The Cumulative Effect of Mild Traumatic Brain Injury (MTBI) on the Properties of Perceptual Decision Making

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Abstract

The current study investigated the cumulative effects of mild traumatic brain injury (concussion) on the properties of perceptual decision-making and confidence. Participants were assigned to groups based on total number of self-reported past concussions involving a loss of consciousness (LOC) lasting up to 30 minutes in duration. A total of 67 participants were assigned to one of three groups: one past concussion (n = 23), two or more past concussions (n = 19) and a control group with no history of past concussion (n = 25). Participants were assessed on a number of measures including the Rivermead Post-concussion Symptom Questionnaire (RPQ), Center for Epidemiological Studies Depression Scale (CES-D), and the Paced Auditory Serial Addition Task (PASAT), and a novel psychophysical judgment and subjective accuracy (confidence) task with proposed sensitivity to the cumulative effects of concussion. Significant group differences emerged only on the psychophysical measure of discriminative accuracy (p = .026) with the multiple concussion group demonstrating worse performance relative to the single concussion and control groups. Contrary to expectation, the multiple concussion group also exhibited the quickest response times, potentially indicating a differential speed-accuracy trade-off strategy. No significant group differences emerged on measures of confidence and error awareness (calibration, resolution, bias), indicating that meta-cognitive awareness was functionally intact for the single and multiple concussion groups. The current findings support the recent notion that if cumulative and chronic effects of mild traumatic brain injury exist, they are probably very subtle.

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Mild Traumatic Brain Injury

Concussion, or mild traumatic brain injury (MTBI, concussion) is the most prevalent form of brain injury, accounting for approximately 70 - 90% of all incidents. The majority of individuals who sustain MTBIs are young adults (Ryan & Warden, 2003), with an estimated population-based incident rate of over 600/100 000 individuals (Sterr et al., 2006); MTBI is so prevalent that it has been described as an epidemic in the United States (Bernstein, 2001). Contact sports, falls, and motor-vehicle accidents account for the majority of MTBIs (Gerstendbrand & Stepan, 2001). While the term "mild" suggests that the injury is fairly innocuous in nature, emerging evidence suggests that neuropathological, neurophysiological, and neurocognitive changes can occur (Ryan & Warden, 2003), and that long-term cognitive, emotional, and somatic sequelae may result from these supposedly "mild" injuries -- especially in cases of repeated trauma.

However, consensus is far from being established. Studying brain injury in humans presents a number of methodological challenges, and the definition and grading of mild traumatic brain injury varies considerably between specific research paradigms and special interest groups. While attitudes among health care professionals and the general public are beginning to change with increased awareness of the problem, the perception of MTBI as an insignificant injury remains prevalent.

Much more research is needed to better understand the consequences of MTBI, especially the potential long-term and cumulative effects. According to Iverson et al. (2006), the findings to date on the cumulative effects of concussion should be considered preliminary and interpreted cautiously. Due to endemic problems in the concussion literature pertaining to methodology and/or generalisability, many more studies are required before any decisive conclusions can be drawn about the short, medium, an long-term cumulative effects of concussion, and who is at risk (Iverson et al., 2006). Frencham et al. (2005) also emphasized the need for further research to focus on outcome in the post-acute phase, recommending the development of more rigorous measures that are proposed to be highly cognitively demanding, with greater potential sensitivity to the effects of MTBI (Frencham et al., 2005).

Thus, the goal of this thesis is to assess whether self-reported MTBI results in any objectively measurable neuropsychological deficits in undergraduate-level university students, using a novel perceptual judgment task that is proposed to be more sensitive to the chronic effects MTBI than many currently available neuropsychological tests. Furthermore, this study aims address an important controversy in the literature: whether and to what extent there is a cumulative effect of MTBI. A secondary goal of the this study is to investigate the relationship between cognitive performance, and self-reported post-concussion symptoms and depression.

Definition of MTBI

The definition of MTBI varies widely in the literature, reflecting the complex nature of cerebral injuries (Voller et al, 2001). Nomenclature also consistently varies; MTBI has been alternatively referred to as cerebral concussion, mild head injury, minor head injury, and even Commotio cerebri (Gerstenbrand & Stepan, 2001), among other terms. MTBI is currently the most frequently used term in the literature to describe light traumatic brain damage, and is often used synonymously with, or in close association with the term concussion -- especially in the sports-medicine context (e.g. Moser et al, 2005; Cantu, 2006; Fijalkowski et al., 2006). The literature is inconsistent in defining how MTBI and concussion are related, however (Willer & Leddy, 2006), and for the purposes of this study, concussion (a constellation of physical, cognitive, and emotional/behavioural symptoms caused by a brain injury) will be used synonymously with MTBI.

Mild traumatic brain injury is defined as a traumatically induced physiological disruption of brain function, indicated by at least one of the following neurological symptoms:

1. Loss of consciousness (LOC) for any period up to approximately 30 minutes;
2. Post-traumatic amnesia (PTA), either retrograde (i.e. difficulty in recalling events during the period immediately preceding the trauma) or anterograde (i.e. difficulty in forming new memories after the trauma) not exceeding 24 hours;
3. Any alteration of consciousness at the time of the accident (e.g. dazed, disoriented, or confused); or
4. Focal neurological deficit(s) that may or may not be transient.

This definition was established by the Mild Traumatic Brain Injury Committee of the Head Injury Interdisciplinary Special Interest Group of the American Congress of Rehabilitation Medicine (ACRM; Kay et al., 1993), and is roughly equivalent to a Glasgow Coma Scale[1] (GCS) rating of 13-15 at 30 minutes post-injury (Gerstenbrand &

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The Glasgow Coma Scale (GCS) was the first scale developed to classify the severity of traumatic brain injury (TBI). The focus of the GCS was on more severe brain traumas, however the scale also included a category for "minor head injuries" -- scores that fall between 13 and 15 during the early phases of recovery

Stepan, 2001). While there are a number of classification systems for MTBI, the ACRM has been gaining in recognition over the past decade, and is consistent with the diagnostic criteria used in a number of other recent MTBI studies (Mooney et al., 2005). More serious symptoms (e.g. LOC greater than 30 minutes and/or PTA exceeding 24 hours; GCS < 13), and the presence of abnormalities on standard imaging tests[2] suggest either a moderate or severe traumatic brain injury.

Grading Scales. Similarly to how TBI is categorized in terms of severity, a number of classification scales for grading MTBI have been developed. Used primarily in sports as a means of establishing return-to-play guidelines for concussed athletes, use of these measures remains controversial. Numerous scales have been published, e.g. the American Academy of Neurology (AAN), Cantu, Colorado Medical Society, etc., and each differs in its criterion for rating the severity of MTBI and in its subsequent return-to-play recommendations. However, these instruments lack appropriate scientific support, and their heterogeneity has caused confusion in the classification of MTBI, which in turn has hindered understanding of the research findings and ramifications discussed in the literature (Mrazik et al., 2000). See Mrazik et al. (2000) for a comparison of MTBI scales.

Post-Concussion Symptoms (PCS). In addition to the primary signs noted above, a number of physical, cognitive, and emotional/ behavioural sequelae have been associated

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(Ruff, 2005).

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In general, neuroimaging results should be negative, but "this defining characteristic may be more complex" (Voller et al., 2001).

with MTBI, and are frequently referred to as post-concussion symptoms or PCS (Ryan & Warden, 2003). The ACRM describe these as follows (Kay et al., 1993):

1. Physical symptoms (e.g. nausea, vomiting, dizziness, headache, blurred vision, sleep disturbance, quickness to fatigue, lethargy or other sensory loss) that cannot be accounted for by peripheral injury or other causes.
2. Cognitive deficits (e.g. involving attention, concentration, perception, memory, speech/language, or executive functions) that cannot be completely accounted for by emotional state or other causes.
3. Behavioural change(s) and/or alterations in degree of emotional responsivity (e.g. affective change, irritability, quickness to anger, disinhibition or emotional lability) that cannot be accounted for by a psychological reaction to physical or emotional stress or other causes.

Post-concussion symptoms typically resolve within three months post-injury (Mooney et al., 2005), a period of time typically referred to as the acute stage or acute phase of recovery. Conversely, the period of time beyond three months post-injury is typically referred to as the chronic or post-acute stage of recovery. Chronic cases of PCS will be discussed subsequently in the context of persistent-PCS.

Pathophysiology of MTBI

Despite being a prevalent clinical entity, the pathophysiological basis for MTBI remains to be fully elucidated (McCrory & Berkovic, 2001). Empirical data for MTBI is scarce, and research is hindered by amorphous criteria for defining and grading severity of injury. To date, it is not certain whether MTBI is associated with lesser degrees of the diffuse structural damage that is observed in severe traumatic brain injury, or, conversely, is a consequence of reversible changes in neurological functioning (Sterr et al., 2006).

Diffuse Axonal Injury (DAI). Axonal sheering and tensile strain damage, usually due to rotational acceleration forces, is the primary pathological injury observed in traumatic brain injury. Severity of axonal injury correlates with duration of loss of consciousness, and post-traumatic amnesia. Following the initial trauma, a cascade of injury ensues with the release of GABA (an inhibitory neurotransmitter) and glutamate, acetylcholine, and asparate (excitatory neurotransmitters) that can lead to further neuronal damage. Furthermore, other post-injury changes, including excessive calcium influx into damaged neurons, the release of inflammatory cytokines, oxidative free radical damage, damage to cell wall receptors, and changes in the acetylcholine, catecholamine, and serotonergic neurotransmitter systems can further lead to diffuse neurological injury (Hall et al., 2005).

Some evidence suggests that mild and severe TBI have the same underlying neuropathology: DAI and vascular injury occurring in the parasagital white matter, spreading from the cortex to the brainstem (Voller et al., 1999). Recent findings from pathological studies also indicate DAI in patients with mild-to-moderate brain injury. The pattern of injury in the most affected regions, the orbitofrontal and temporal regions, may be responsible for the commonly reported neuropsychological sequelae following MTBI. Similarly, behavioral evidence suggests that frontal lobes are especially affected in TBI, as survivors with diffuse axonal injuries often demonstrate patterns of executive dysfunction similar to patients with focal prefrontal lesions (O'Keeffe et al., 2004). A post-mortem examination of MTBI patients who died of unrelated causes (Blumbergs et al., 1994; 1995) revealed damage to the corpus callosum and fornices, suggesting that these pathways are also susceptible to insult from MTBI; congruent with the aforementioned findings, the frontal and temporal lobes also displayed evidence of diffuse axonal damage.

Very few studies have focused strictly on MTBI, however, and contemporary imaging technology (e.g. MRI, CT, PET, SPECT) is of limited utility due to resolution constraints and the diffuse nature of the damage associated with MTBI. For example, as of 2004, the most sensitive MRI scanners are limited to detecting lesions larger than one mm3 in size, and a lack of detection on this scale does not preclude damage to white matter.

DAI and Information Processing Speed. Normal information processing relies on intact neural structures and functional pathways. Following severe TBI, slowed information processing involving basic tasks is the most consistently demonstrated finding. It has been postulated that this effect is either due to diffuse cytotoxicity resulting in oblique neural transmission, or from loss of myelination or diminished dendritic branching causing slower or incomplete neuronal propogation (Mathias et al, 2004).

In a recent study, Felmingham et al. (2004) examined the impact of DAI on information processing speed using simple and two-choice reaction time (RT) tasks in patients with severe TBI showing evidence of DAI (diffuse TBI group), TBI patients whose injuries were primarily focal and not diffuse (mixed injury group) and matched control subjects without TBI. The results indicate that basic speed of information processing was slowest in the diffuse TBI group followed by mixed injury group, and the controls, respectively. Complex RT was significantly slower with the TBI groups (diffuse and mixed injury, with no significant difference between TBI groups) than with the control group. If mild, moderate, and severe TBI (excluding cases where focal cerebral injuries are present) are to some extent the result of quantifiable differences in degree of diffuse axonal injury, then demanding tests of complex reaction time (as a measure of processing speed) should be sensitive to MTBI. This conjecture is supported by a recent meta analysis (Frencham et al., 2005), where it was reported that the largest effect of MTBI on neuropsychological functioning by cognitive domain was for speed of information processing, which includes simple and choice reaction time.

Acute Effects of MTBI

To date, the majority of research into the effects of MTBI has been conducted during the acute phase of recovery (Gaetz & Bernstein, 2001). There is a general consensus that mild cognitive impairment may be evident immediately following MTBI (i.e. during the first 10 days), and that this usually resolves within one to three months for the 'typical' patient (Frencham et al., 2005). Specific deficits in the acute phase have been noted in the areas of attention, working memory, general memory, speed of processing (including simple and complex reaction-time), and continuous performance (Alexander, 1995; Guskiewicz et al., 2003; Iverson et al., 2003; Iverson et al., 2004; Lovell et al., 2004; Macchiocci et al., 2001; Makdissi et al., 2001; Nolin, 2006; Voller et al., 1999; Warden et al., 2001). Furthermore, MTBI is associated with increased response time variability on computerized neuropsychological tests administered within several days post-injury (Makdissi et al., 2001). According to Bernstein (2001): "While it is virtually uncontested that concussion can produce transient disruptions to cognitive and behavioral functioning immediately after injury, the evidence for long-term impairment is mixed" (Bernstein, 2001). Thus the need for research into the chronic effects of MTBI.

Chronic Effects of MTBI

When investigating the potential long-term effects of MTBI, two somewhat overlapping issues need to be considered. Foremost is the controversial notion of post-concussion syndrome (persistent-PCS, post-concussional disorder). First recognized in association with the Miserable Minority[3] (Ruff, 2005), the etiology of persistent-PCS (psychogenic vs. physiogenic) continues to be stridently debated in the literature. Patients often report a continuation of subjective post-concussion symptoms, including headache, fatigue, dizziness, and emotional, behavioural and cognitive problems many months after injury that impede their ability to return to work and engage in leisure activities (Moser et al., 2005). However, since it is generally agreed that persistent-PCS typically afflicts a minority of MTBI patients, perhaps a more compelling issue to consider is whether any objectively measurable neuropsychological deficits exist long after injury in the absence of subjective PCS symptoms. Since it is arguable that non-injury and premorbid factors may contribute to the development and maintenance of persistent-PCS (as will be discussed in the subsequent section), any neuropsychological deficits detected beyond the

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A somewhat pejorative label for MTBI patients who fail to recover normally, and seek treatment for protracted symptoms acute stage in ostensibly recovered patients would constitute strong evidence that MTBI is a non-trivial injury.

Chronic Effects of MTBI Part I: Post-concussion Syndrome/Persistent PCS/Post-concussional Disorder (PCD). Although post-concussion symptoms usually resolve within three months post-injury, some individuals can experience persistent symptoms for months and even years following MTBI, resulting in significant disability. When this cluster of post-concussion symptoms becomes persistent in nature, it is often referred to as post-concussion syndrome, persistent-PCS, or post-concussional disorder (PCD). Since many of its symptoms are subjective, however, post-concussion syndrome is difficult to define medically (Hall et al., 2005). Furthermore, differential diagnostic criteria exist, each influenced by the speciality of the examining physician (e.g. psychiatry, neurology, pain management, etc.) and the clinical setting (e.g. emergency room, clinic, forensic evaluation, etc.)

An attempt has been made in the fourth edition of the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 1994; DSM-IV) to standardize the diagnosis of PCD. According to the DSM-IV, postconcussional disorder is defined as a syndrome following significant cerebral concussion resulting in quantifiable deficits in memory or attention, and the onset, or substantial post-injury worsening, of any three of the following symptoms: tiring easily, disordered sleep, headaches, vertigo/dizziness, irritability, anxiety/depression/affective lability, changes in personality, or apathy. The disturbance resulting from these symptoms must result in a considerable decline in social or occupational functioning, and the symptoms should not be better accounted for by other diagnostic categories. The DSM-IV recommends that PCD should only be diagnosed three months following a significant concussion, however no specific criteria for diagnosing a concussion are recommended, aside from a five-minute period of LOC, and a period of PTA that lasts more than 12 hours after the closed head injury. The latter recommendations contradict existing diagnostic criteria (e.g. AAN) for MTBI, however, so reconciliation is warranted. For the purposes of clarity, post-concussional disorder and post-concussion syndrome will be henceforth referred to as persistent-PCS, except when explicitly referring to results from other studies based on the DSM-IV criteria for PCD.

