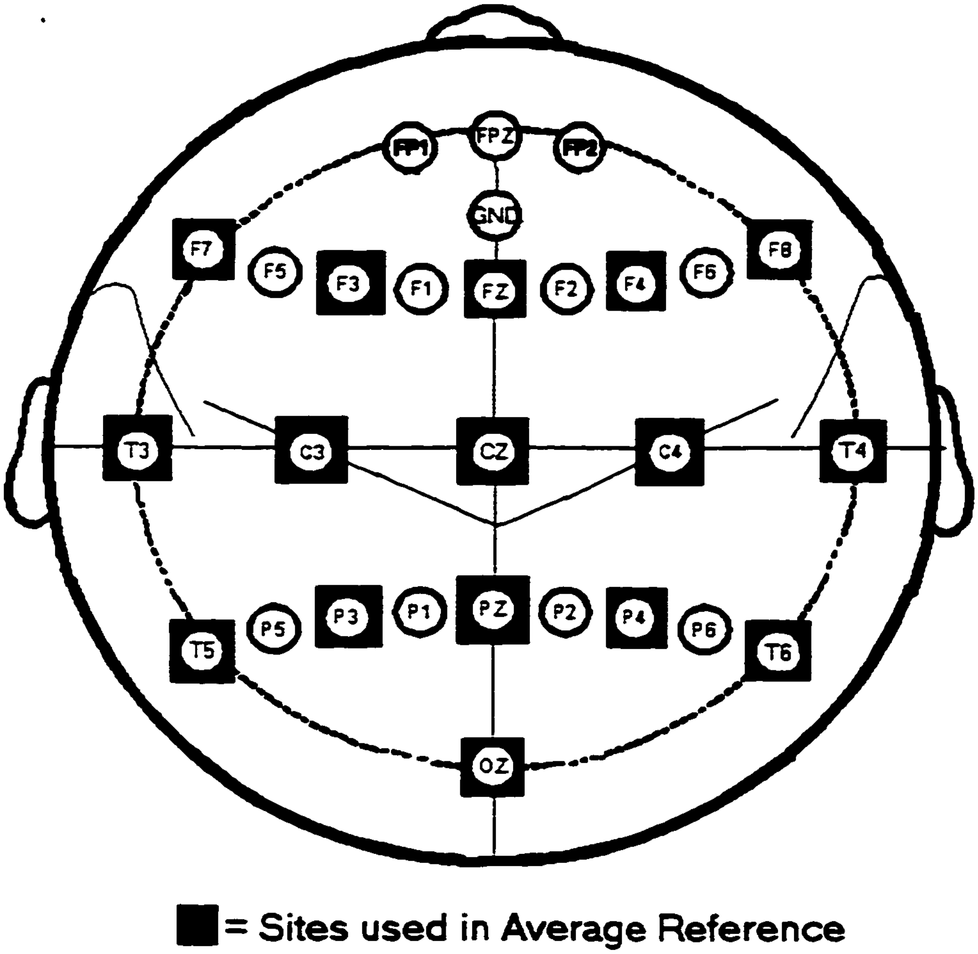

Figure 9: Mean RT as a Function of Task and Stimulus Difficulty During Duration Discrimination Tasks in Experiment 1

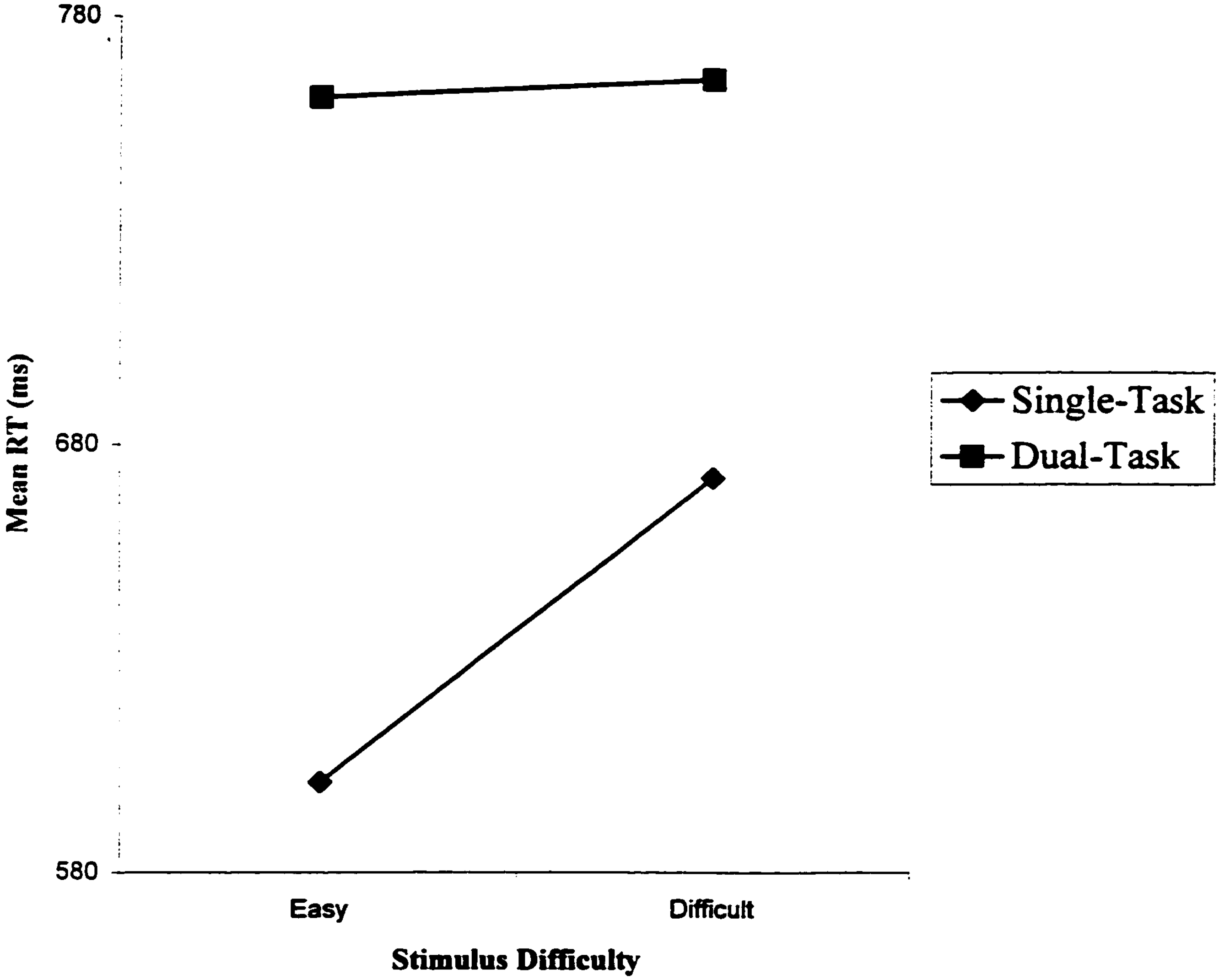

Figure 10: Mean d' as a Function of Stimulus Difficulty and Task Condition During Duration Discrimination Tasks in Experiment 1

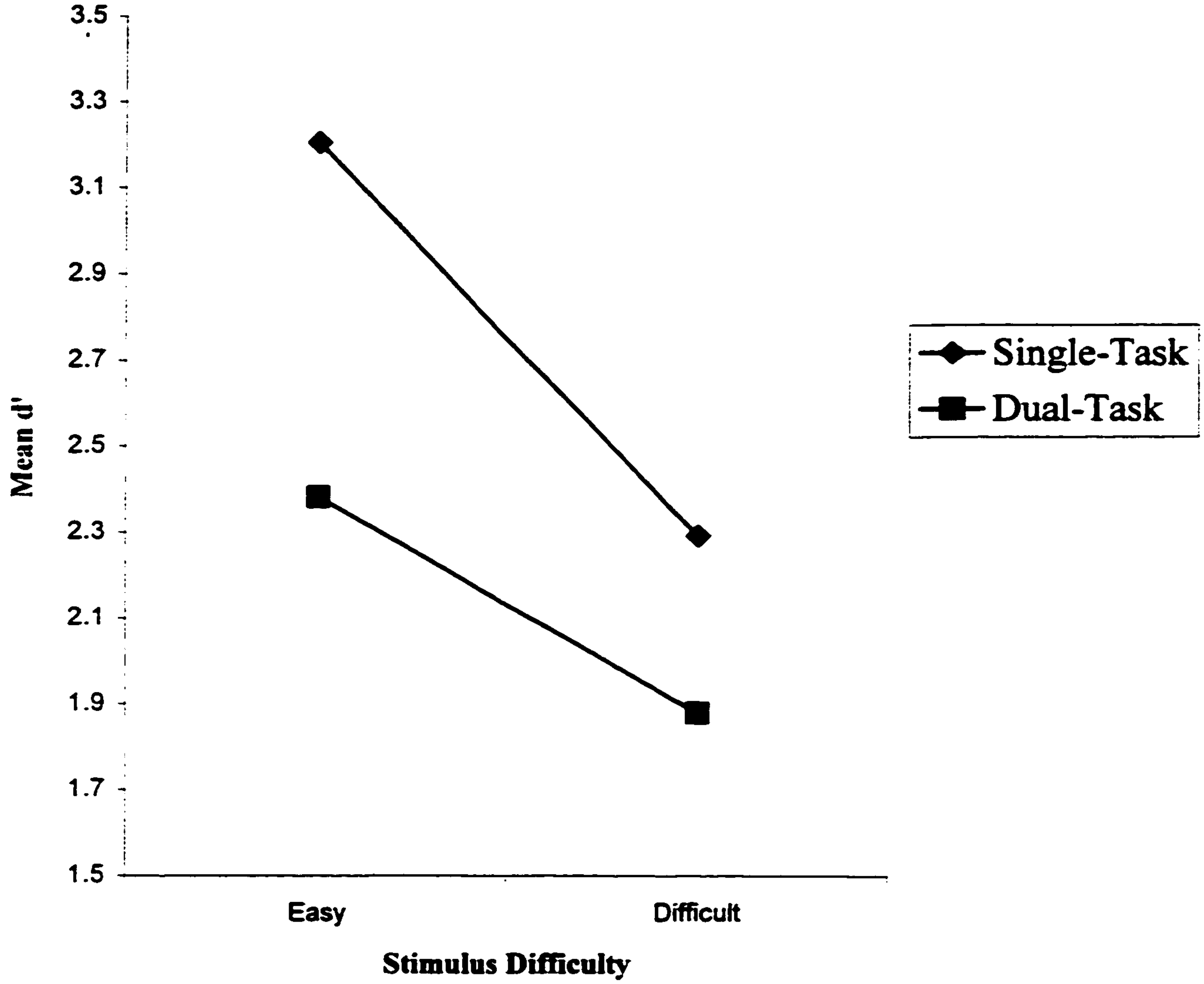

Figure 11: Mean Beta as a Function of Stimulus Difficulty and Task Condition During Duration Discrimination Tasks in Experiment 2

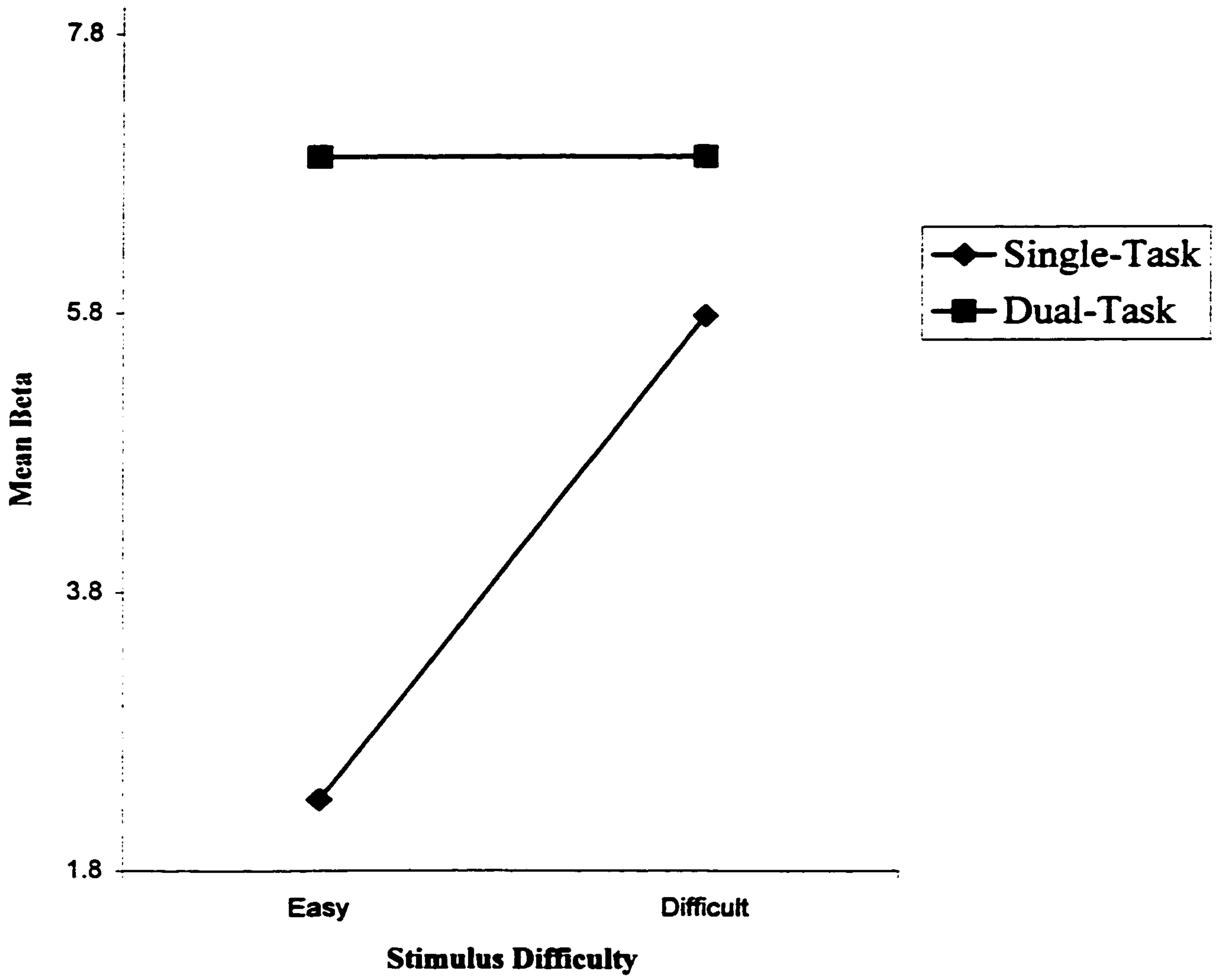

Figure 12: Mean Percentage of Correct Responses as a Function of Stimulus Difficulty for the Duration Discrimination vs. Distractor Tasks