Estimates of persistent-PCS vary considerably in the literature. It is suggested that methodological and operational differences between studies contribute to inconsistent reports of incidence, e.g. variable criteria for MTBI and persistent-PCS, and a lack of homogeneity among the population of individuals with persistent-PCS. For example, study participants involved in litigation and those actively seeking treatment for MTBI demonstrate significantly more symptoms at three months post-injury than participants selected primarily on the basis of having sustained a MTBI (Belanger et al., 2005). Not surprisingly then, reported prevalence rates at three months post-injury vary considerably. For example, Mooney et al. (2005) reported that 91% of their sample had persistent-PCS after three months post-injury, while Suhr & Gunstad (2002) found that 60% of MTBI patients reported PCS symptoms three months following injury, with up to 40% remaining symptomatic at 12 months post-injury. In contrast, Rutherford (1989) reported a more conservative estimate, with up to 15% of patients in his sample remaining symptomatic after one year; similarly, Hall et al. (2005) noted that only 7-15% of all individuals have any symptoms one year after injury, and can thus be considered to suffer from persistent-PCS.

The etiology of persistent-PCS remains to be empirically explained. Neuro-trauma such as diffuse axonal injury has been suggested as a primary physiological factor in its development by some authors (Umile et al., 2002; Ruff 2005). However, an increasing body of evidence suggests that a host of other factors mediate outcome in persistent-PCS. Moreover, it has been argued that "post-concussion" symptoms are not specific to TBI, and can manifest as a result of mood disorders such as depression and anxiety, even in individuals without a history of brain injury. For example, Iverson & McCracken (1997) found that 39% of an outpatient pain sample with no history of head injury met diagnostic criteria for PCS based on their symptom report, while 94% of these patients met at least three of the four criteria necessary for DSM-IV diagnosis of post-concussional disorder. Similarly, Iverson & Lang (2003) investigated the prevalence of PCS-like symptoms in a cohort of healthy individuals. Participants were co-administered a post-concussion symptom inventory and the Beck Depression Inventory (BDI). The authors found that specific endorsement rates for PCS-like symptoms were as high as 76% during the previous two weeks. Post-concussion-like symptoms were also moderately-to-highly correlated with BDI depression score. Suhr et al. (2002) explored self-reported PCS symptoms in individuals with head injury and depression, head injury without depression, depression without head injury, and controls. It was found that depression, rather than head-injury status, primarily accounted for increases in PCS symptom reports, including cognitive symptoms (Suhr et al., 2002). Likewise, King (1996) demonstrated that when a battery of neuropsychological, emotional, and traditional measures of brain injury severity were administered to patients early after a brain injury, anxiety and depression scores and patients' subjective impact of the event accounted for the most variance in post-concussion symptom scores three months later (King, 1996).

In addition, PCS-like symptoms was found to be high among non-brain-injured normal controls, chronic headache sufferers, medical patients, psychiatric patients, and chronic pain patients (Ryan & Warden, 2003), and additional factors such as psychological problems, stress, neurological signs, older age, and prior history of brain injury have been implicated in the development of persistent-PCS. For example, Luis et al. (2003) investigated persistent-PCS in a sample of veterans with a history of mild TBI, and a control group without a history of head injury. Factors such as pre-existing psychiatric difficulties, demographic and social support variables, and history of accidental injurious events were investigated as predictive factors for persistent-PCS. All groups displayed PCS, however symptoms were most prevalent in subjects who had suffered mild TBI with loss of consciousness. Interestingly however, the most significant predictors of PCS were early life psychological problems such as anxiety and depression, lack of social support, lower intelligence, and interactions between these predictors. This suggests that individual resilience, premorbid psychological status, and psycho-social support mediate PCS. However due to the particular characteristics of the population used in this study, caution must be employed in generalizing the results.

Mittenberg et al. (1992) had earlier posited that the incidence and persistence of

PCS may be explained by the degree to which an individual reattributes common complaints (e.g. depression symptoms) to the brain injury, given their expectations about the effects (Mittenberg et al., 1992). Gunstad & Suhr (2001) examined this "expectation as etiology" theory by having participants report current symptoms and symptoms expected subsequent to a hypothetical MTBI. The authors found that depressed individuals reported increased current symptoms of PCS relative to normal controls and healthy athletes. The notion that individuals expect negative consequences following brain injury was supported by the finding that all groups expected more symptoms following MTBI. However, athletes, who ostensibly expect speedy recovery and/or are highly motivated to return to play, expressed fewer symptoms than normal or depressed individuals (Gunstad & Surh, 2001). Mackenzie & McMillan (2005) also investigated the role of expectations in maintaining symptoms, the ability to simulate persistent PCS, and the extent to which doctors might attribute patient complaints to MTBI. In contrast with the previous findings, however, it was concluded that pre-injury expectations about MTBI are unlikely to maintain PCS symptoms. Participants had difficulty simulating PCS without any prompting or tutoring, and it was suggested that lay-people have an insufficiently detailed pre-injury concept of the effects of MTBI to support the "expectation as etiology" hypothesis (Mackenzie & McMillan, 2005).

The cause of persistent PCS in MTBI patients has debated for decades. The subjective and vague nature of post-concussion symptoms and persistent-PCS has served to generate a great deal of controversy concerning etiology. Despite a considerable amount of research, the primary causes of persistent-PCS remain contested. Whether and to what extent these symptoms are due to direct and secondary physiological changes in the brain, premorbid and post-injury psycho-social factors, or an interaction between these factors remains to be established. Determining what causes these protracted and often debilitating symptoms in some MTBI patients is of substantial clinical importance due to the large impact these symptoms can have on quality of life, occupational functioning, and so forth. Until the issue can be resolved, current evidence suggests that the best approach is to consider the influence of both neurological and psychological factors in affecting post-acute outcome in MTBI (Mackenzie & McMillan, 2005).

Chronic Effects of MTBI Part II: Neuropsychological Deficits. Although it has been well established that MTBI results in acute-stage neuropsychological deficits, empirical evidence for measurable dysfunction persisting into the post-acute/chronic stage of recovery is inconsistent and controversial. Some studies have demonstrated enduring effects of a single MTBI, while others conclude that recovery is complete by three months post-injury, with the majority of patients exhibiting no further complications (Belanger et al. 2005).

To date there have been six meta-analytic reviews published about the effects of MTBI on neuropsychological function in adults. The results of these reviews highlight both the inconsistent nature of findings in the field, as well as the myriad of factors than can influence outcome in MTBI. Binder et al. (1997) conducted the first comprehensive review of the findings relating to chronicity of cognitive deficits following MTBI, strictly including studies that examined participants at least three months post-injury. In order to avoid a selection bias, only unselected samples were used -- i.e. participants were selected solely on the basis of having sustained a MTBI[4]. In total, 11 effect sizes were derived from eight studies, and it was found that the overall effect size was small but significant ($d = .12$). However, when a more conservative weighted effect size calculation was used, the effect failed to reach significance ($g = .07$). The study also evaluated effect size separately for seven cognitive domains, with only attention demonstrating a significant deficit ($g = .17$), suggesting that neuropsychological measures of attention and concentration are most sensitive to persistent cognitive dysfunction following MTBI.

The next major meta-analysis (Zakzanis et al, 1999) included 12 studies, however unlike Binder et al. (1997), the authors did not consider participant selection criteria and thus included some clinically-based or referred samples in addition to unselected samples. Furthermore, Zakzanis et al. did not report an overall effect size, instead reporting individual effect sizes for seven cognitive domains. Moderate-to-large effect sizes were obtained for all cognitive domains, the largest for cognitive flexibility ($d = .72$), and the smallest for manual dexterity ($d = .44$). Time since injury was not specified in this study, thus the presence of acute-stage samples may have contributed to the large effect sizes. Furthermore, the inclusion of clinic-based samples (i.e. patients who were actively seeking treatment for their symptoms) may have produced inflated effect sizes.

Schretlen & Shapiro (2003) aimed to reconcile the discordant findings of the previous studies, including MTBI studies in addition to moderate-to-severe TBI studies, and including only population-based unselected samples. Based on 15 studies, the overall

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As opposed to clinic-based samples, which consist primarily of individuals actively seeking treatment for symptoms or complications.

neuropsychological effect size for MTBI was (*d* = .24), and (*d* = .74) for moderate-to-severe TBI. The authors further investigated time since injury as a potential moderator variable, and found significant differences across four time intervals (*d* = .41, .29., .08, and .04 for seven days, 7-29 days, 30-89 days, and greater than 89 days post-injury, respectively). By the 30-89 day time interval, the neuropsychological effect size for MTBI was not significantly different from zero, however since effect sizes were not reported for each cognitive domain, it was suggested that possible residual impairments in some domains were masked by this averaging across domains. Regardless, it was concluded that the inclusion of studies with clinic-based, acute-stage participants likely resulted in the larger effect sizes obtained by Zakzanis et al (1999).

Belanger et al. (2005) examined the magnitude of impairment in MTBI participants across a number of dimensions to determine effect sizes for nine cognitive domains (global cognitive ability, attention, executive functioning, fluency, memory acquisition, delayed memory, language, visuospatial ability, and motor abilities), time since injury, and sample selection type (litigation vs. clinic-based vs. unselected). A total of 41 effect sizes were obtained from 39 studies. The authors also examined the influence of cognitive domain, time since injury (less than 90 days vs. 90 or more days post-injury), and selection context of the participants as potential moderator variables. The overall effect of MTBI on neuropsychological performance was (*d* = .54) for the 39 studies. MTBI was found to be associated with significant deficits in all domains except for motor functions; most effect sizes were moderate to large, with fluency and delayed memory having the largest effects. When time since injury was considered as a moderating factor, it was revealed that for seven of eight cognitive domains, the effect of MTBI on neuropsychological function averaged .23 standard deviation units less when measured post-acutely than when measured during the acute stage. Litigation and clinical samples continued to demonstrate significant deficits during the post-acute stage however, with moderate to large effect sizes; the authors noted that it was unclear whether the cause of these persistent adverse effects was due to lasting brain dysfunction or psychosocial factors. It was concluded that MTBI has little to no effect on neuropsychological function by three months or greater post-injury in the general population. However, the authors pointed out that more post-acute studies using unselected samples are clearly necessary (Belanger et al. 2005).

As a follow-up to Binder et al.'s 1997 meta-analysis, Frencham et al. (2005) conducted a summary of the research subsequently published on the effects of MTBI on neuropsychological functioning in adults. Studies with both acute and post-acute samples were included in the analysis in order to address the effect of time since injury, and only prospective MTBI studies were included since clinical samples are more likely to represent complicated recoveries, and hence lead to an overestimate of morbidity. Since specific neuropsychological domains may have different recovery curves post-injury, the goal of the study was to address overall outcome and outcome by seven specific cognitive domains; 17 studies were included in the analysis. It was found that speed of processing, working memory/attention, memory, and executive function had significant effect sizes, speed of processing being the largest effect obtained (g = .47); effect sizes ranged from small to moderate. Time since injury was found to be a significant moderating factor, accounting for approximately 22 percent of the variance in the effect of MTBI on neuropsychological function, and the overall effect size tended toward zero with increased time since injury. It was concluded that the results are congruent with the notion that the main part of recovery after MTBI occurs within a period of three months post-injury.

According to the authors, a review of the literature since 1995 revealed only five studies that address the post-acute phase, with even fewer studies addressing outcome post six months (Frencham et al., 2005). For example, Segalowitz et al. (2001) demonstrated that well-functioning university students who had experienced a mild brain injury (mean time since injury = 6.4 years) performed significantly worse than controls on both accuracy and reaction time for a difficult auditory vigilance task. Bernstein (2002) compared university students with self-reported concussion (mean time since injury = 8 years) with matched controls on difficult speed of processing and working memory tasks. Despite time since injury, controls significantly outperformed the MTBI group in both domains. Likewise, Mangels et al. (2002) compared MTBI patients, moderate-to-severe TBI patients, and controls (within three years of injury for the TBI groups) on episodic memory and a range of standard neuropsychological tests of memory and frontal-lobe functions. MTBI patients were found to be impaired when items were encoded under divided attention (which substantially increases task difficulty), indicating executive control and secondary memory deficits. Finally, Potter et al. (2001) compared MTBI participants (within five years of injury) with controls. A three-stimulus auditory target detection task did not reveal significant differences between the groups on either accuracy or reaction times, however neuropsychological test results indicated that the MTBI group demonstrated mild memory and attention impairments. In light of the relative scarcity of post-acute research, Frencham et al. (2005) reiterated the sentiments of previous reviewers by calling for further research in this area.

Finally, Belanger and Vanderploeg (2005) conducted a meta-analysis of MTBI studies involving only athletes, based on the argument that athletes differ substantially from other patients, with higher motivation to return to activity, less secondary gain issues, and differential diagnoses (i.e. more liberal on-field vs. hospital), among other factors. As such, it was suggested that the results of MTBI studies involving athletes cannot be meaningfully compared to similar studies involving non-athletes. Effect sizes from 21 studies were calculated for several dimensions, including nine cognitive domains, time since injury, computer vs. traditional assessment technique, method of assessment across time (between or within participants, to discern the influence of practice effects), and concussion history. 21 studies were included in the analysis. A significant overall effect of sports concussion on neuropsychological performance was obtained, (d = .49) based on 32 effect sizes. When an overall effect size was calculated separately by assessment type (single assessment vs. multiple, repeated measures assessment), the influence of practice effects became evident: single assessment yielded an effect size of (d = .98), whereas the effect size for serial assessments (averaged across assessments) was (d = .44).

Similarly, the effect size for studies involving control group designs was significant, (d = .89), while studies using a pre-post comparison design yielded a small significant effect, ($d = .19$), with the differences being attributed to practice effects. Concussion history was also found to be a significant moderating variable -- whereas the overall effect size for studies excluding participants with a past history of concussion was ($d = .11$; not significant), a significant effect, ($d = .65$) was obtained for studies not excluding such participants. Interestingly, significant deficits were found for all cognitive domains except attention and executive function; conversely, Frencham et al. (2005) found attention to exhibit the largest effect among cognitive domains in their analysis. Regardless, by 10 days post-injury, the sports-concussion participants did not differ significantly from controls in terms of overall neuropsychological function (although significant deficits in delayed memory were still present at 51 days post-injury for the MTBI group). It was concluded that athletes do not differ significantly from non-athletes in terms of neuropsychological outcome after MTBI.

Cumulative Effects of MTBI

Whether or not a single MTBI results in any chronic deficits, long-term problems are thought to be associated with multiple concussions. Especially in the context of contact sports including boxing, football, and ice hockey, anecdotal and clinical reports of the detrimental effects of repeated concussions has existed for some time. In recent years, a number of high-profile athletes have suffered from repeated concussions, some players ending their careers prematurely due to the injuries. In fact, awareness of the problem goes back almost 80 years; dementia pugilistica, known colloquially as punch-drunk syndrome, was first reported in the Journal of the American Medical Association in 1928, and later chronic and traumatic boxer's encephalopathy were the subject of clinical investigation. Despite the common-sense notion that repeated mild head injuries are likely to produce permanent brain damage, the issue remains contested. The very same issues that beleaguer other MTBI studies also hamper those investigating the cumulative effects; as discussed earlier, comparisons between studies are confounded by the lack of universal agreement on the definition of MTBI and its various grades of severity, as well as sample size issues, and other methodological and test sensitivity and specificity issues.

A study by Guskiewicz et al. (2003) investigated the association between history of prior concussions and the likelihood of experiencing recurrent concussions in U.S. college football players. Recovery time subsequent to concussion was also investigated - to this end, athletes with a history of previous concussion were compared to those without a history of past concussion. The principal measure used in this study was the Graded Symptom Checklist (GSC), an instrument used to quantify the severity of several complaints frequently reported following concussion. Consisting of 17 symptoms, participants were asked to indicate the subjective severity of each using a 7-point Likert scale; this device is similar in nature to the RPQ scale employed in the present study. Concussion sustained prior to the study were retrospectively graded for severity, while concussions incurred during the study were evaluated by a certified athletic trainer.