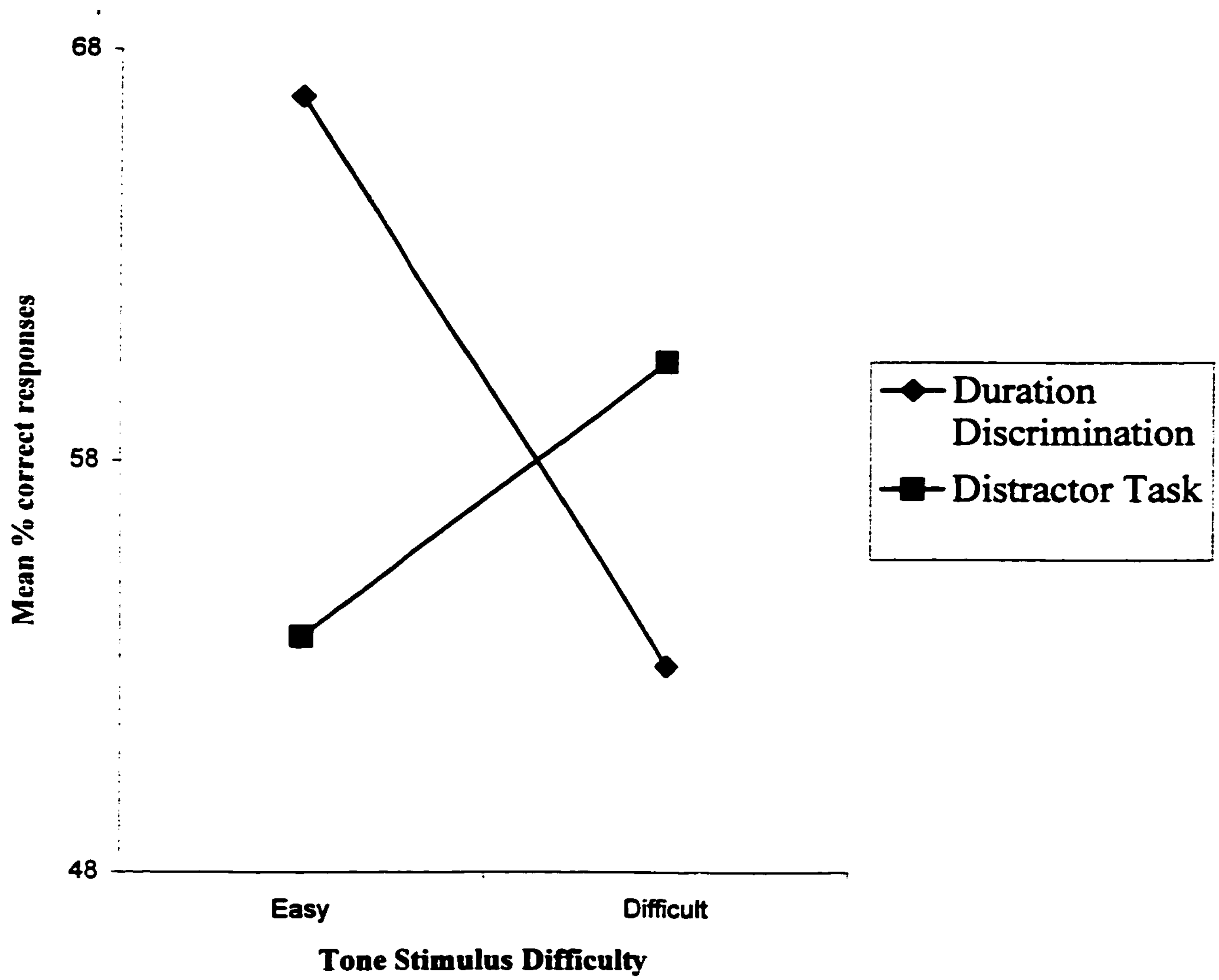

Figure 13: Mean RT for Each Group as a Function of WM Load During the n-Back Task in Experiment 2

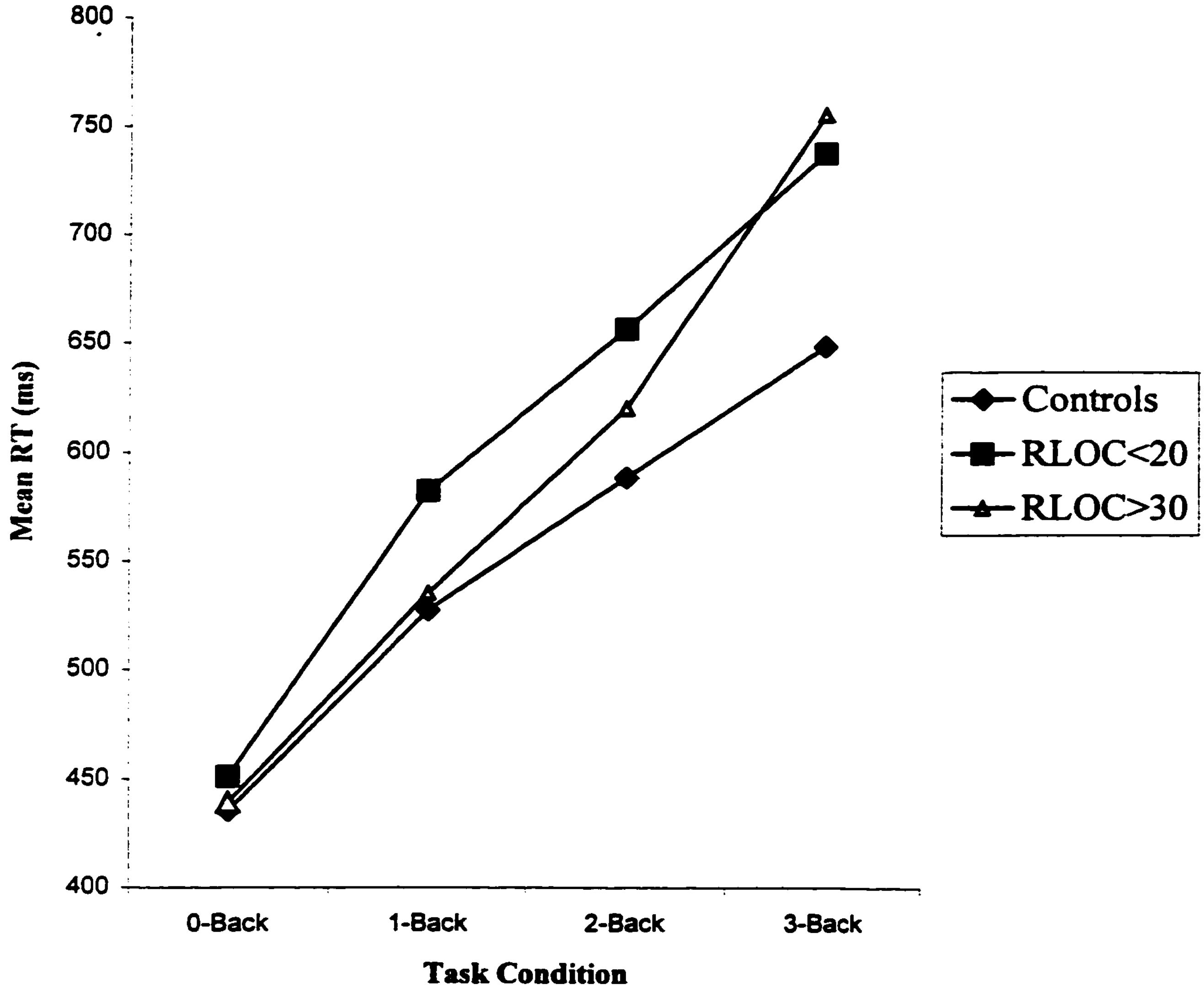

Figure 14: Mean P3 Amplitude as a Function of Stimulus Difficulty and Task Condition During the Duration Discrimination Task in Experiment 2

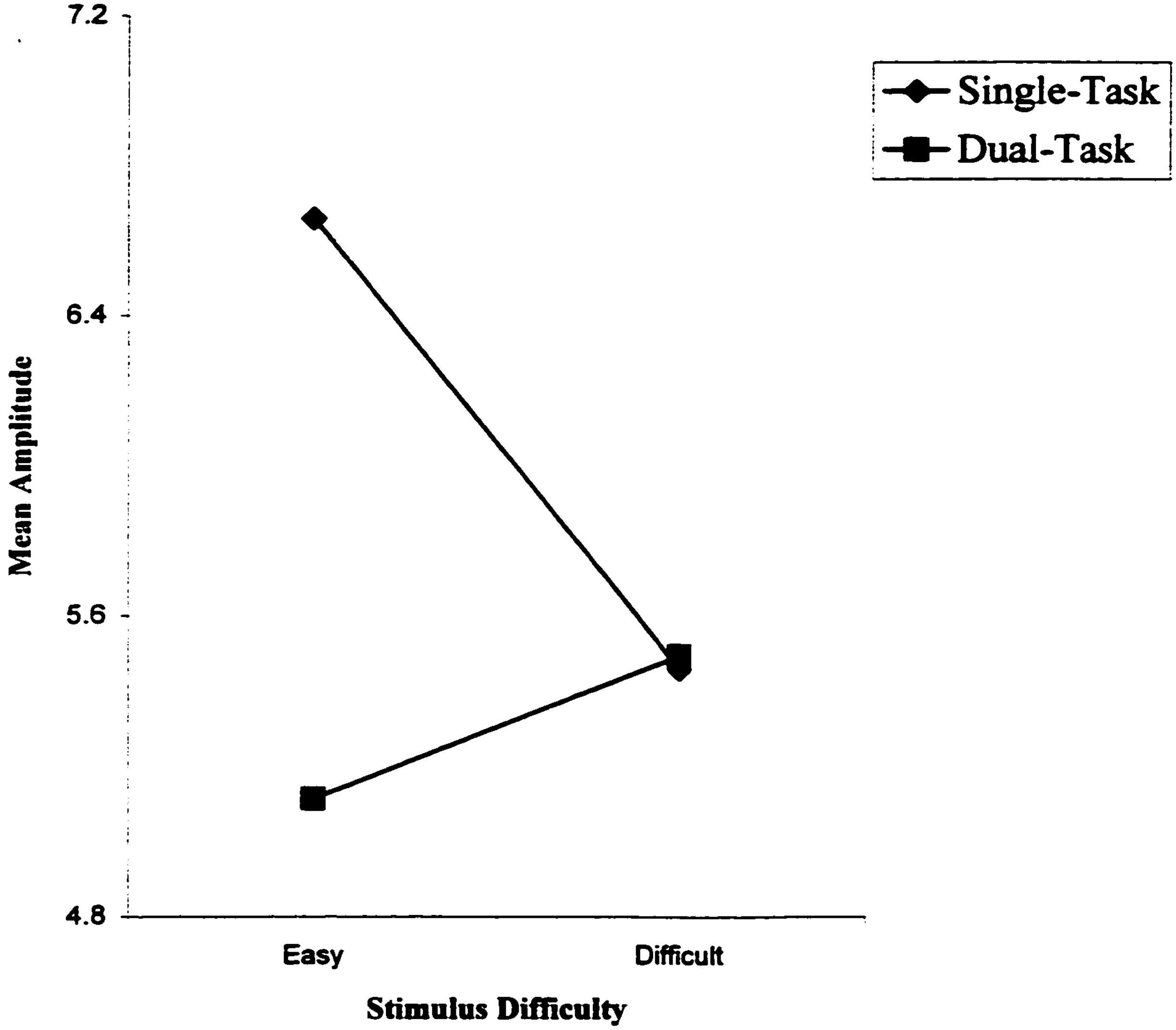

Figure 15a: **Averaged ERP Waves for a Single Control Participant in the Easy Duration Discrimination Single Versus Dual-Task.**

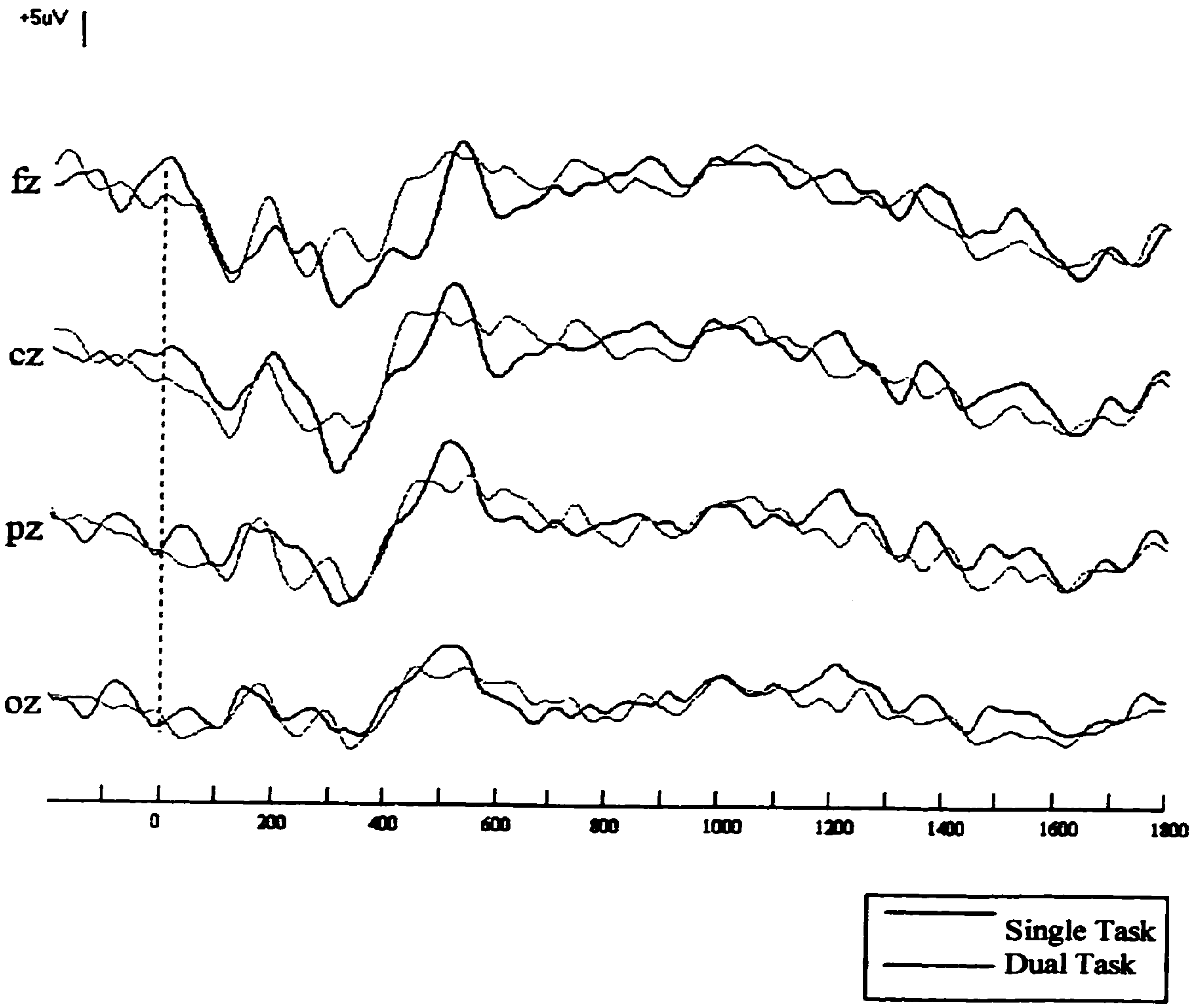

Figure 15b: Averaged ERP Waves for a Single Control Participant in the Difficult Duration Discrimination Single Versus Dual-Task.