It was found that the likelihood of sustaining a concussion during the study was associated with a history of self-reported prior concussion. Specifically, players with a history of three or more past concussions were three times more likely to sustain a subsequent concussion, while an elevated risk was reported for players with one or two previous concussions. Even after a number of confounds were controlled for, such as division of play, playing position, years of participation in football, and body mass, this "dose-response" relationship between previous concussion history and risk for sustaining a subsequent concussion persisted. When recovery from a concussion during the course of the study was evaluated, it was found that athletes who had a history of multiple concussions experienced a significantly longer recovery time relative to athletes without a past history. While there was no LOC or amnesia associated with the majority of concussions, the presence of these two factors was positively associated with a slower recovery. These findings are congruent with the results of two earlier studies on the cumulative effects of concussion in American football players. Kelly & Rosenberg (1997) noted that the risk of sustaining a concussion is four-to-six times greater if the player has already sustained a concussion, while a large study by Collins et al. (1999) involving collegiate football players revealed that athletes with a history of two or more concussions reported more baseline symptoms and performed more poorly on tasks of information processing speed than control athletes with no history of concussion (Collins et al., 1999).

Seeking to further replicate and extend these findings, Iverson et al. (2004) compared a sample of high school and college amateur athletes with a history of three or more concussions with an equal number of athletes matched on age, education, level (high school or college), gender, and sport, but with no prior history of concussion. Each athlete was assessed at baseline (i.e. preseason), and 1-2 days after suffering a concussion during the course of the study; the dependent variables measured were total symptoms, reaction time, processing speed and memory. Despite low statistical power, a significant difference between groups was detected at pre-season, with the athletes who had multiple concussions reporting more symptoms, and displaying a clear trend toward lower memory scores at baseline. Furthermore, athletes with multiple concussions were approximately eight times more likely to demonstrate a major decline in memory performance relative to athletes without a prior history of concussion -- specifically, multiply concussed players performed much worse on memory testing performed at two days post-injury than the singly concussed players. Finally, athletes with a history of concussion were significantly more likely to display five or more minutes of mental status disturbance, and were six times more likely to experience post-traumatic amnesia subsequent to receiving a concussion relative to players without a past history of concussion. Thus, the evidence for a cumulative effect of MTBI is manifold: the pre-season data suggests a lingering effect of multiple concussions, as does the disparity between groups in the presentation of on-field markers and the manifestation of adverse consequences in the acute recovery period subsequent to injury.

Moser & Schatz (2005) found that athletes with a history of two or more past concussions and no current physical, medical, or cognitive difficulties (with the most recent concussion occurring at least six months prior to the beginning of the study) demonstrated decreased overall neuropsychological functioning and decreased attention/mental speed relative to a group of youth athletes with a history of one or no concussion. Furthermore, the athletes with a history of two or more past concussions demonstrated similar neuropsychological performance to recently concussed athletes, suggesting mild, enduring effects of concussion.

However, not all recent studies have reported evidence for a cumulative effect of MTBI, and others have reported contradictory findings. For instance, Macciocchi et al. (2001) found that there were no statistically significant differences on neuropsychological test scores between football players with either one or two concussions and matched controls; tests used included the PASAT, Trails A and B, and the Symbol Digit Test (Macciocchi et al, 2001). Moser and Schatz (2002) found that recently concussed athletes differed on neuropsychological testing from athletes with a prior history of zero or one concussion, but not from athletes with a past history of two or more previous concussions. However, athletes with two or more previous concussions did not differ from athletes with zero or one previous concussion. The authors suggested that this paradoxical finding may have been due to low statistical power.

A recent study compared the preseason neuropsychological test performance and subjective symptom reporting of amateur athletes with zero, one, or two previous concussions. No significant main effects for group were found on any of the dependent variables, which included verbal and visual memory, reaction time, processing speed, and a PCS scale composite score. Unlike many previous studies investigating the cumulative effects of MTBI, Iverson et al.'s study had a very large sample size. The authors concluded that if a cumulative effect of one or two previous concussions exists, it is probably very small (Iverson et al., 2006). The primary measure in this study was the ImPACT brief neuropsychological assessment battery, an on-field tool used to assess when concussed athletes can safely return to play. While the authors claim that the measure is very sensitive, the evidence cited to support this suggestion is derived primarily from acute-stage MTBI studies using ImPACT. Possible limitations of ImPACT and similar brief sideline batteries will be considered in the ensuing section.

Neuropsychological Assessment: Traditional vs. Computerized

The use of neuropsychological testing in assessing concussive injury has increased substantially during the past two decades, and recent developments in computer technology are facilitating a shift away from traditional paper-and-pencil assessment, especially in sporting contexts. The current popularity of neuropsychological testing, particularly in the management of sports concussion, stems from awareness of the difficulties inherent in relying solely on subjective reporting of symptoms by athletes; neuropsychological tests allow for a more objective analysis of MTBI sequelae (McCrory et al. 2005). However, such testing is not without limitation, and the equivocal nature of recent findings, especially relating to the chronic and cumulative effects of MTBI, suggest the possibility that commonly employed measures might themselves be inadequate in essence or application.

The vast majority of standard neuropsychological tests are designed to assess cognitive dysfunction caused by neurological or psychiatric illness or brain lesions, and are not especially sensitive to subtle changes in cognitive function (Collie et al., 2006). Furthermore, standard neuropsychological tests are often limited by a marginal range of possible scores, floor and ceiling effects, poor test-retest reliability, practice effects, as well as limited accuracy and sensitivity of measurement. For example, simple attention and working memory tasks such as the Digit Span, a test commonly used in the assessment of MTBI, have been found to be insensitive to subtle cognitive deficits

(Frencham et al., 2005), and thus are of little or no utility in this regard. The obvious implication for the research is an inflated proportion of type-II errors when relying on tests that are inadequate for detecting subtle deficits in cognition.

The use of computerized testing that measures response time (RT) as a dependent variable is an effective means of dealing with some of the psychometric limitations of the traditional neuropsychological tests. Since RT can be measured by computers with significantly greater accuracy and sensitivity -- thus allowing for detection of subtle cognitive deficits in the millisecond range -- there are thousands of possible measurable levels of performance. Test-retest reliability and the reduction of error variance is possible with RT tests since they do not suffer greatly from practice effects, and they can be repeated over many trials. Measuring performance variability is potentially instructive in assessing TBI, since several studies have revealed inconsistent performance by TBI patients on RT measures. Traditional neuropsychological testing is often unable to provide an indication of performance variability, since responses on these measures are often recorded in a binary fashion.

Other advantages of computerized neuropsychological testing over the paper-and-pencil variety include: standardization of the stimulus presentation; short administration time/rapid testing; presentation of multiple and equivalent alternative forms of a test within a brief period of time; accurate analysis of performance stability/variability; computerized analysis; centralized data storage, analysis, and reporting; and potential for internet based delivery (McCrory et al. 2005). A study by Bleiberg et al. (1998) compared the performance of MTBI patients with controls on six computerized RT measures of performance and on a standard neuropsychological battery consisting of 12 tasks. 80% of the computerized RT measures properly distinguished MTBI patients from controls, while only 17% of the standard neuropsychological measures differentiated the two groups.

A number of computerized neuropsychological test batteries have been developed in recent years (i.e. CogSport, ImPACT, and HeadMinder), the main impetus for their inception being an increased awareness of the dangers of concussion in sport coupled with the desire of many amateur and professional sports organizations to establish effective return-to-play guidelines for concussed athletes. Traditional neuropsychological tests usually require a trained psychologist to administer, and entail numerous and lengthy testing sessions. These factors render traditional neuropsychological tests, for the most part, impractical for use on-field in sports related contexts. The most widely referenced computerized batteries, however, typically require only about 20 minutes to administer, and can be performed on location by a sports trainer. Each of these batteries assess a number of cognitive processes (for instance, CogSport measures reaction time, information processing, memory, attention, problem solving, and decision making, while ImPACT assesses attention, memory, reaction time, impulse control, and visual processing speed and accuracy). The conventional mode of application is to test players during the pre-season to establish a baseline level of performance for each player, and subsequent to MTBI at regular intervals in order to determine when it is safe for a player to return-to-play (typically when post-concussion scores return to baseline, and the player's subjective complaints have resolved).

While computerized batteries such as CogSport and ImPACT offer a number of practical and theoretical advantages over traditional paper and pencil tests, most computerized tests have yet to be validated for use in assessing sports-related MTBI. It is also important to note that such tests were devised for ascertaining when athletes can safely return to play by evaluating the acute deficits of MTBI, not to assess any chronic deficits that may result from the injury. Nonetheless, several recent studies have used these measures to address the issue of chronic and cumulative effects of sports concussion, and in at least one case concluded that no such effects were evident (e.g. Iverson et al., 2006). It is feasible that, despite being computerized, these tests may lack the requisite sensitivity to detect lingering deficits; a recent meta analysis of the neuropsychological impact of sports-related concussion revealed that the overall effect size associated with existing computerized measures was comparable to that of traditional measures, despite claims in the literature of superior sensitivity. Also, it has been noted that despite randomization routines, these batteries are susceptible to practice effects across sessions; practice effects may be confounded with recovery, thus underestimating the true effect size associated with MTBI (Belanger & Vanderploeg, 2005). Furthermore, unlike the majority of traditional neuropsychological tests, most computerized test batteries are presently limited by the lack of normative data (Collie et al. 2006).

The Current State of MTBI Research

To summarize, it is evident that much more research into the chronic and cumulative effects of mild traumatic brain injury is necessary, especially in unselected samples. It has yet to be proven whether concussion history is related to neurocognitive performance in the post-acute stage of injury; to resolve this issue, it has been recommended that new, highly cognitively demanding measures are developed with enhanced sensitivity to subtle cognitive performance deficits (e.g. Frencham et al, 2005, Iverson et al, 2006). With this need for more sensitive measures in mind, the focus of the current discussion will now shift to perceptual psychophysics, an area of psychology concerned with the quantitative relationships between physical stimuli and the psychological experience thereof.

Psychophysics

Challenging measures of complex reaction time and processing speed that require sustained attention are suggested to be of particular utility in discerning the potential subtle, long-term effects of MTBI (Bernstein, 2002; Mangels et al., 2002). If this is the case, then the methods of psychophysics lend themselves particularly well to this challenge. The properties of perceptual decision-making in normal adults are well established and have been studied for more than a century. With a wealth of normative data available, and the ability of psychophysical judgment tasks to quickly, reliably, and highly accurately assess performance along the dimensions of choice reaction time, accuracy, and subjective accuracy across varying levels of difficulty, there is little question that these tasks are of potential utility in studying the effects of traumatic brain injury.

Typical decision-making challenges in perceptual psychophysics are comprised of two sub-tasks: a primary judgment and a confidence judgment. Initially, participants are asked to make a choice between two stimuli based on an instruction of magnitude, e.g. the brighter (dimmer) of two lights, the louder (softer) of two tones, the shorter (longer) of two lines, etc. Difficulty of the process can be controlled by the experimenter in two ways: by manipulating the relative magnitude of each stimuli that comprise the pair, or by limiting the amount of time allotted for rendering each judgment. After rendering each primary decision, participants are often asked to make a confidence judgement - the degree to which they believe that their decision was correct. Confidence is usually measured on a scale ranging from a guess (50) to complete certainty (100) in increments of 10. By comparing these subjective ratings to actual performance, a number of interesting questions can be answered. For example, how accurate is one's confidence, and to what extent can it be trusted? (Lucas, 2005) Under what conditions do individuals have valid insight into their own performance, and conversely, under what conditions is this insight abysmal? These questions are not only of interest to psychophysicists, but to neuropsychologists as well -- recent evidence suggests that mild traumatic brain injury might affect error awareness and subjective assessment of performance, and future research to assesses confidence in decision-making has been suggested (O'Keefee et al, 2004).

To understand how confidence and accuracy are related requires familiarity with some of the more fundamental properties of human judgment. Research dating back to Henmon (1911) has greatly expounded the relationship between speed, accuracy, and discriminability (i.e. difficulty) in perceptual judgments tasks. One of the most robust findings to emerge from this empiricism is known as the speed-accuracy trade-off. In short, experimental conditions that involve explicit instructions to emphasize decision speed usually elicit significantly faster response times than conditions that emphasize discriminative accuracy. However, when speed is emphasized, accuracy invariably suffers (hence the *trade-off*). However, it has been demonstrated that within a condition that emphasizes accuracy, longer response times are associated with reduced accuracy; when discriminations are very difficult, it takes considerably longer to render a judgment (e.g. when the ratio between line lengths under comparison is very small). Finally, under both accuracy-stress and speed-stress, as judgments become easier, accuracy increases and response time decreases (Lucas, 2005).

How the speed-accuracy trade-off is affected by traumatic brain injury was the focus of a study by Winogran (1986). A series of three experiments compared severely head-injured, mildly head-injured and normal control children on visual measures of simple and complex reaction time. In the first experiment, participants responded to simple visual stimuli with variable foreperiods. It was found that the severely injured group was significantly slower on simple response time overall, but that they did not differ in how they processed probabilistic information about the temporal distribution of the foreperiods. The second experiment used a perceptual judgment task to assess accuracy and response time. Discriminative accuracy did not vary between groups, however the severely injured group took the longest to render correct responses. The third experiment, an extension of the second, revealed that even the severely injured group could speed their judgments in response to an external criterion with only a small decline in accuracy. It was concluded that speed-accuracy tradeoffs were similar across groups (Winogran, 1986), although the pediatric sample limits the generalizability of the findings.

Subjective Probability and Decision-Making

The effect of traumatic brain injury on awareness and subjective probability has been of interest for some time; that the aforementioned study, now over twenty years old, included a measure of probabilistic reasoning attests to this fact. However, the focus of this research has traditionally been on moderate and severe traumatic brain injury, and many of the findings to date are nonetheless inconclusive. Part of the problem in assessing self-awareness or metacognition, is that the terms are amorphously defined, and the tools for their investigation are various and often unsubstantiated. It was recently posited that *online monitoring* of performance during tasks should be examined as an important facet of metacognition, and that to effectively do so would require a multi-modal approach rather than a single measure (O'Keefee et al., 2007). Additionally, there is some evidence to suggest that MTBI impairs an individual's ability to assess and correct errors in judgment. As such, it has been suggested that a future study employ a methodology that allows participants to judge their accuracy after each assessment (O'Keefee et al., 2004) -- the proposed study offers exactly such an approach through the methods of calibration research.

The accuracy of subjective probability -- in other words, the realism of human confidence -- is the embodiment of calibration research. Calibration research entails three normative indices of performance which are used to assess the validity of a set of subjective probability judgments: calibration, under/overconfidence (bias), and resolution (Baranski & Petrusic, 1997).

Calibration. An index of the accuracy of confidence judgments, calibration measures one's ability to match subjective probability, as represented by discrete confidence categories, with actual proportion of correct answers for those categories over a number of trials. For example, in order for perfect calibration to occur, an individual must be correct 60% of the time when assigning a probability of .60 to a proposition, 90% of the time when a probability of .90 is assigned, and so forth. In other words, over N trials, subjective probability will ideally equal the relative frequency correct for each discrete confidence category utilized. The *calibration* index is defined by

$\frac{1}{n}\sum_{j=1}^{J} n_j(\bar{p}_j - \bar{e}_j)^2$, where $\bar{p}_j$ and $\bar{e}_j$ denote mean proportion confidence and mean proportion correct in confidence category j, n_j denotes the number of observations for confidence category j, and n is the total number of observations (Petrusic & Baranski, 1997). The range for a calibration score is from 0 (optimal), to 1 (abysmal). Confidence/accuracy scores can be plotted as a calibration curve, with percent confidence on the abscissa, and percent correct on the ordinate. To construct a calibration curve:

1. Collect numerous probability assessments for each discrete proposition used in the experiment.
2. Group assessments into categories according to the probability assigned by participants.
3. Within each category, calculate the proportion correct.
4. For each category, plot the mean confidence response against percent correct

(Lichtenstein & Fischhoff, 1977).