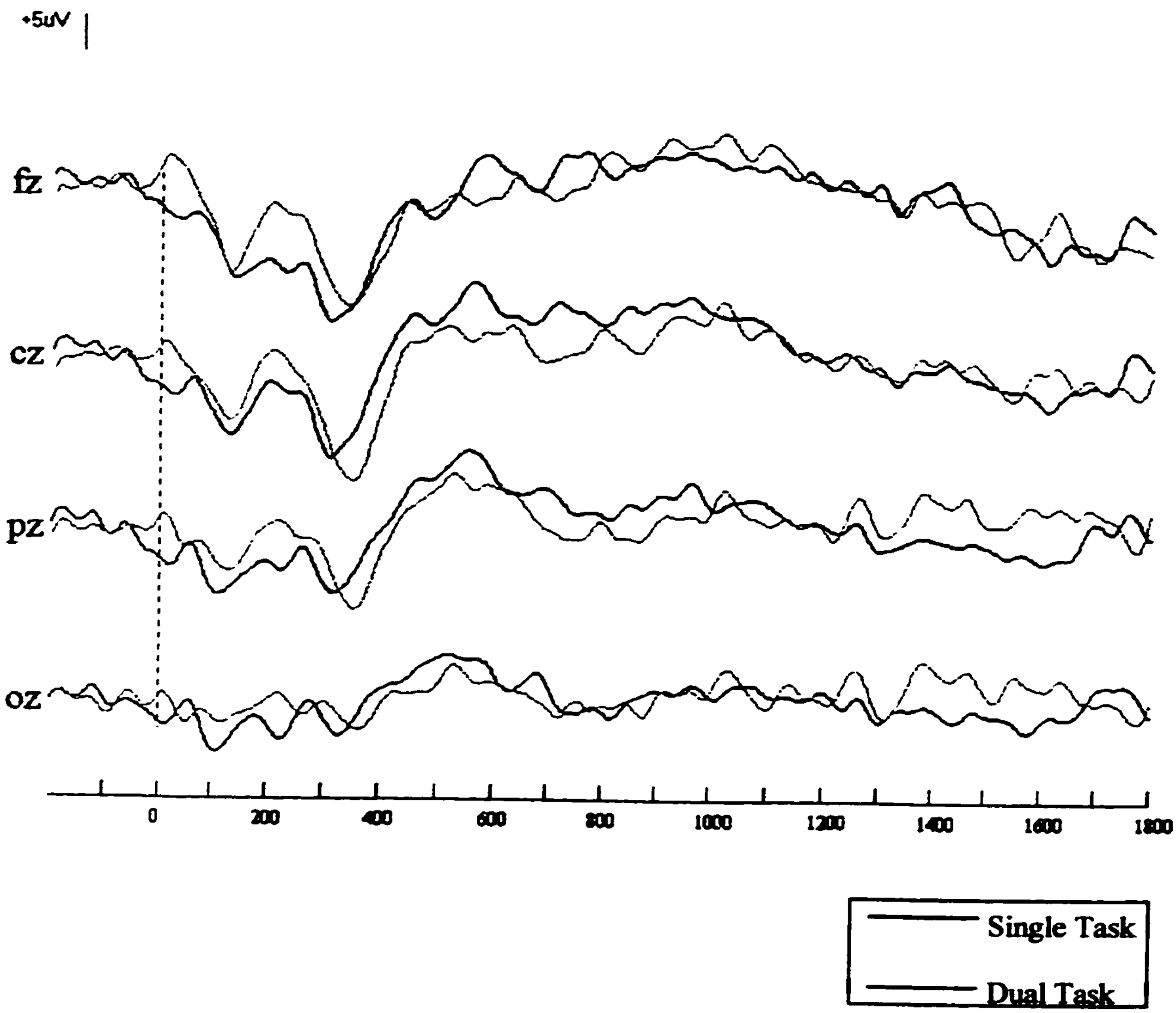

Figure 15c: Averaged ERP Waves for a Single Control Participant in the Easy versus Difficult Stimulus Discrimination in the Single-Task Condition.

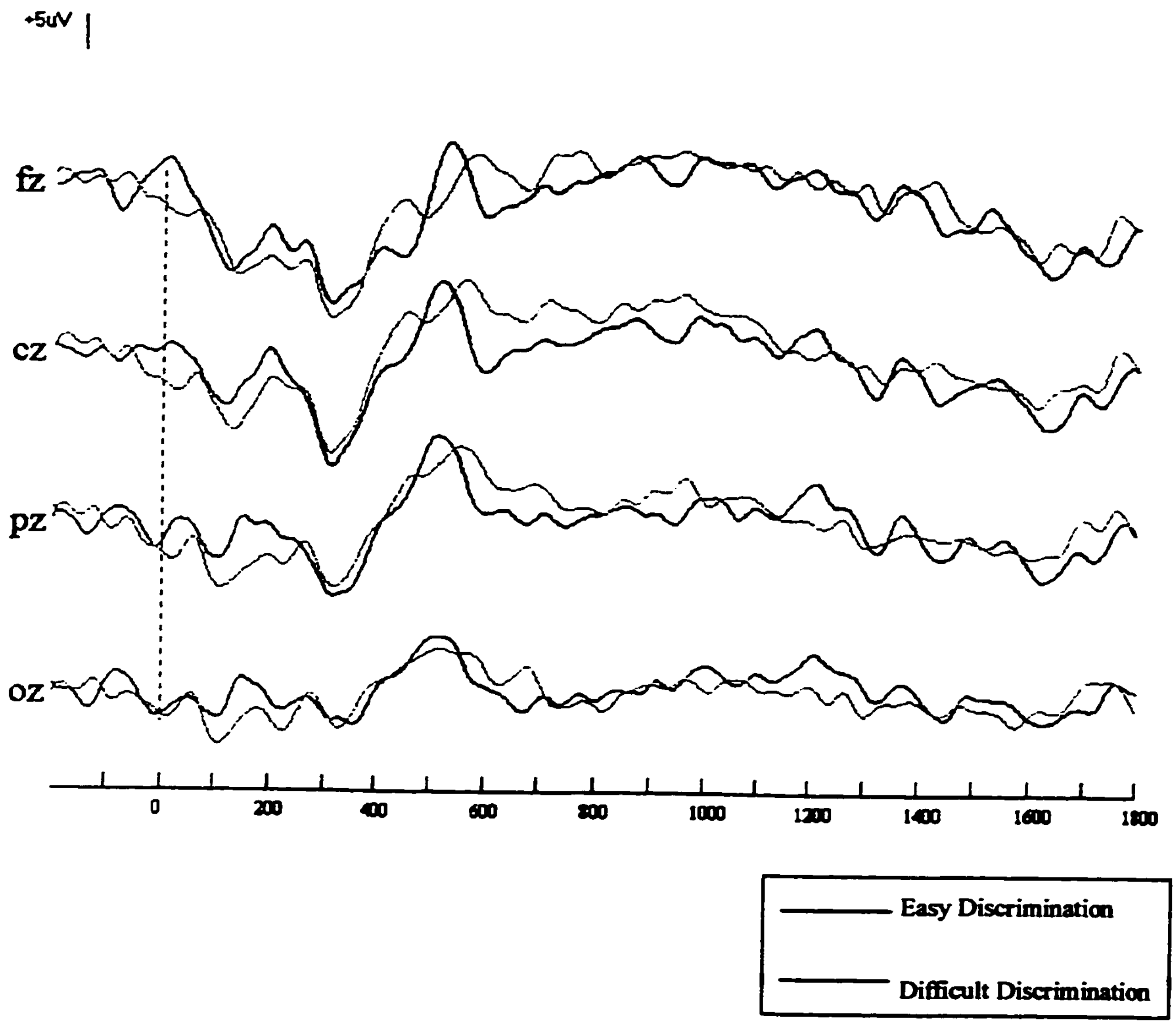

Figure 15d: Averaged ERP Waves for a Single Control Participant in the Easy versus Difficult Stimulus Discrimination in the Dual-Task Condition.

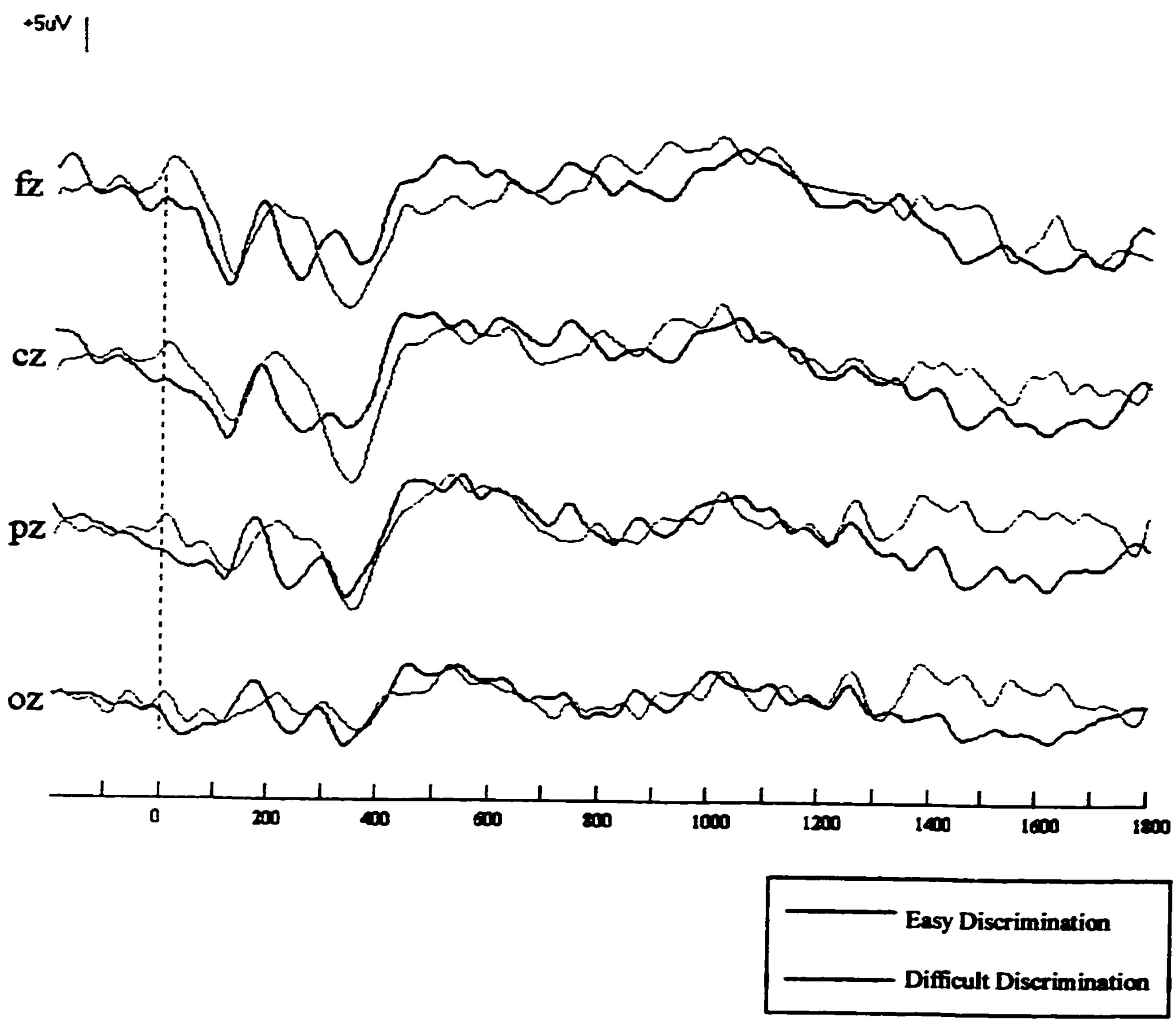

Figure 16: Mean N1 Amplitude as a Function of WM Load and Electrode Site During the n-Back Task in Experiment 2

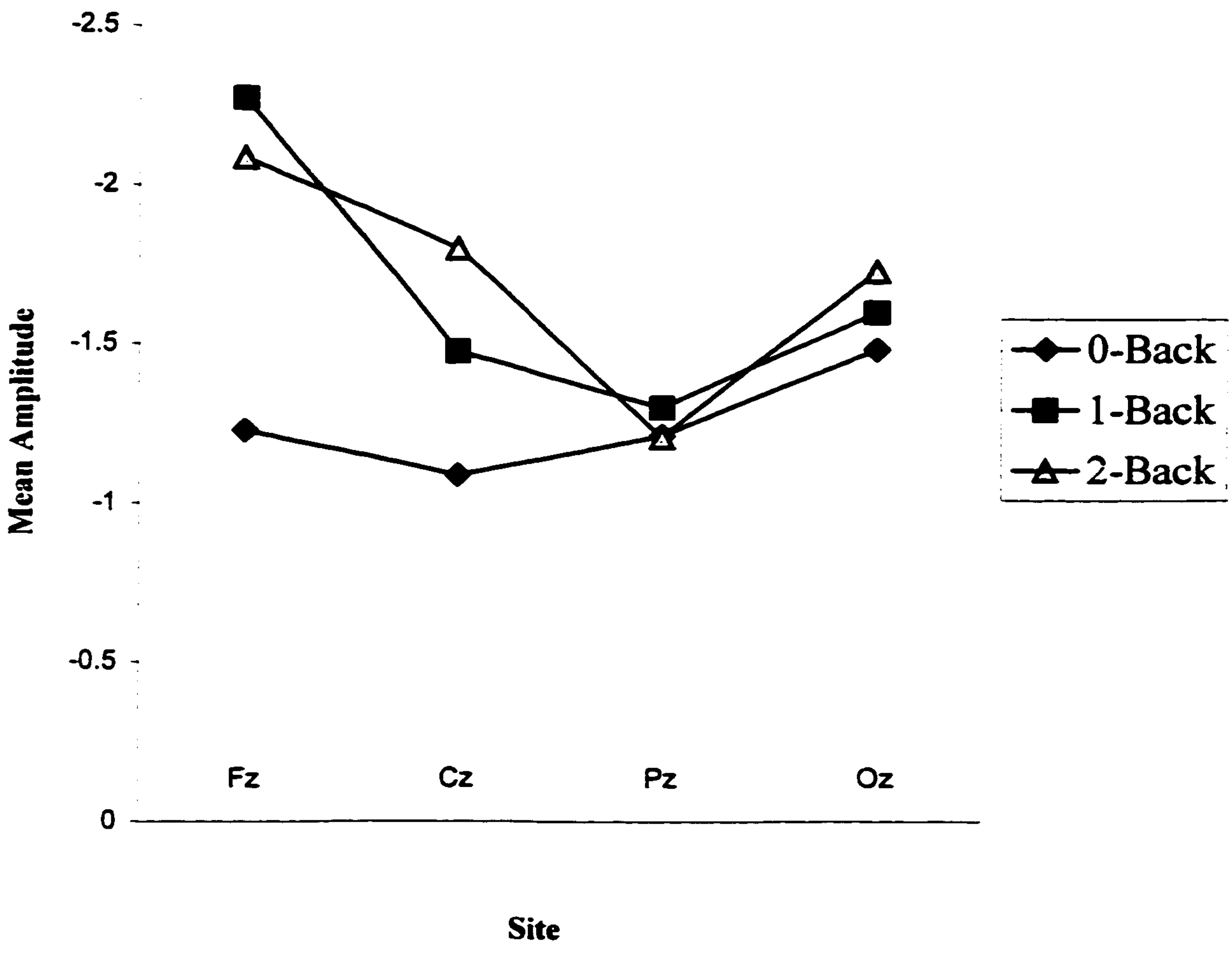

Figure 17: Mean N2 Amplitude as a Function of WM Load and Electrode Site During the n-Back Task in Experiment 2

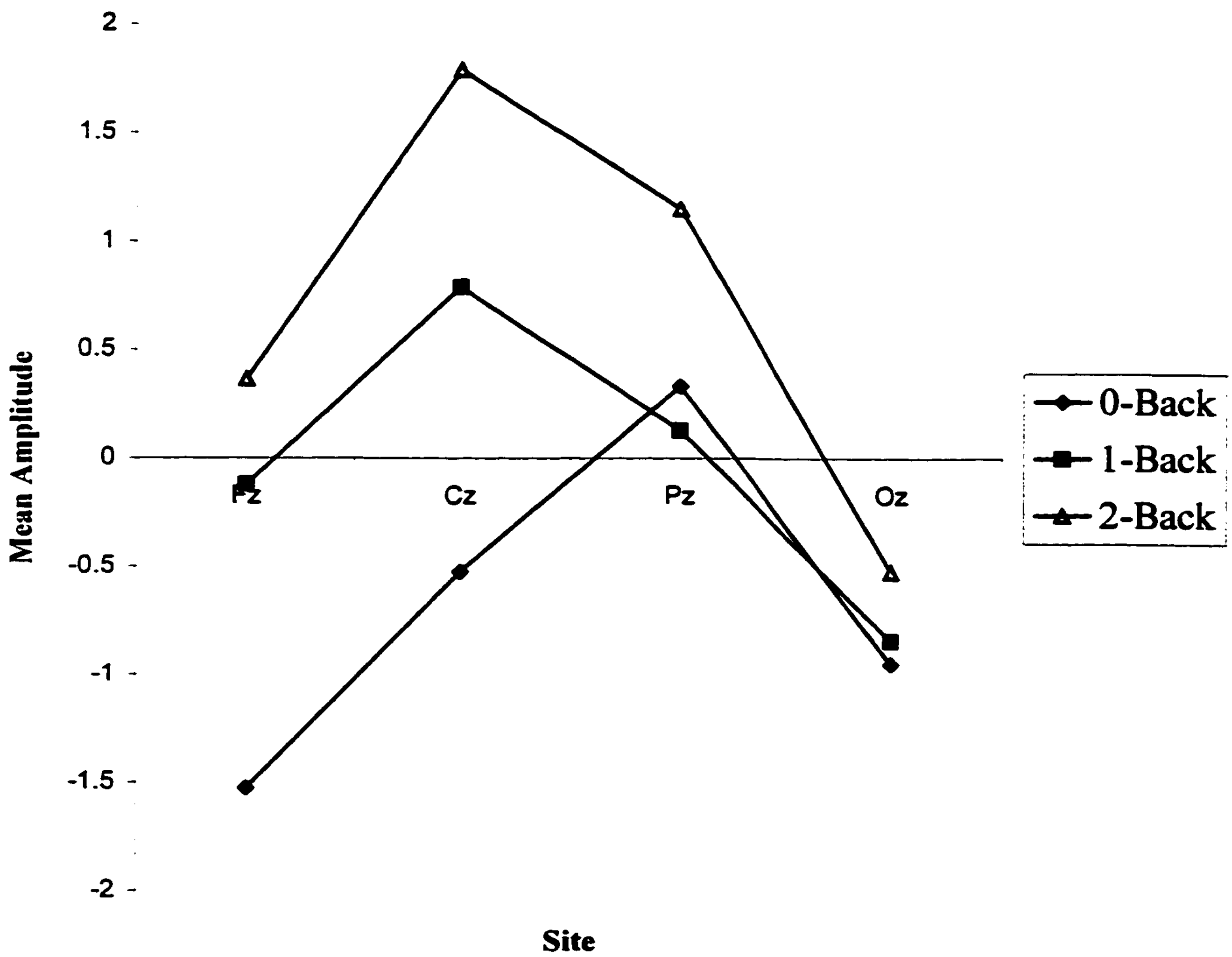

Figure 18: Mean P3 Amplitude as a Function of WM Load and Electrode Site During the n-Back Task in Experiment 2