Perfect calibration is represented by scores that lie along the diagonal identity line, which connects the corresponding probabilities with their ideal percent correct (i.e., .5 with 50%, .6 with 60%, etc.). Poor calibration is associated with curves that lie above the identity line (underconfidence), and below it (overconfidence).

Under/overconfidence (bias). Under/overconfidence is another index used to determine performance in calibration research. Judgments are overconfident when the mean proportion confidence exceeds the mean proportion correct. Alternatively, judgments are underconfident when the assessed probabilities are lower than the proportion correct. *Under/overconfidence* is defined as $\bar{p} - \bar{e}$, where $\bar{p}$ denotes mean proportion confidence (subjective probability), and $\bar{e}$ is mean proportion correct (Petrusic & Baranski, 1997). A positive score is indicative of overconfidence, whereas a negative score indicates underconfidence.

Resolution. Resolution measures the degree to which participants can use their confidence ratings to distinguish correct from incorrect judgments. A horizontal (flat) calibration curve shows no resolution, whereas a steep curve indicates excellent resolution. *Resolution* is defined by $\frac{1}{n}\sum_{j=1}^{J} n_j(\bar{e}_j - \bar{e})^2$. Resolution scores are typically normalized by the "knowledge index", $\bar{e}(1-\bar{e})$. The resulting score, η^2 ranges from 0 - 1, with a higher score indicating better performance (Petrusic & Baranski, 1997).

To date, no studies have directly investigated the affect of MTBI on the calibration and resolution of confidence judgments. Even normal populations are only moderately well calibrated in this regard -- an over/under confidence phenomenon and even total miscalibration can occur under certain conditions (Baranski & Petrusic, 1999; Kemp, 2003).

Hypotheses

H1. Since MTBI has been shown to induce deficits in processing speed (e.g. choice RT), and repeated injuries are thought to be associated with a cumulative effect, participants with a history of two or more MTBIs are expected to perform significantly more slowly, and with more response time variation, on difficult choice reaction-time judgments than participants with a history of one or no prior brain injuries.

H2. Since recent empirical findings suggest that 1) general higher-order cognitive deficits in MTBI are mediated by deficits in speed of mental processing, and 2) the extent to which processing demand is manipulated may be the critical factor in discerning chronic deficits in MTBI (Bernstein, 2001), then accuracy of decision in the accuracy-stress condition is not expected to be significantly affected. Accuracy differences, however, are hypothesized to surface under the speed-stress condition, since the subtle deficits in processing speed expected to have resulted from repeated diffuse axonal injury in the multiple-MTBI group should further compound the well documented speed-accuracy trade-off phenomenon that results when individuals are forced to render a perceptual decision under a strict time constraint. Thus the multiple MTBI group is expected to perform worse on proportion correct than the single- and no-MTBI groups when judgments are rendered under speed-stress.

H3. Hypotheses concerning calibration of confidence judgments are based on several lines of evidence. Working memory deficits in the acute stage of MTBI are a robust finding in the neuropsychological literature. Should this deficit become chronic with repeated injury (recent evidence suggests that the axonal projections of the cholinergic system, widely implicated in memory processes, are damaged by MTBI) then confidence judgments -- especially under the speed-stress condition -- are expected to be more highly miscalibrated in the multiple concussion group since confidence is processed entirely post-decisionally when under the speed-stress condition (for a discussion on the locus of confidence processing, Baranski & Petrusic, 1998), and thus is reliant, at least to some extent, on working memory processes.

H4. Resolution measures the degree to which individuals can use their subjective confidence ratings to distinguish correct from incorrect judgments. It was recently suggested that MTBI impairs an individual's ability to assess and correct errors in judgment (Faidhnait et al., 2004). Thus, the multiple MTBI group should perform more poorly on resolution than the single- and non-MTBI groups.

Methods

Participants

Eligible participants for this study were identified through the 2006 mass testing questionnaire for Psychology 1001/1002, where students were asked “Have you had a head injury or concussion in which you lost consciousness, even if only briefly?”, and “If so, how many times?”. Since the purpose of study was to investigate the post-acute (i.e. chronic, greater than three months post-injury) effects of MTBI, participants with recent injury (< 3 months post-injury) were excluded. Since the cumulative effects of MTBI were also of primary interest, the design consisted of three groups: 1) participants with a history of one MTBI; 2) participants with a history of two or more MTBIs; and 3) control participants with no history of brain injury. Glasgow Coma Scale classification for mild head injury (GCS score of 13-15) was used as upper limit cutoff for MTBI participants, such that reported loss of consciousness (LOC) did not exceed 30 minutes, posttraumatic amnesia (PTA) did not exceed 12 hours post-injury. Participants received 1.5 percent course credit for taking part in the study.

Measures

Many factors, both neurological and non-neurological, can significantly affect an individual's cognitive test scores, before and after a MTBI. These factors include past history, including previous concussions, other head injuries, educational background, previous testing, drug and alcohol use; psychological factors, including test anxiety, depression and other emotional states; genetic factors, including age, intelligence, sex, handedness, visual acuity, auditory acuity; methodological factors, including testing situation, practice/learning effects, administrator expertise, and; other factors, including cognitive function, test setting/distractions, motivation, fatigue, random variance/chance (McCrory et al., 2005). The present study attempted to control for a large number of these factors by administering a comprehensive background questionnaire in addition to depression and post-concussion symptom scales.

Rivermead Post-concussion Questionnaire (RPQ). Since the relationship between post-concussion symptoms (PCS), MTBI factors, and neuropsychological performance - especially beyond the acute stage of recovery - is highly ambiguous, a measure of PCS was included in this study. While a number of different (albeit very similar) measures for assessing PCS exist, the most popular is the Rivermead Post Concussion Symptoms Questionnaire (King, Crawford, Wender, Moss & Wade, 1995). The RPQ consists of 16 items, and patients are asked to rate, on a scale of 0 to 4, the degree to which each item (symptom) is currently a problem relative to premorbid (i.e. pre-injury) levels. The most common convention in assessing PCS is to ask each participant to what degree each symptom has been a problem in a period of time preceding the evaluation (i.e. during the past two weeks). The RPQ was modified for the proposed study, since control participants with no history of MTBI were also be required to fill out the questionnaire. Participants were asked to rate symptom severity in the previous 2 weeks. The total score was calculated by summing the individual symptom scores (range = 0 to 64).

King et al. (1995) assessed the RPQ's reliability when used as a self-report questionnaire administered by patients themselves, as well as the inter-rater reliability when used as a questionnaire administered by two different clinicians. Since the specific symptoms experienced have been shown to vary over time within individuals, as well as between individuals, total score was the dependent measure used in the study. It was found that the RPQ is reliable in rating the PCS total score, irrespective of administration type, during both the acute and chronic stages of recovery. The authors reported some differences in the reliability of individual symptom ratings, it was concluded that these discrepancies are not significant enough to detract from the questionnaire's overall robustness.

Center for Epidemiologic Studies Depression Scale (CES-D). The Center for Epidemiologic Studies Depression Scale or CES-D (Radloff, 1977) freely available and widely used self-report scale was designed to identify depression among the general population. The CES-D consists of 20 items, and is a well-validated and reliable self-report measure of depressive symptoms. Furthermore, the CES-D has been demonstrated to be appropriate for use in patients with mild-to-moderate TBI (McCauley et al., 2006). Because depression may follow a MTBI, and depressed individuals have been shown to report higher rates of PCS symptoms than normal controls (Gunstad & Suhr, 2001), and since postconcussion-like symptoms are highly correlated with depressive symptoms in healthy non-head injured individuals (Iverson & Lange, 2003), this brief inventory was included to allow for statistical control of this potential confound.

Concussion History Questionnaire. Participants were asked to fill out a self-report questionnaire that assessed 1) the number of past concussions involving a loss of consciousness, 2) how each concussion was sustained 3) whether it was formally diagnosed and by whom (e.g. sports trainer, family doctor, visit to the ER). This questionnaire was developed for the present study.

Background Information Questionnaire. GPA, years of formal education including post-secondary schooling, sex, handedness, age, average number of alcoholic beverages consumed per week, diagnosed learning disabilities, and diagnosed psychiatric disorders were assessed with this questionnaire.

Paced Auditory Serial Addition Test (PASAT). The Paced Auditory Serial Addition Test (Grunwall, 1977) is a test of sustained attention and working memory that has demonstrated efficacy in detecting subtle deficits subsequent to MTBI (Frencham et al., 2005). The PASAT was included as a benchmark measure against which to compare the sensitivity of the novel psychophysics measure. Participants listened to a series of numbers, and attempted to add consecutive pairs as they listened. Numbers were presented at even intervals within conditions, at a rate of every 2 seconds and 1.6 seconds, respectively. The dependent variable is the total number of correct sums given in each trial.

Apparatus

The experimental apparatus consisted of a personal computer with an Intel Celeron D processor, 512 megabytes of system memory, and Microsoft Windows XP operating system. Stimuli were displayed on a 17" monitor set to a resolution of 800x600 pixels. A task-specific response panel was constructed exclusively for the experiment using a standard 104 key serial keyboard. Individual keys not necessary for the task were removed, and the underlying space was covered with a faceplate constructed with laminated cardboard. The resulting panel consisted of an array of nine buttons in two rows. The bottom row consisted of two keys labeled "L" (left) and "R" (right), which were used to render each primary judgment. The top row, used only during confidence trials, contained seven keys, labeled "50", "60", "70", "80", "90", "100", and "X", respectively. These keys were used to assess confidence -- the former six for probabilistic assessments, and the latter key to designate a perceived error in judgment. Proximity between the two rows of keys, as well as adjacent keys in the same row, was 20mm.

Stimuli and Design

Stimuli were designed with Adobe Photoshop CS2, and the experiment was programmed and executed with Superlab Pro. During each trial, the computer displayed and instruction (SHORTER or LONGER) followed by two horizontal lines on the screen, presented in a side-by-side orientation. Each line extended laterally from a point 5mm left or 5mm right, respectively, from the central vertical axis of the screen, thus leaving a 10mm blank space between the two lines. The lines appeared black on a white background. Six pairs of lines were used, as follows, with the bracketed sections indicating the respective line lengths of each pair in pixels (left, right): (101, 100) or (100, 101); (102, 100) or (100, 102); (104, 100) or (100, 104); (106, 100) or (100, 106); (108, 100) or (100, 108) and (110, 100) or (100, 110). The relative *a priori* difficulty of these pairs, as determined by their ratio, was: 1.01, 1.02, 1.04, 1.06, 1.08, and 1.10, from most difficult to easiest, respectively.

The computerized portion of the experiment was structured into two successive conditions (accuracy-stress and speed-stress), each with three sessions (no confidence, confidence, no confidence) divided into four blocks of 24 individual trials. Trials in each block arose from the randomized factorial combination of the six stimulus pairs, two possible presentation orders for each pair, and two possible instructions.

For both groups, a confidence judgment was not required during the first and third sessions; the third session served to replicate the first, and to serve as a measure of sustained attention during the experiment. During the second session, after each individual trial participants were instructed by the computer to render a confidence judgment. During the accuracy-stress condition, participants were instructed to emphasize accuracy over speed, and were allowed an unlimited amount of time to render each decision. In the speed-stress condition, participants were issued a response deadline of 500ms to render each primary judgment. For each decision that exceeded the deadline, the message "Primary decision was too slow" was presented on the screen. Confidence judgments for both the accuracy-stress and speed-stress conditions proceeded without a deadline. For a schematic representation of the perceptual judgment and confidence task, see Appendix A.

Procedure

Prior to performing the experiment, each participant was asked to carefully read the informed consent form, and decide whether or not they wanted to participate in the study. Participants were informed of their right to discontinue the experiment at any time, should they not wish to continue. Upon consenting, the computerized portion of the experiment was initiated. Participants were asked to read the instructions presented on screen (every session was preceded by a set of instructions), and any points requiring clarification were addressed. Sessions were performed in succession, with rest periods between sessions as well as blocks. Participants controlled how long they rested before initiating the next block or session. The accuracy-stress condition was presented first, followed by the speed-stress condition for all participants; conditions were not counter-balanced in order to mitigate boredom during the testing session (pilot testing revealed that the experiment was perceived as less monotonous if the speed-stress condition followed the accuracy-stress condition).

During the first and third sessions for both conditions, confidence was not required and participants were instructed to ignore the top row of buttons. During these sessions, participants were instructed to use only the "L" (left), "R" (right) keys. Trials were initiated automatically following a 1000ms break subsequent to end of the previous trial. At the beginning of each trial, the computer displayed an instruction on the screen (LONGER or SHORTER), indicating which of the two subsequently displayed lines is to be selected. The instruction appeared in the centre of the screen, followed 1000ms later by the stimulus pair. The lines remained on the screen until the participant made a decision by pressing either the "L" or the "R" button on the response panel.

Prior to initiating the second session (confidence trials), participants were informed that, for this session, a confidence judgment was required after each primary judgment had been rendered. After each primary judgment was rendered, the computer displayed the word "CONFIDENCE" on the screen, prompting the participant to select the value on the input panel that corresponded most accurately with his or her subjective sense that they have selected the correct line. During the third session -- a replication of the first -- participants were again instructed to ignore the confidence keys as they did during the first session.

During all sessions, participants were informed that their responses were being timed. Participants were carefully instructed, however, to emphasize accuracy over speed in the accuracy-stress condition, and speed over accuracy in the speed-stress condition. After completion of the experiment, participants were administered the questionnaire package, followed by the two PASAT trials. Participants were subsequently debriefed, and any questions and/or concerns that they had about the study were addressed.

Results

Data sets for eight participants were excluded from the analysis for the following reasons: corrupted data due to a power-failure during the testing procedure ($n = 1$); response time > 4 standard deviations above the grand mean ($n = 1$); failure to properly comply with instructions during the testing session ($n = 4$); and diagnosed learning disability, ($n = 2$). Of the remaining 67 participants, 25 were in the control group, 23 in the one concussion group, and 19 in the two or more concussion group. Prior to conducting statistical analyses, data sets were examined for influential outliers and violations of normality and homogeneity of error variance. For all repeated-measures analyses, significance testing was based on Huynh-Feldt adjusted degrees of freedom when the assumption of sphericity was violated; however degrees of freedom reported are those specified by the design. Significance was set at $\alpha = .05$ for all statistical tests.

Frequencies of males and females between groups was not significant $\chi^2(2, N = 67) = 4.02, p =.17$. Participants ranged in age from 18 to 36 years ($M = 20.35$, $SD = 3.19$). Difference in age between groups was also not significant $F(2,64) = 1.74, p = .18$. Neither GPA ($M = 6.49$, $SD = 1.74$), or average alcohol consumption ($M = 4.52$, $SD = 5.30$) were significantly different between groups, $F < 1$, and $F(2,63) = 1.46, p = .24$, respectively. The three groups were thus well matched on gender, age, GPA and average alcohol consumption.

RQP and CESD

Total RPQ scores ranged from 1 to 37 out of a possible total of 64, ($M = 17.46$, $SD = 10.15$). RPQ did not differ significantly between groups $F(2,63) = 1.35, p = .27$. Total

CESD scores ranged from 0 to 21 out of a possible total of 30 ($M = 8.10$, $SD = 4.43$. CESD score also did not differ significantly between groups $F(2,63) = 1.21$, $p = .31$. RPQ and CESD were strongly positively correlated, $r(66) = .66$, $p < .001$. A one-sample T-Test revealed that the overall RPQ score for the control group was significantly different from zero, $t(24) = 9.61$, $p < .001$, which suggests that post-concussion symptoms are not specific to traumatic brain injury.

PASAT

Groups did not differ significantly on either the 2 second test pace, $F < 1$, or the 1.6 second test pace, $F < 1$. The group x PASAT level interaction was also non-significant $F(2,63) = 1.41$, $p = .25$.