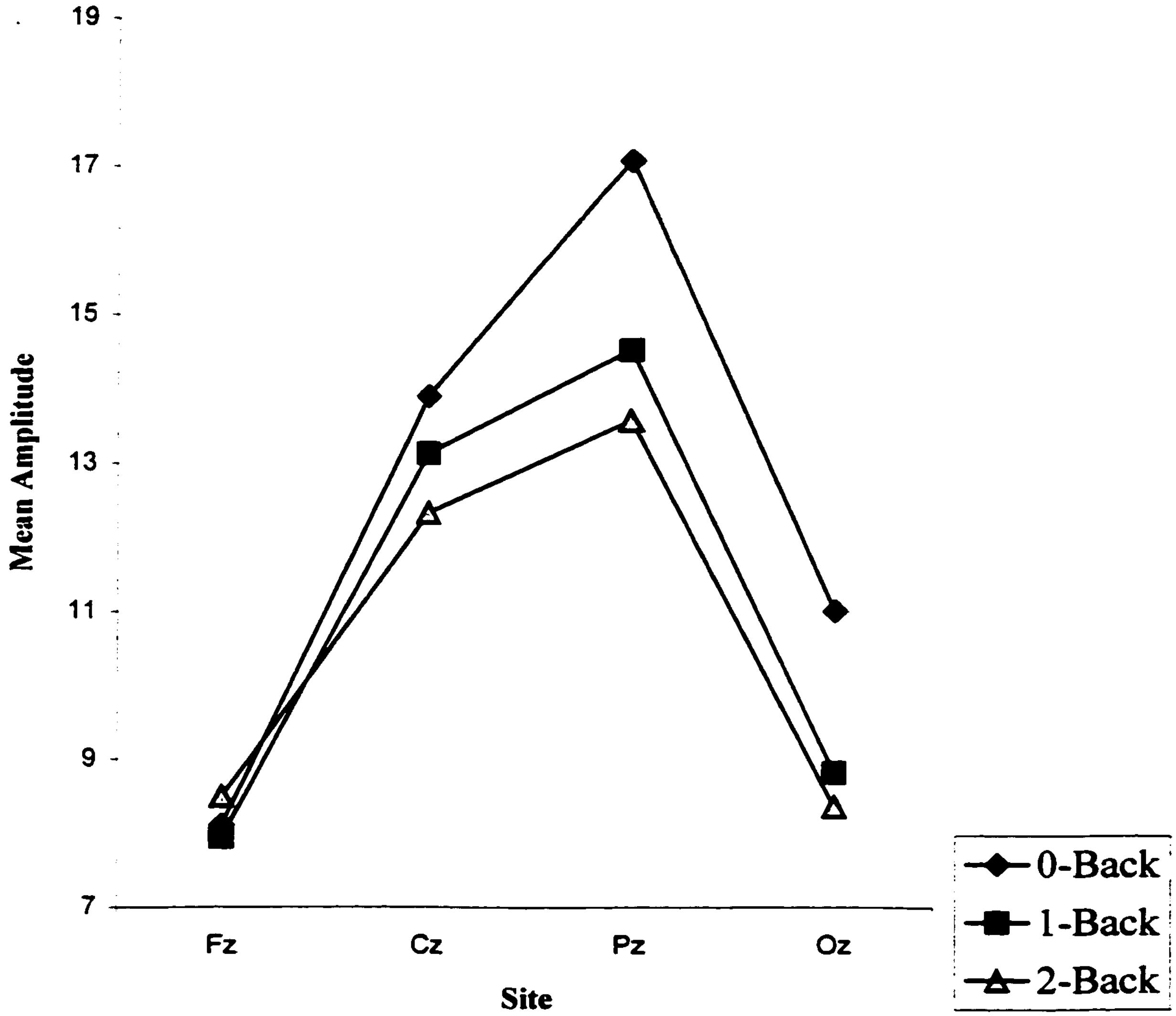

Figure 19: Averaged ERP Waves for a Single Control Participant in the 0-back, 1-back and 2-back Conditions of the n-Back Task.

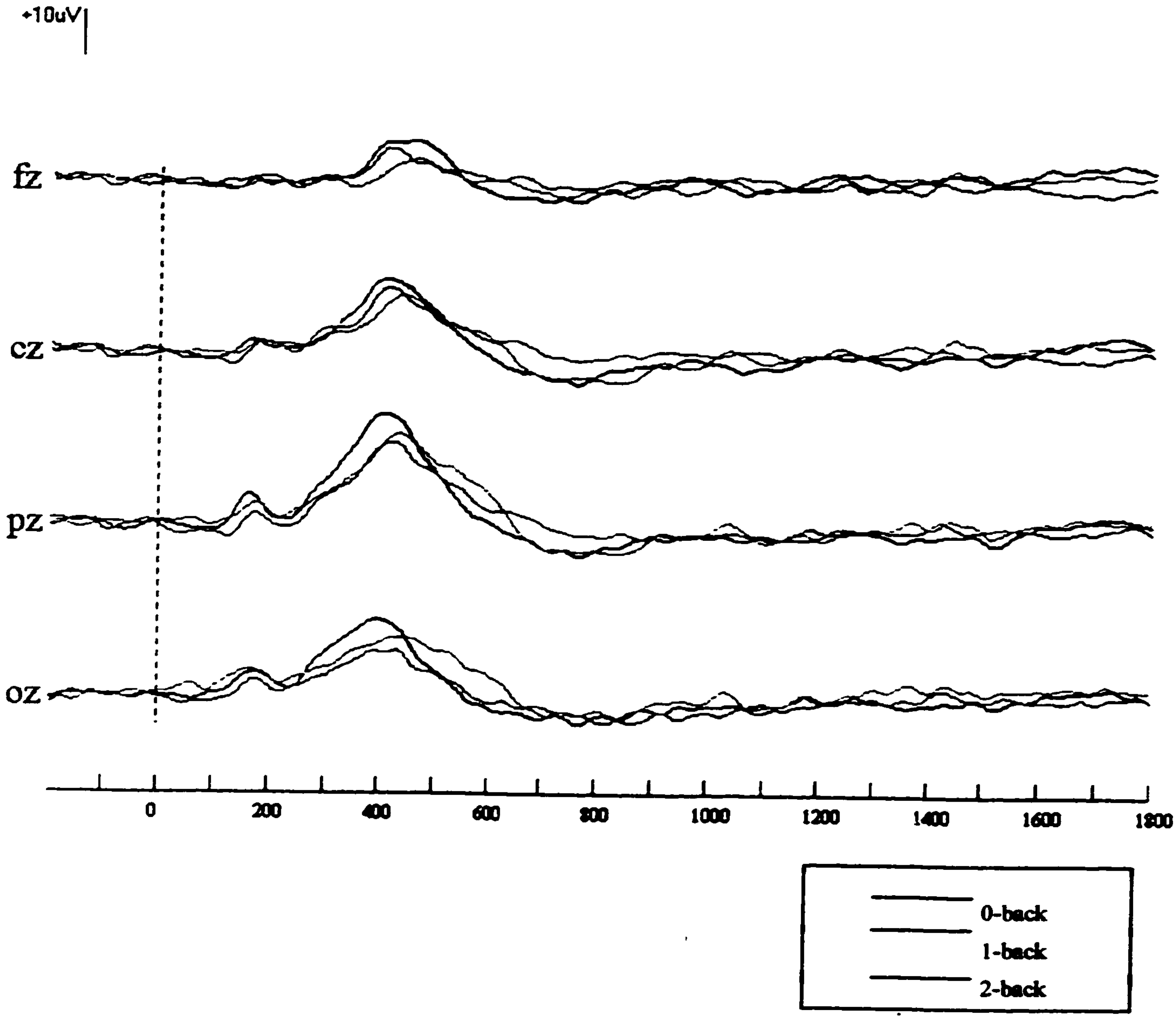

Figure 20: Mean P3 Amplitude for Each Group as a Function of Electrode Site During Performance of the n-Back Task