Accuracy Analyses: Difficulty

A repeated-measures analysis of variance was conducted with *a priori* difficulty level (the six stimulus pairs) and condition (accuracy, speed) as the within-subjects factors, concussion group as the between-subject factor, and proportion of correct responses as the dependent variable. There was a significant between-subjects main effect of concussion group on proportion of correct responses, $F(2,64) = 3.86$, $p = .026$. Post hoc analyses using the Tukey criterion for significance indicated that only the one concussion group ($M = .75$, $SD = .04$) and the multiple concussion group ($M = .71$, SD = .06) differed significantly, $p = .03$, however the difference between the multiple concussion group and the control group ($M = .74$, $SD = .05$) approached significance, $p = .06$. Alternatively, an *a priori* linear contrast revealed that mean proportion correct for the multiple concussion group was significantly lower than the average mean of the other two groups, $t(64) = 2.79$, $p = .007$ (two-tailed), consistent with the hypothesis of a cumulative effect of concussion (i.e. that deficits in discriminative accuracy would emerge only for the multiple concussion group). However, when the data was analyzed separately by condition, the main effect of group was reliable for accuracy-stress, $F(2,64) = 3.41$, $p = .04$, but not for speed-stress, $F(2,64) = 2.39$, $p = .10$. These findings are depicted in Figure 1. The interaction between concussion group and condition was not significant, $F < 1$.

Insert Figure 1 about here

As expected, there was a highly significant within-subjects main effect of *a priori* difficulty (stimulus pair) on proportion of correct responses, $F(5, 320) = 434.63$, $p < .001$. The top panel of Figure 2 illustrates that, for all groups, accuracy declined as pairs of lines became more difficult to discriminate, and vice-versa. The group x difficulty interaction, however, was not significant, $F<1$.

Insert Figure 2 about here

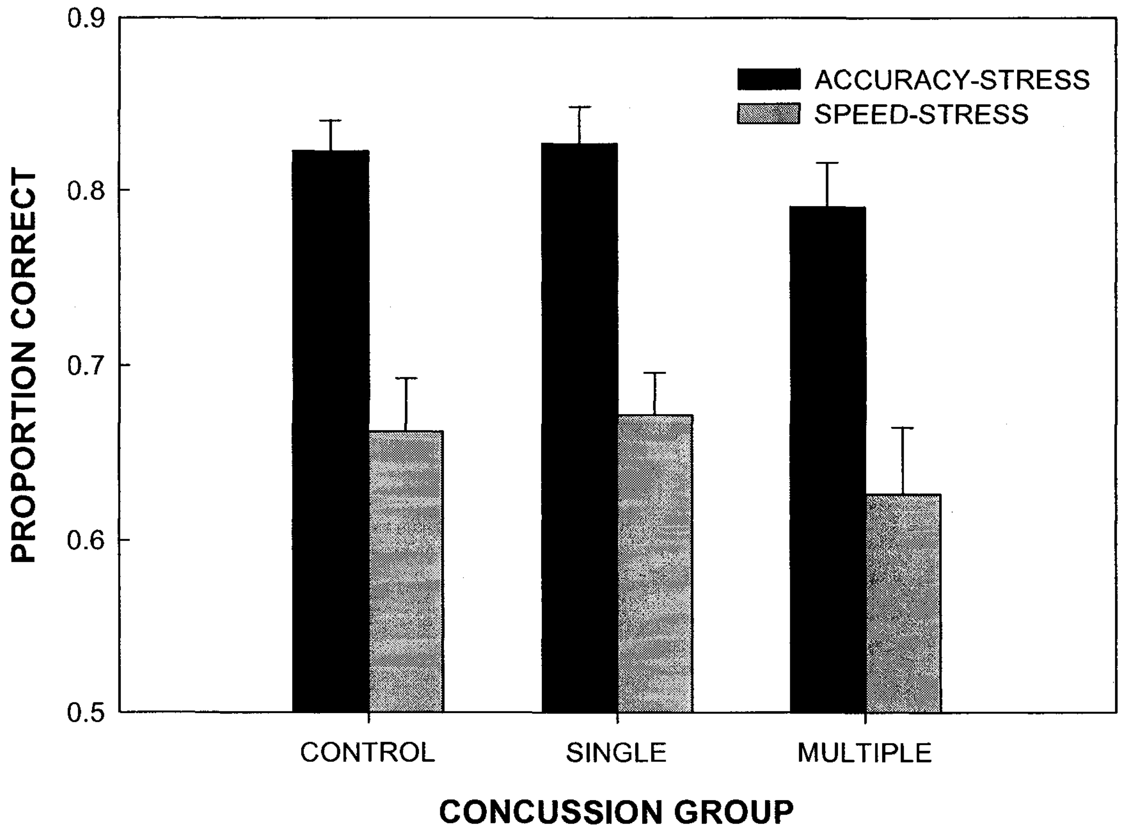

Figure 1. Mean proportion correct for accuracy-stress and speed-stress conditions by concussion group.

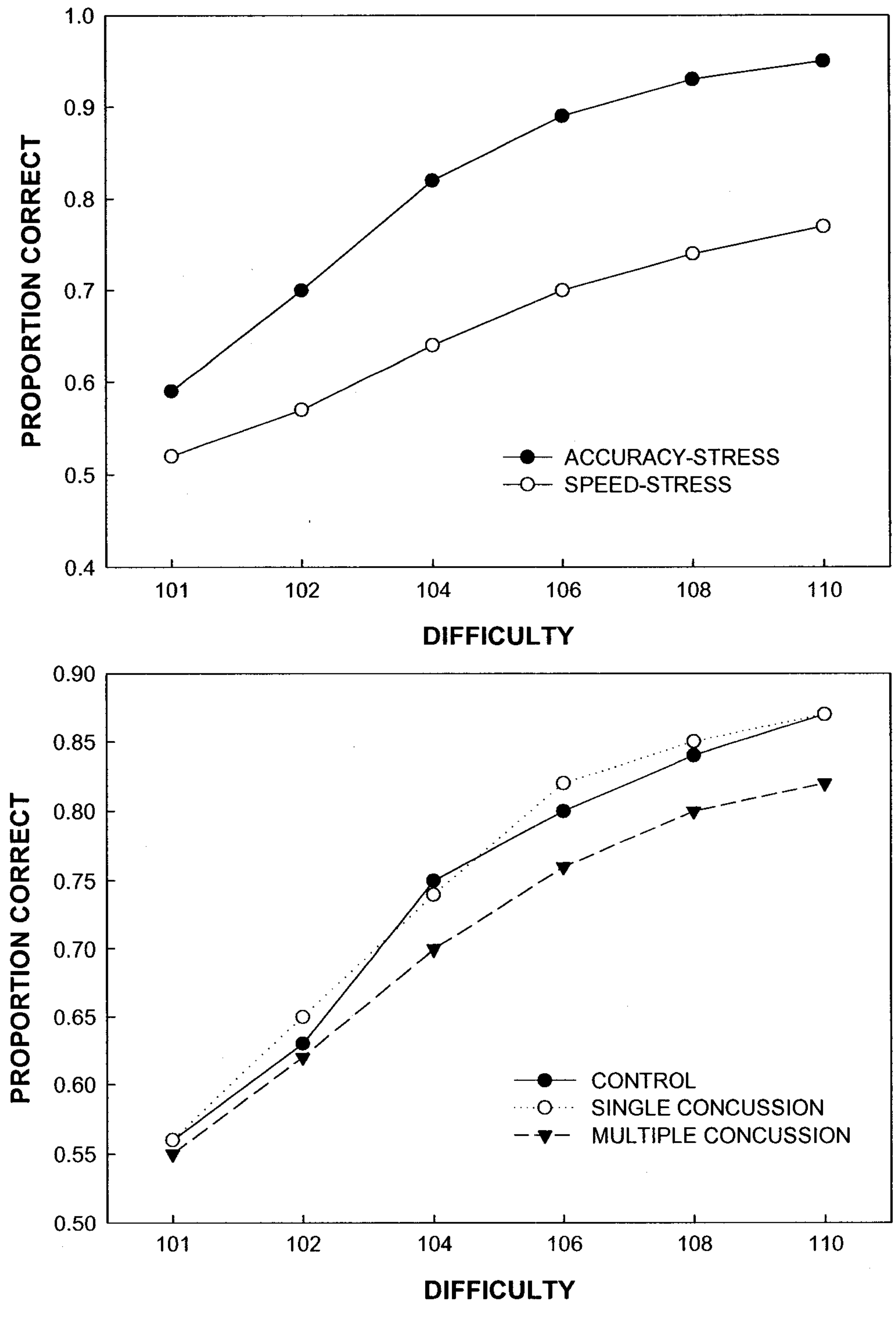

Figure 2. Mean proportion correct by difficulty and condition (top) and by concussion group (bottom).

There was a highly significant within-subjects main effect of condition on proportion of correct responses, $F(1,64) = 422.62, p < .001$. As expected, participants were significantly more accurate in rendering decisions under accuracy-stress ($M = .82$, $SD = .05$) than they were under speed-stress ($M = .67$, $SD = .07$), exemplifying the classic speed-accuracy trade-off. The difficulty x condition interaction was also significant, $F(5,320) = 23.87, p <.001$. It is evident from the bottom panel of Figure 2 that for all groups, as pairs of stimuli became more difficult to differentiate, the disparity between proportion of correct responses for the respective conditions increased. This suggests that easier decisions are more adversely affected by constraints on decision time; in other words, in the absence of a decisional deadline, fairly easy comparisons are rendered with a high degree of accuracy. However, as comparisons become very difficult (i.e. as they begin to approach the limits of perceptual ability), increased decision time beyond a certain point does not further facilitate discriminative accuracy. The three-way difficulty x condition x concussion group interaction was not significant, $F < 1$, indicating that the aforementioned property did not differ as a function of concussion group.

Accuracy Analyses: Session and Block

A repeated-measures analysis of variance was conducted with session, block and condition as the within-subjects factors, concussion group as the between-subjects factor, and proportion of correct responses as the dependent variable. The within-subjects main effect of block on proportion of correct responses was marginally significant, $F(3,192) = 2.50, p = .06$. Accuracy declined very slightly with each successive block, probably an indication of fatigue ($M = .74, .74, .73$, and $.73$ for blocks one through four, respectively).

The block x concussion group interaction was non-significant, $F(6,192) = 1.85, p = .09$, however, from Figure 3 it is evident that the multiple concussion group displayed the largest decline in accuracy across blocks.

Insert Figure 3 about here

There was a significant within-subjects main effect of session on proportion of correct responses, $F(2,128) = 22.27, p < .001$. A series of Tukey adjusted paired-sample T-Tests revealed a non-significant increase in proportion of correct responses from session 1 ($M = .74$, $SD = .05$) to session 2 ($M = .75$, SD = .06), $t < 1$, and significant decreases in accuracy from session 1 to session 3 ($M = .72$, $SD = .06$), $t(66) = 5.19, p < .001$, and session 2 to session 3, $t(66) = 5.73, p < .001$. There was also a significant session x condition interaction, $F(2,128) = 8.99, p < .001$; Figure 4 illustrates that proportion of correct responses drops off substantially during session three of the speed-stress condition. This is likely indicative of fatigue and/or boredom, since this was the last session presented during the task. The session x concussion group interaction was not significant, $F < 1$, nor was the session x condition x concussion group interaction, $F < 1$, thus the aforementioned findings did not differ as a function of concussion group.

Insert Figure 4 about here

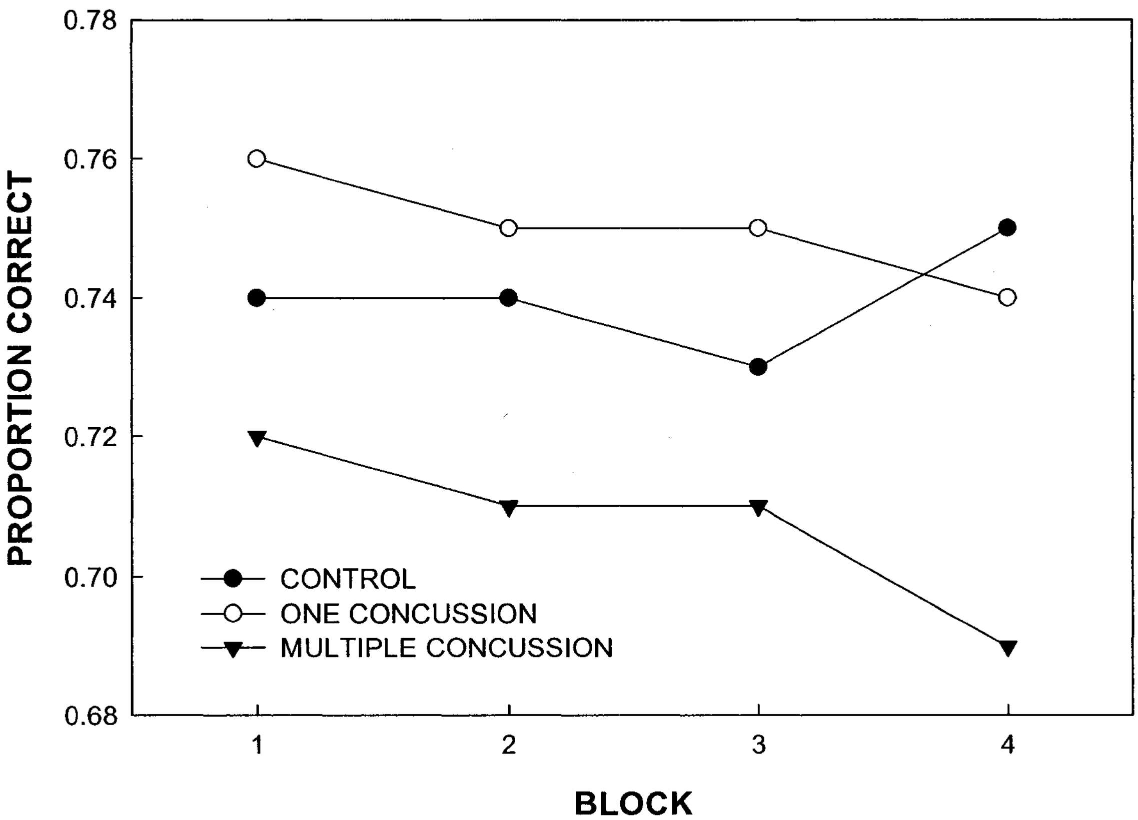

Figure 3. Mean proportion correct by block and concussion group.

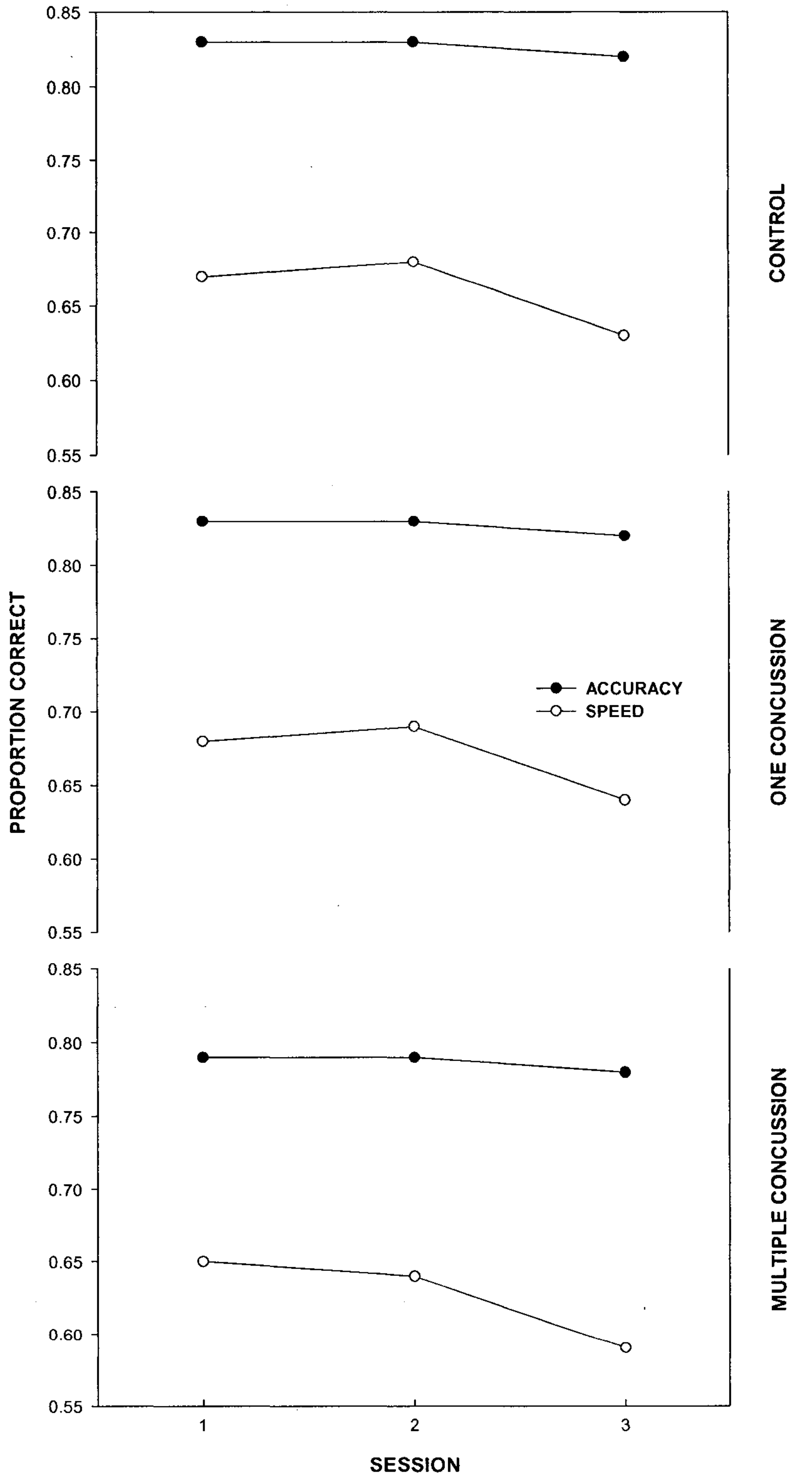

Figure 4. Mean proportion correct by condition and concussion group.

Response Time (RT) Analyses: Difficulty

A repeated-measures analysis of variance was conducted with *a priori* difficulty level and condition as the within-subjects factors, concussion group as the between-subject factor, and response time as the dependent variable. Response time did not reliably differ between concussion groups, $F < 1$. However, it is interesting that the one concussion group exhibited the highest overall mean response time ($M = 1292.39$, $SD = 424.45$), while, contrary to expectation, the multiple concussion group performed the fastest ($M = 1139.08$, $SD = 321.50$).

As expected, there was a highly significant within-subjects main effect of *a priori* difficulty on response time, $F(5,320) = 100.97$, $p < .001$. Figure 5 demonstrates that response time increased monotonically as a function of comparison difficulty. This effect was similar for all concussion groups; the difficulty x group interaction was non-significant, $F < 1$. The within-subjects main effect of condition was highly significant, $F(1,64) = 251.08$, $p < .001$, also evident in Figure 5. As expected, response times were considerably slower under accuracy-stress ($M = 2002.14$, $SD = 810.59$) than they were under speed-stress ($M = 425.54$, $SD = 56.53$). Also expected was the significant within-subjects difficulty x condition interaction, $F(5,320) = 99.94$, $p < .001$. During accuracy stress, response time was positively related to decision difficulty, while under speed stress, response time was similar for all levels of difficulty, reflecting the presence of the 500ms response deadline in the latter condition. The two-way group x condition interaction, $F < 1$, and three-way group x condition x difficulty interaction were both non-significant, $F < 1$.

Insert Figure 5 about here

RT Analyses: Session and Block

A repeated-measures analysis of variance was conducted with session, block and condition as the within-subjects factors, concussion group as the between-subjects factor, and RT as the dependent variable. There was a significant within-subjects effect of block on RT, $F(3,192) = 27.73, p < .001$. Response times decreased with each successive block, ($M = 1297.99$, 1229.32, 1178.98, and 1151.37 for blocks one through four, respectively) indicating that participants became quicker with practice. However, Figure 6 and the significant block x condition interaction, $F(3,192) = 26.16, p < .001$, indicate that this main effect of block was a function of the accuracy-stress condition. During speed-stress, response times -- irrespective of block -- remained relatively uniform and quick.

Also significant was the within-subjects main effect of session on response time, $F(2,128) = 37.83, p < .001$, and the session x condition interaction, $F(2,128) = 27.98, p < .001$. The lower panel of Figure 6 depicts the effect of rendering confidence on primary decision time, separately for each condition. During accuracy-stress, response time for session two (when post-decisional confidence judgments were required) was substantially higher than for sessions one and three (when no confidence judgments were required). During speed-stress, response time was much more uniform across sessions, reflecting the

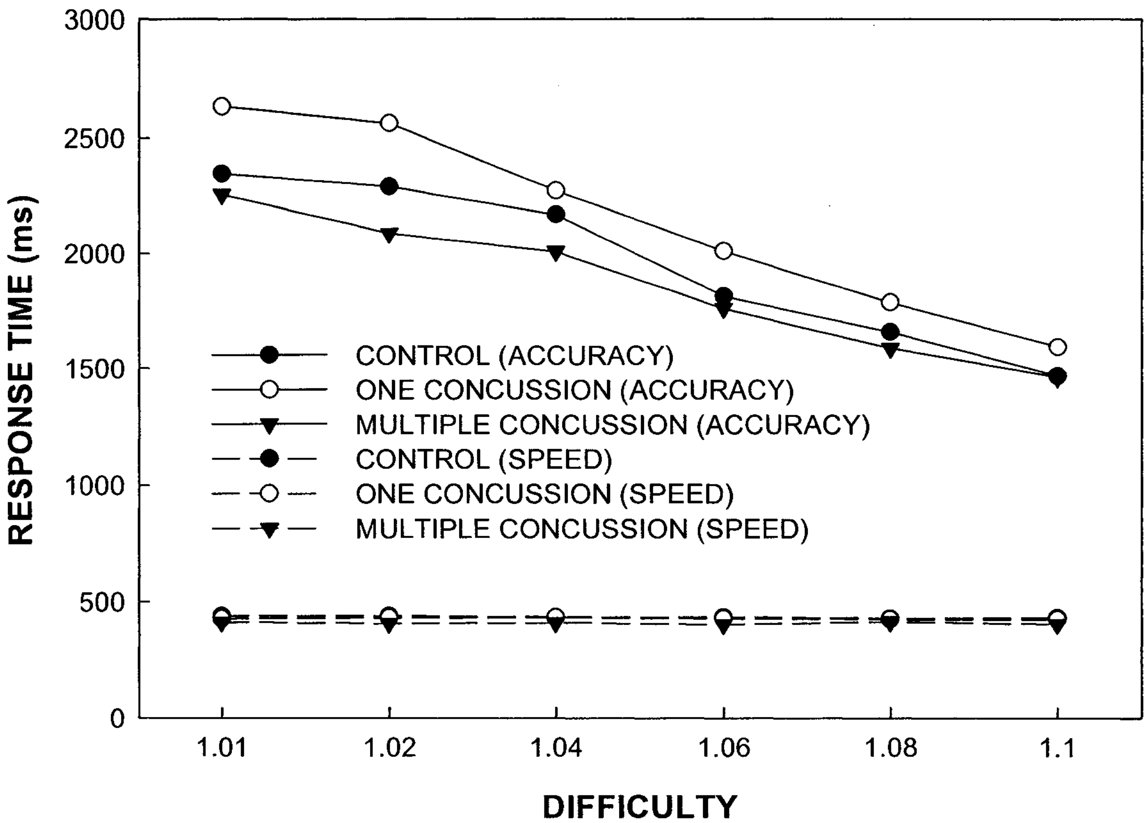

Figure 5. Mean response time by condition and concussion group.

presence of the 500ms deadline for that condition. This supports previous findings of a (partially) decisional locus of confidence processing under accuracy-stress.

Insert Figure 6 about here

Response Time: Correct vs. Error

It is well established that when instructions to emphasize accuracy are effectively implemented in psychophysical experiments, the response time for errors are typically much longer than for correct responses under accuracy-stress, whereas under speed-stress, errors are usually slightly quicker (Lucas, 2005). Also, Halterman et al. (2006) recently found that the RT cost to generate accurate versus inaccurate responses was significantly larger in participants with recent MTBI than controls, a finding that did not diminish during the one month post-injury testing period. An ANOVA was conducted with response (correct, error) and condition as the within-subjects factors, concussion group as the between-subjects factor and response time as the dependent measure. There was a significant main effect of response, $F(1,64) = 109.08, p < .001$, a significant effect of condition, $F(1,64) = 244.94, p < .001$, and a significant response x condition interaction, $F(1,64) = 118.93, p < .001$. However, the concussion group x response interaction was not significant, $F < 1$. It is evident from Figure 7 that errors made under accuracy-stress took considerably longer than correct responses. Conversely, under speed-stress, errors were slightly quicker than correct decisions.

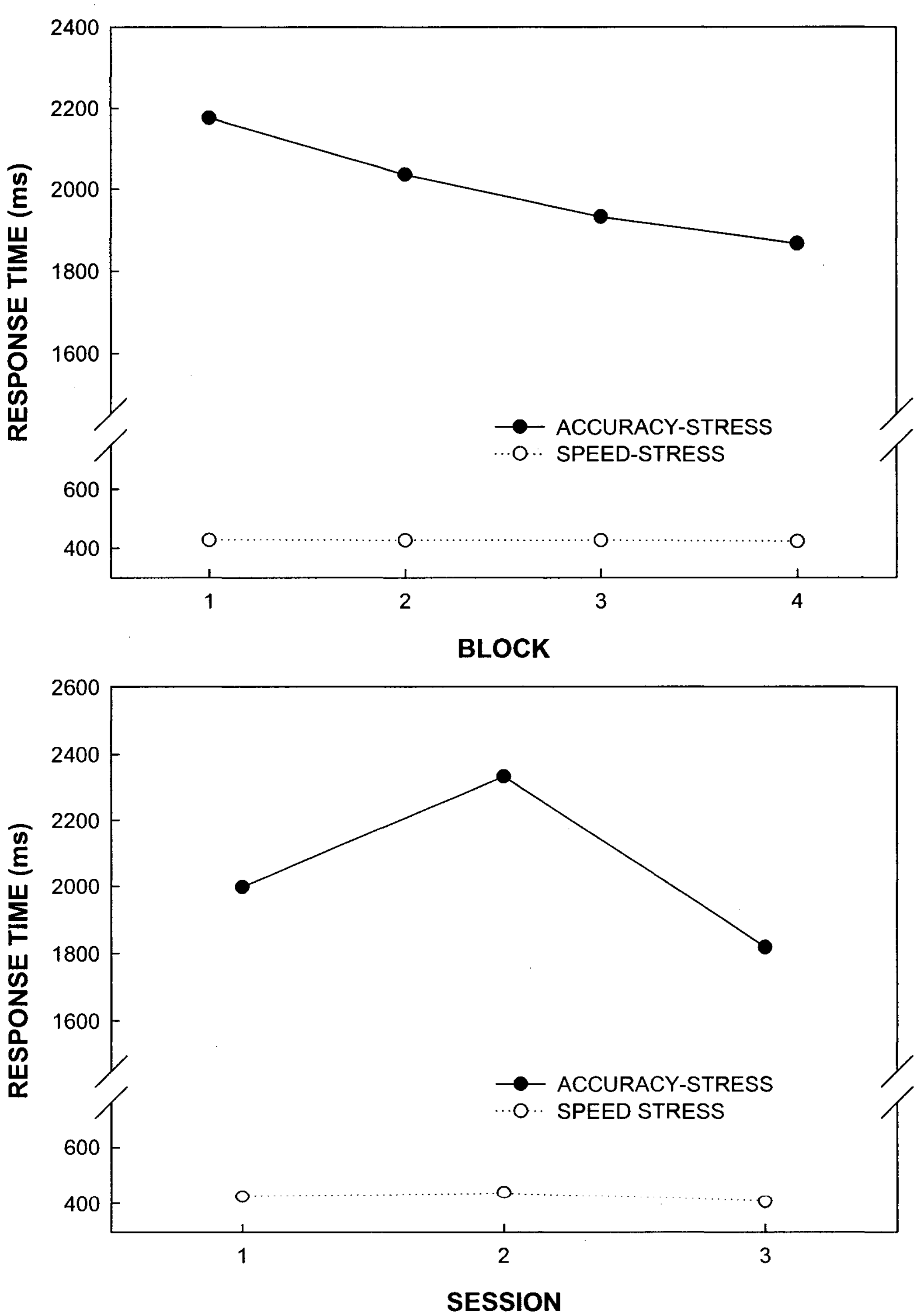

Figure 6. Mean response time by block and condition, and by session.

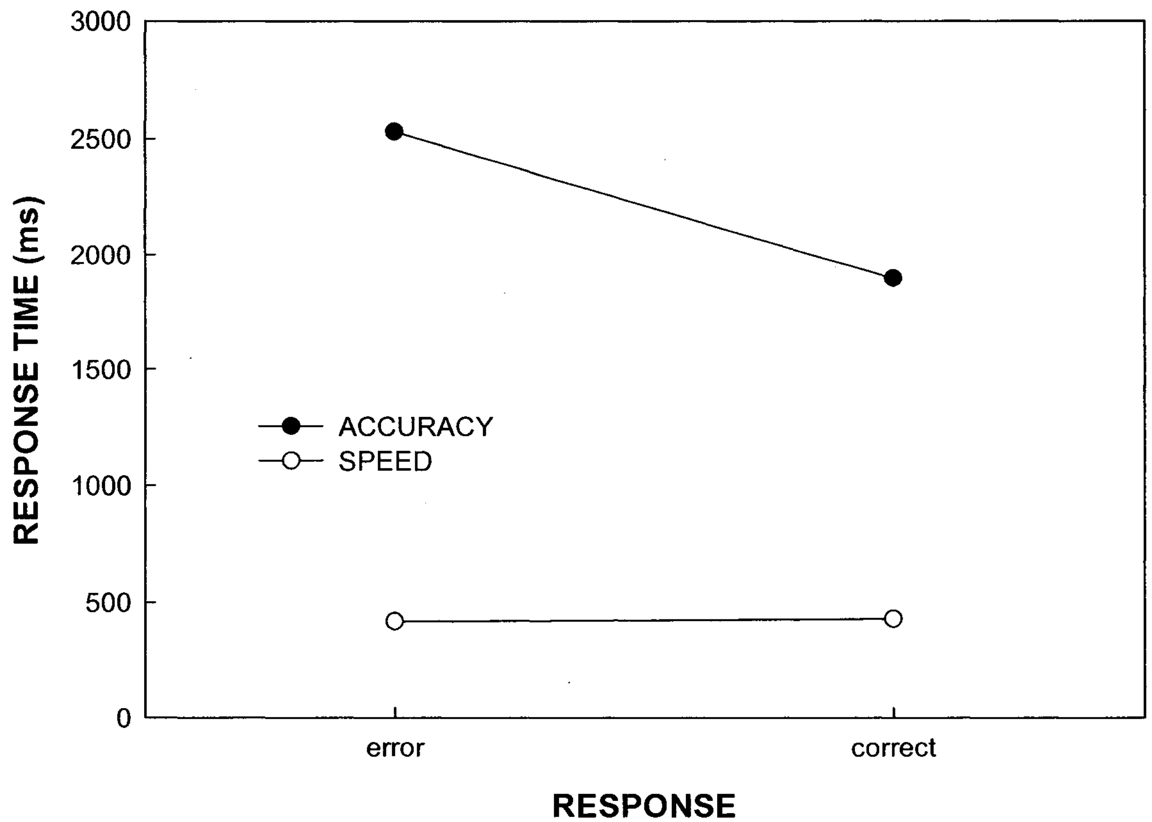

Figure 7. Mean response time for correct responses and errors, by condition.