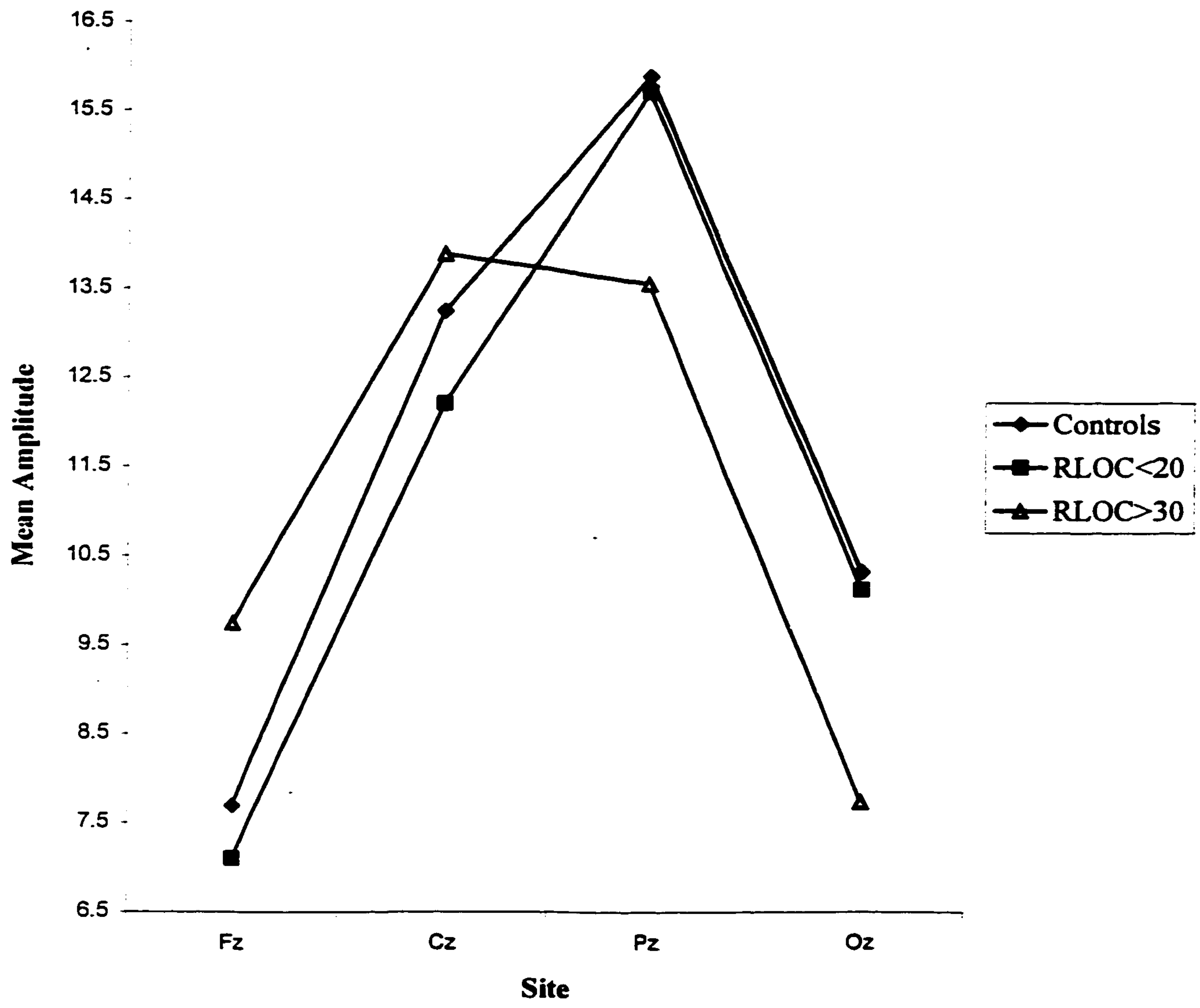

Figure 21: Mean F-P Beta Coherence in Left Hemisphere for Each Duration Discrimination Task Condition by Group in Experiment 2

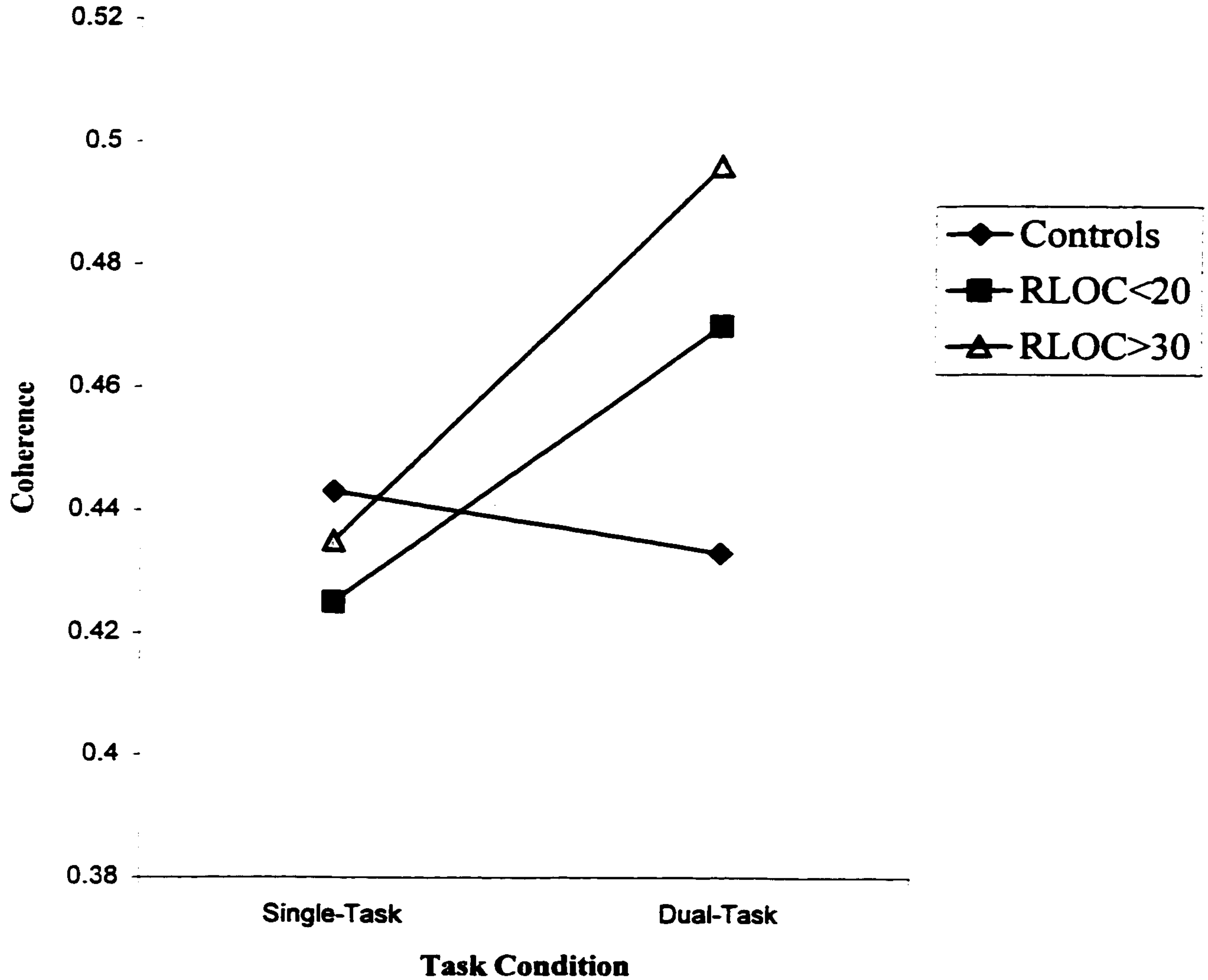

Figure 22: Mean F-P Beta Coherence For Each Group by Hemisphere During n-Back Task in Experiment 2