Insert Figure 7 about here

Response Time Variability Analysis

It was hypothesized that the multiple concussion group would demonstrate increased variability in response time relative to the one concussion and control groups. However, an ANOVA revealed that groups did not differ significantly in this regard, either for accuracy-stress, $F(2,64) = 2.82$, $p = .12$, or speed-stress judgments, $F < 1$.

Error Awareness

On trials where confidence was rendered, participants were instructed to press the 'error' key subsequent to each perceived mistake (i.e. when they accidentally chose the wrong line). During accuracy-stress, only 64 errors were reported by all participants on a total of 6432 confidence trials (1%). The control group reported an average of .65 errors per participant, the one concussion group .91 per participant, and the multiple concussion group reported 1.37 errors per participant; the groups correctly reported errors 65%, 81%, and 46% of the time, respectively. From the low number of errors reported under accuracy-stress, it is evident that, in general, participants had little knowledge of when they had actually made an error. Under speed-stress, however, participants used the error key on 696 of the 6432 trials (11%). The control, one concussion and multiple concussion groups reported 10.04, 9.74, and 11.63 errors per participant, respectively, correctly assessing errors 78%, 76%, and 72% of the time. Taken together, it is evident that 1) participants were much more aware of having made errors under speed-stress than under accuracy-stress, and 2) the multiple concussion group were slightly less adept at correctly assessing errors than were the control and one concussion groups. Due to the number of empty cells, however, these results were not subject to formal significance testing, and thus must be interpreted cautiously.

Confidence Judgments

A repeated-measures ANOVA was conducted with difficulty and condition as the within-subjects factors, concussion group as the between-subjects factor, and mean confidence rating as the dependent variable. The effect of concussion group on mean confidence rating was not significant, $F < 1$. The within-subjects effect of difficulty was significant, $F(5,320) = 149.34$, $p < .001$; it is evident from Figure 8 that mean confidence rating was inversely related to comparison difficulty. As stimuli became more difficult to discriminate, confidence decreased, and vice-versa. While the effect of condition was not significant, $F < 1$, there was a significant difficulty x condition interaction, $F(5,320) = 12.93$, $p < .001$, depicted in the lower pane of Figure 8.

Insert Figure 8 about here

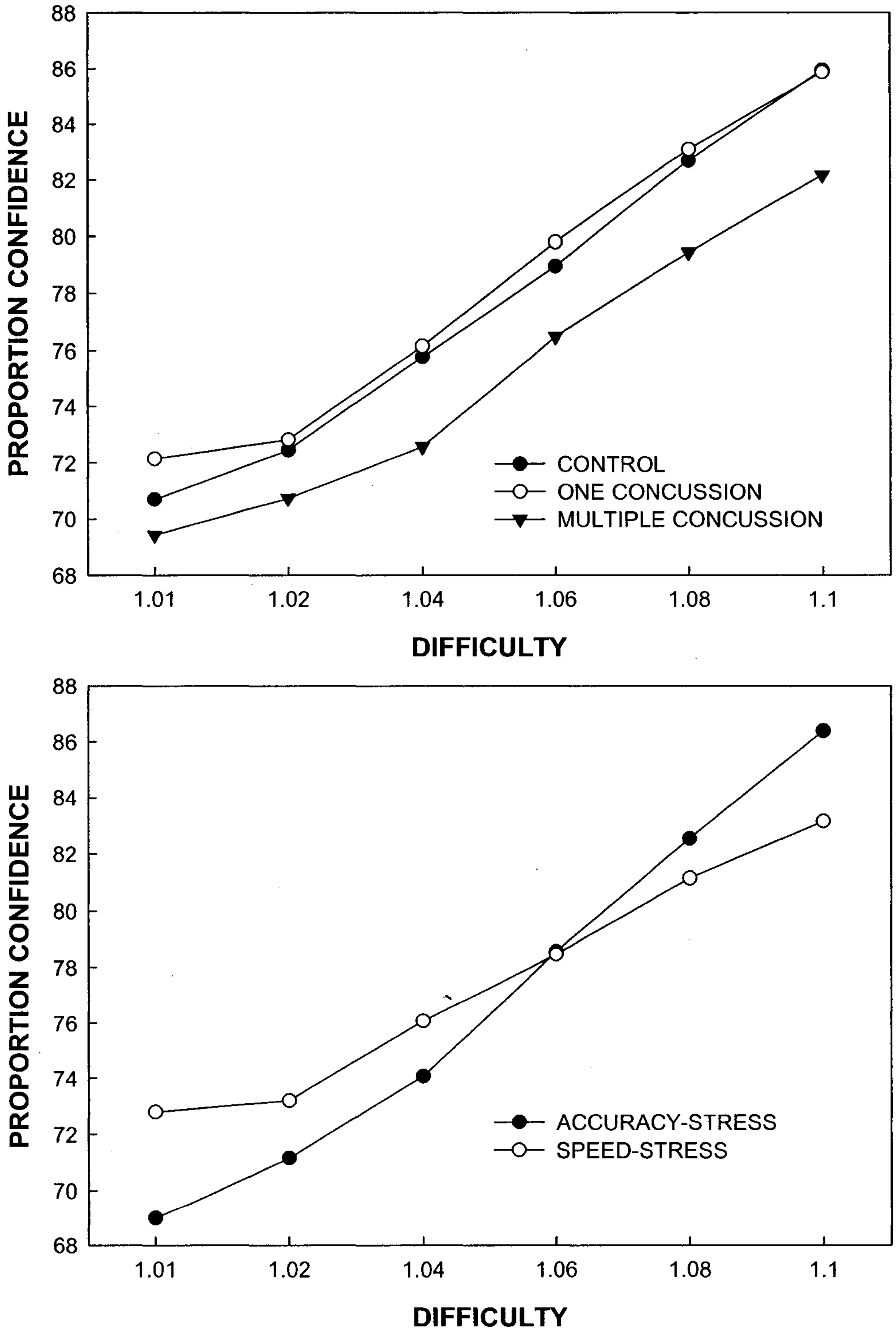

Figure 8. Mean proportion confidence by difficulty, condition and concussion group.

Confidence RT

Confidence RT (the time it took participants to render confidence judgments) did not differ significantly between concussion groups, $F < 1$. The within-subjects effect of block was highly significant, $F(3,192) = 74.33$, $p < .001$; Figure 9 that confidence processing generally became quicker with practice. Also evident is the disparity between confidence RT for the speed-stress and accuracy-stress conditions. Confidence processing took significantly longer when primary decisions were rendered under speed-stress ($M = 1031.31$, $SD = 306.69$) versus accuracy-stress ($M = 851.31$, $SD = 314.88$), $F(1,64) = 30.62$, $p < .001$. Furthermore, Figure 9 illustrates that time to render confidence under accuracy-stress (as well as speed-stress) was not uniform across difficulty levels. Recall that primary response times increased significantly when confidence ratings were required following each judgment (session 2) under accuracy-stress, but not under speed-stress. Taken together, these findings demonstrate that during speed-stress, confidence processing occurs primarily post-decisionally, while under accuracy-stress, confidence processing occurs both decisionally and post-decisionally, replicating earlier findings of Baranski and Petrusic (1998, 2001) and Petrusic and Baranski (2003).

Insert Figure 9 about here

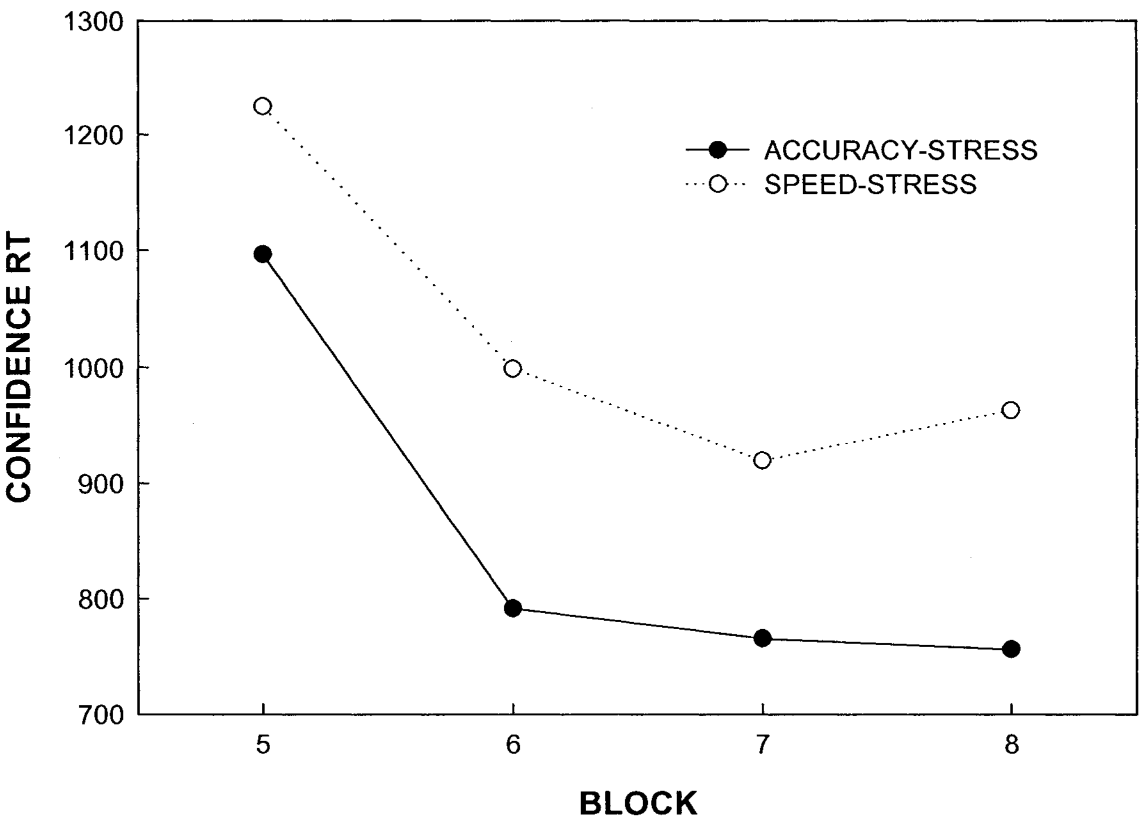

Figure 9. Confidence RT by block and condition.

Calibration, Resolution, Over/Under Confidence (Bias)

Calibration, resolution, and over/under confidence indices were calculated for each participant, separately by condition for each level of *a priori* difficulty. The six difficulty levels were aggregated into three in order to improve the reliability of the indices. However, calibration curves depict all levels of difficulty.

Calibration. Concussion groups did not differ significantly on calibration, $F(2,65) = 1.10$, $p = .34$. The only reliable within-subjects effect was for difficulty, $F(2,130) = 9.87$, $p < .001$. As is evident in Figure 10, calibration improves as decisions became easier (recall that a lower calibration score is better), and vice-versa. In Figure 11, corresponding group calibration curves depict proportion of correct responses for each condition. The diagonal lines represent perfect calibration; scores falling above this line are indicative of under-confidence in judgment, and scores below represent over-confidence. Figure 10 indicates that the multiple concussion group was the worst calibrated, for both accuracy-stress and speed-stress conditions; the bottom pane of Figure 11 indicates that this group was pervasively under confident for speed-stress judgments, although, as stated, groups did not differ significantly on the calibration index.

Insert Figures 10 and 11 about here

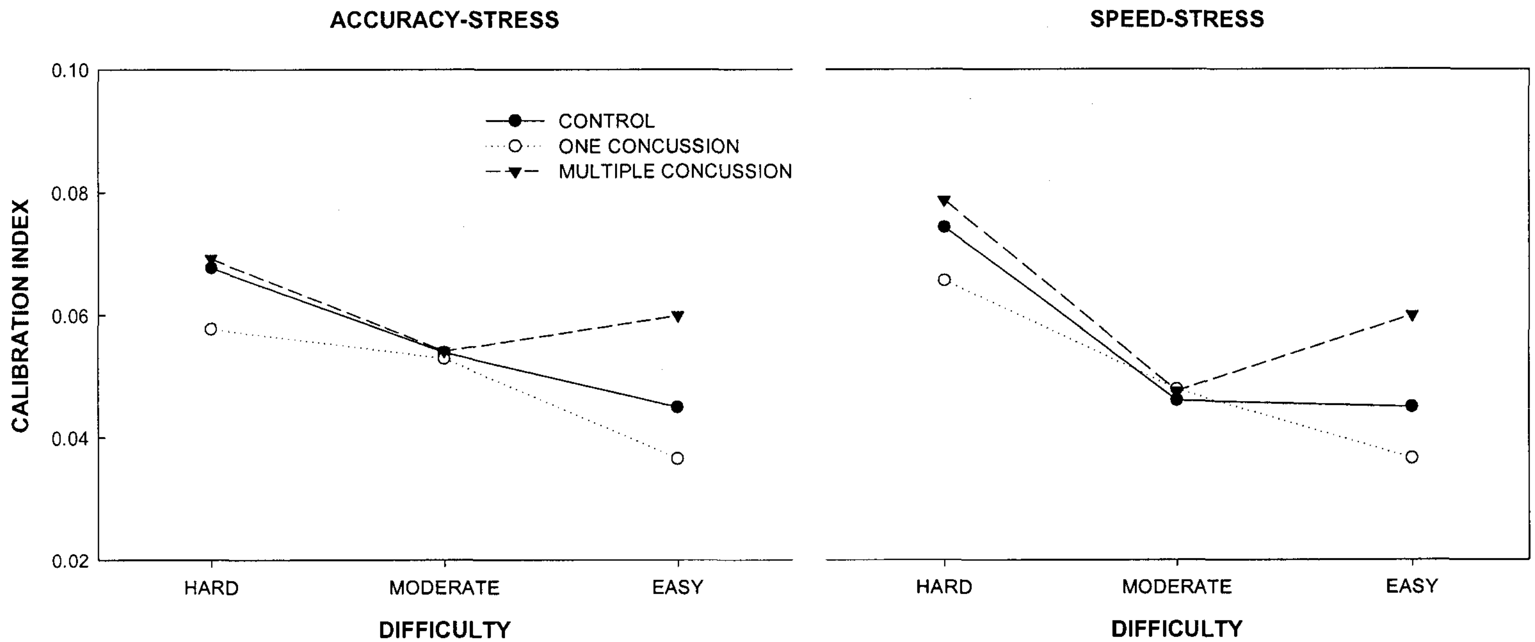

Figure 10. Calibration index for hard, moderate, and easy decisions by concussion group and condition.

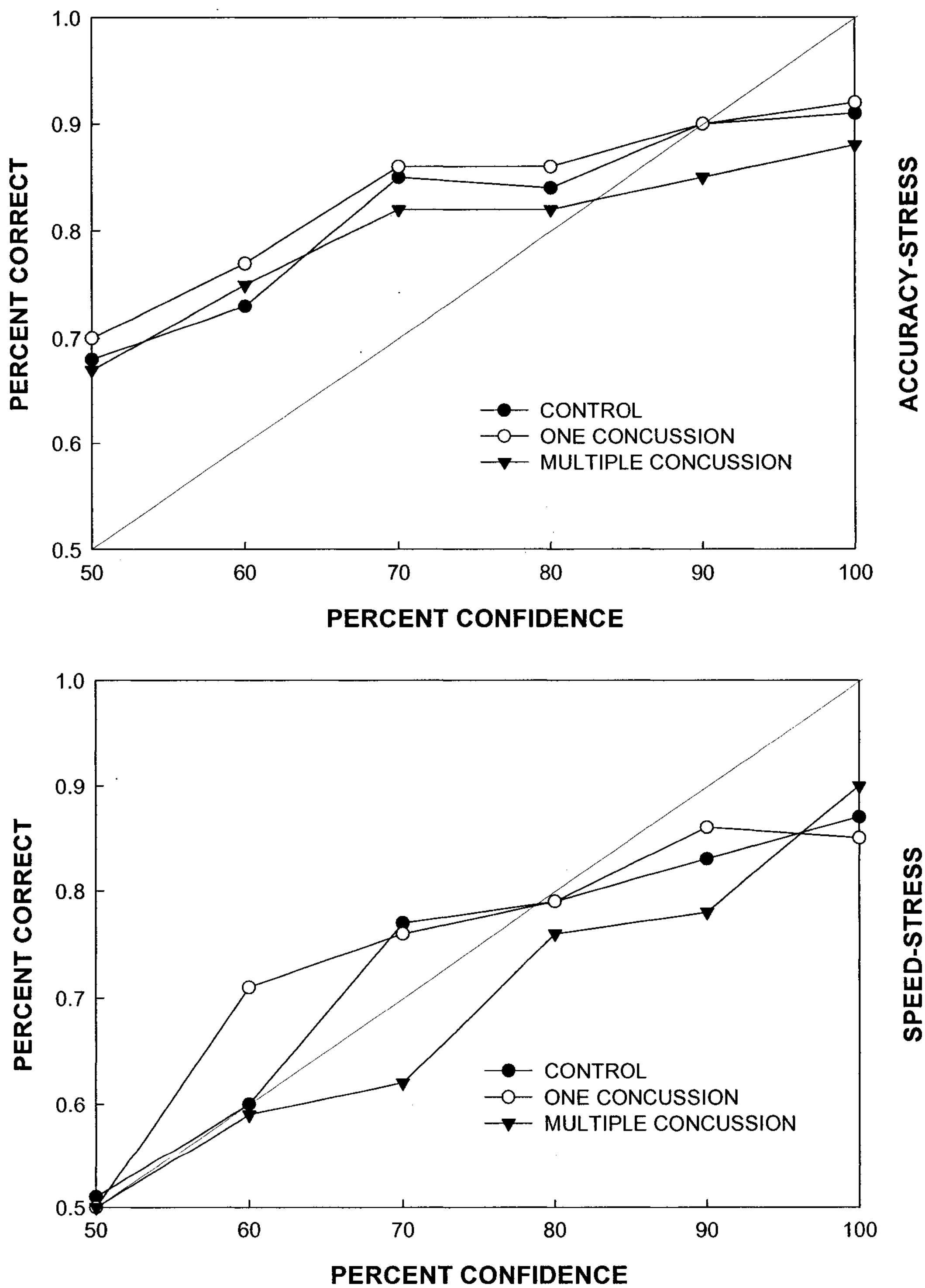

Figure 11. Calibration curves by concussion group and condition.

Bias. Groups did not differ significantly on bias, $F < 1$. As is evident in Figure 12, bias varied as a function of condition. Participants were, on average, under-confident for accuracy-stress judgments, and over-confident for speed-stress judgments. This within-subjects main effect of condition on bias was highly significant, $F(1,64) = 62.87$, $p < .001$. The within-subjects main effect of difficulty on bias was also highly significant, $F(2,128) = 179.09$, $p < .001$, indicating that, on average, participants were over-confident on difficult decisions, and under-confident on easy decisions, exemplifying the classic hard-easy effect.

Insert Figure 12 about here

Normalized Resolution (η^2). Normalized resolution also did not differ as a function of concussion group, $F(2,47) = 1.06$, $p = .36$. The within-subjects effect of condition was significant, $F(1,47) = 10.29$, $p = .002$. Figure 13 illustrates that normalized resolution was better under speed-stress than under accuracy-stress. The effect of difficulty was also highly significant, $F(2,94) = 34.90$, $p < .001$. It is evident from Figure 12 that resolution improved dramatically as comparisons became easier. Finally, there was a significant condition x difficulty interaction, $F(2,94) = 8.71$, $p = .001$.

Insert Figure 13 about here

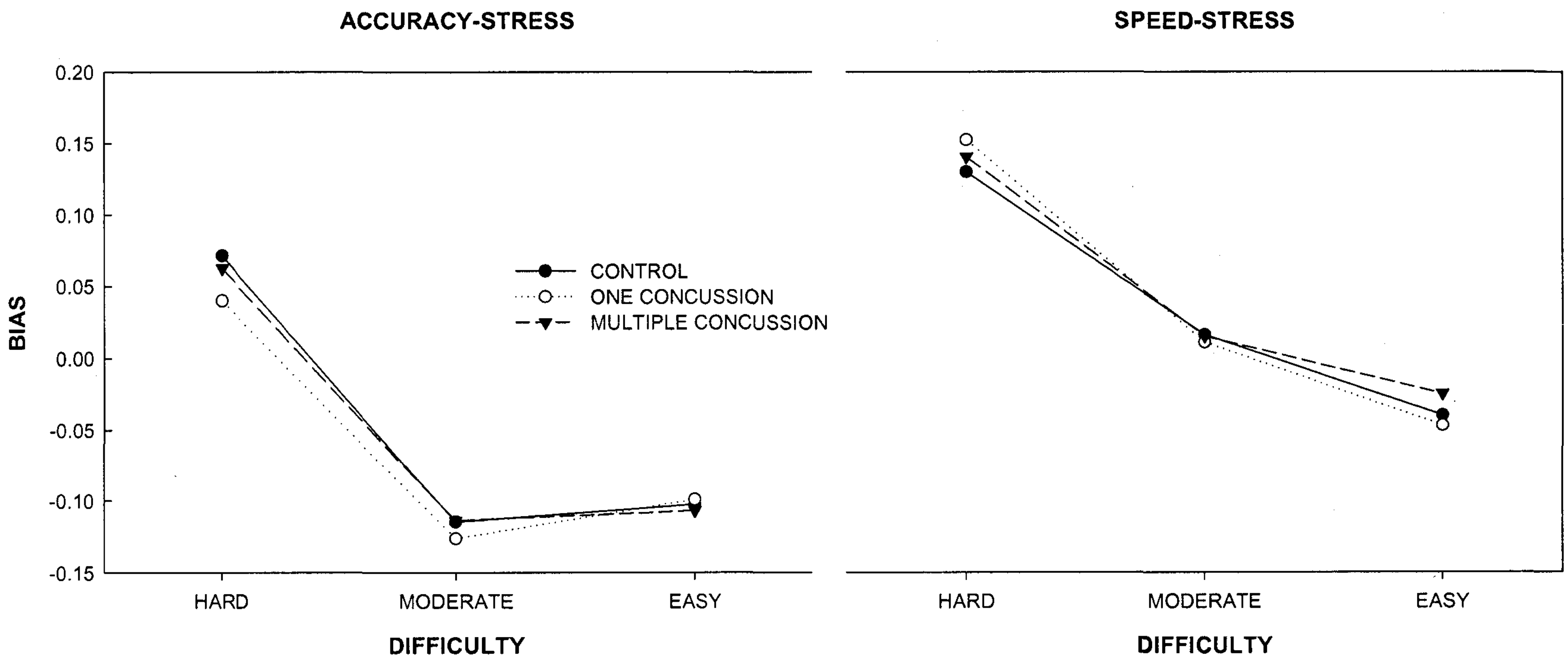

Figure 12. Under/Over-confidence (Bias) curves by group and difficulty.

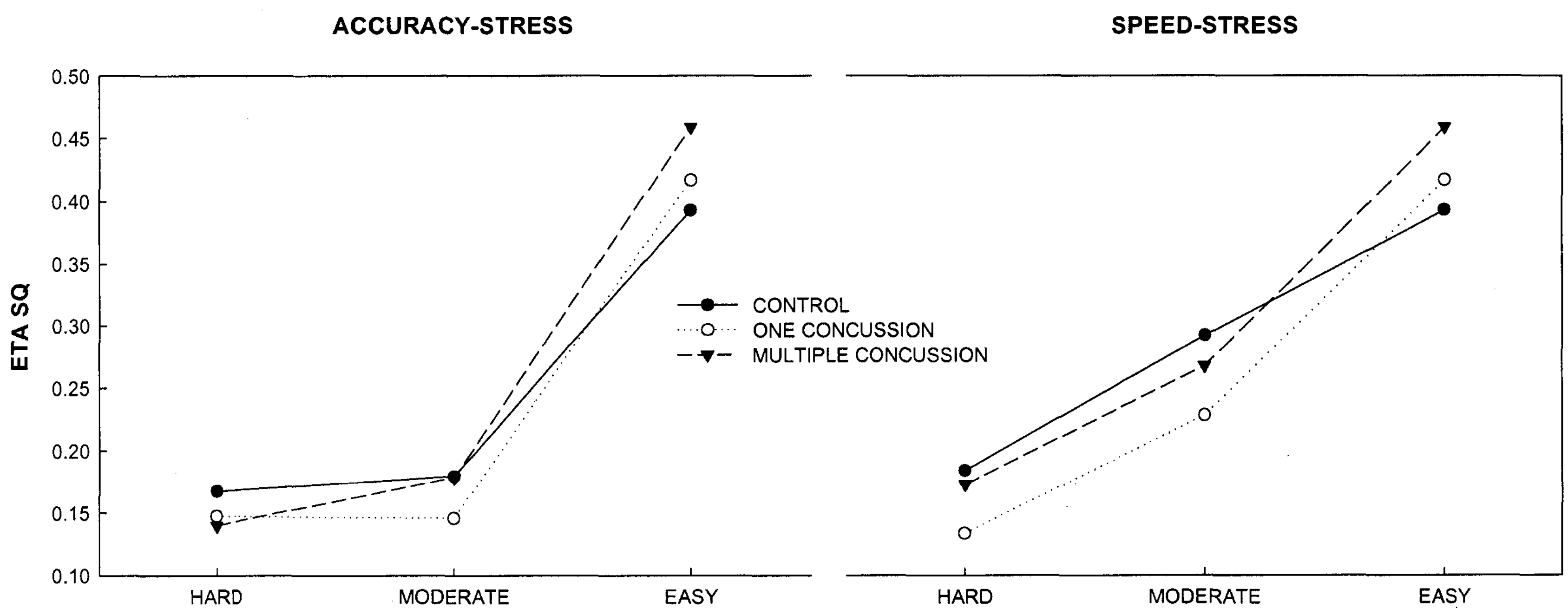

Figure 13. Normalized resolution by difficulty and concussion group.

Discussion

The purpose of this study was to determine whether undergraduate students with a history of single or multiple previous concussions differed from students with no history of concussion on cognitive test performance and self-reported symptoms. Due to the often contradictory nature of post-acute findings in the concussion literature, there have been recent calls for the development of measures that are proposed to be more cognitively demanding (e.g. Frencham et al., 2005). The primary measure of interest in the current study -- a challenging perceptual discrimination task -- was hypothesized to be more sensitive to the potentially chronic and cumulative effects of concussion than many of the traditional neuropsychological tests and computerized sideline assessment batteries that are frequently used in empirical studies to assess the effects of concussion. Furthermore, the current task examined several measures of meta-cognition. Specifically, meta-cognitive error awareness and subjective accuracy (confidence) are thought to be affected by concussion, but have scarcely been examined empirically; the current study addressed recent calls for precisely this type of investigation.

It was hypothesized that the multiple concussion group would demonstrate higher response time and response time variability for decisions rendered under accuracy-stress, especially so for difficult comparisons. While response time and response time variability did not differ significantly as a function of group, the multiple concussion group -- contrary to expectation -- demonstrated the lowest overall response times for both primary decisions and confidence judgments.

It was also hypothesized that the multiple concussion group would perform significantly worse on the psychophysical measure of discriminative accuracy (i.e. proportion correct), especially for difficult decisions rendered under speed-stress. While the multiple concussion group did demonstrate significantly worse discriminative accuracy that the single concussion and control groups, the difference was in overall proportion correct (collapsed across the speed- and accuracy-stress conditions). When examined separately by condition, the main effect was significant only for accuracy-stress judgments.

Finally, it was hypothesized that the multiple concussion group demonstrate worse calibration, resolution, and under/overconfidence (bias) scores than the single concussion and control groups, especially for judgments rendered under speed-stress. Remarkably, there were no significant group differences on any of these indices, indicating that meta-cognitive awareness was functionally intact for the single and multiple concussion groups.

Thus the current study found only one reliable difference in performance between groups and several trends, despite the demanding nature of the task and numerous ways in which participants were assessed. However, despite the number of null findings, there is little doubt that task condition and difficulty were effectively manipulated, and that participants complied with instructions and exerted legitimate effort during the testing session; the expected within-subjects properties of perceptual decision-making and locus of confidence processing were all highly reliable and replicate important findings in the psychophysics literature. Furthermore, the results indicate that the task was sufficiently demanding, especially so for difficult judgments rendered during the speed-stress condition.

The finding of significantly reduced discriminative accuracy in the multiple concussion group, but not in the one concussion group, is consistent with the notion of a cumulative effect of mild traumatic brain injury. However, the characteristics of this finding are not fully congruent with the current set of hypotheses and previous findings. Specifically, it was proposed that discriminative accuracy deficits in the multiple injury group would largely depend on condition (i.e. when participants were rendering judgments under speed-stress). If significant speed of information processing deficits were present, then discriminative accuracy would most likely be affected disproportionately under time pressure, especially with difficult decisions (i.e. when the accrual of evidence process was the most incomplete at the deadline). However, there were no significant group interactions with either condition or comparison difficulty, rather an overall main effect of group on discriminative accuracy. Moreover, previous studies have found that response time is more sensitive to the effects of concussion than measures of performance accuracy.

While there were no significant main effects or interactions involving response time, the multiple concussion group actually performed the fastest on both accuracy- and speed-stress judgments (as well as confidence response time). This trend is counterintuitive, and does not support previous findings or the hypothesis of higher RTs for this group. It is possible that the demonstrated reduction in discriminative accuracy for the multiple concussion group was mediated by their lower response times, and may reflect a different speed-accuracy trade-off response strategy rather than a cumulative effect of concussion. Exactly why the multiple concussion group performed faster and significantly less accurately than the other groups is a matter of speculation, however, since causal relationships cannot be inferred from current design. Nonetheless, it is possible that increased impulsivity in the multiple concussion group lead to faster responses and diminished accuracy (again, as a function of the speed-accuracy trade-off.) There is some evidence to suggest that mild traumatic brain injury is related to impulsivity, although no measure of this construct was included in the present investigation. If impulsive responding was the causal factor, however, two alternative explanations become readily apparent: that multiple concussions lead to increased impulsivity (perhaps through damage to frontal lobe structures), or, conversely, that premorbid impulsivity is a risk factor for concussion.

This study adds to the body of concussion research an investigation of confidence and error awareness in judgment. Recall that calibration refers to how closely confidence ratings (subjective accuracy) correspond to actual performance accuracy, and resolution indicates how well individuals use their confidence ratings to discern correct from incorrect responses. In addition to assessing calibration and resolution, the current study assessed error awareness directly through the frequency and accuracy of error key responses; none of these measures differed significantly as a function of group, which suggests that concussions -- at least for the current sample -- do not substantially affect meta-cognitive awareness in the chronic stage of injury, even in the case of multiple traumas.

Concussion groups also did not differ significantly on response time variability, PASAT, post-concussion symptoms and depression, although the multiple concussion group demonstrated higher mean scores on the latter two measures. That RPQ and CESD scores were strongly correlated supports previous findings, and that participants in the control group endorsed a significant degree of post-concussion symptoms indicates that these symptoms are not specific to traumatic brain injury.

While the current findings appear to provide some evidence for a cumulative effect of concussion, the general constellation of results are less conclusive. That overall accuracy, but not response time and response time variability differed significantly between groups is somewhat puzzling. Also puzzling was the finding that accuracy differences were not contingent on the speed-stress condition. One possible explanation for the general lack of significant differences is the relatively small sample size. However, there are examples of chronic and cumulative effect studies in the literature with smaller sample sizes that did find statistical differences and studies with very large sample sizes that did not find such effects.

In regards to the latter, there is a growing consensus that concussions either do not result in chronic cognitive deficits, or that existing deficits are too subtle to be detected with current neurocognitive batteries (Broglio et al., 2006). For example, a study involving 867 amateur athletes (Iverson et al., 2006) showed no measurable effect of one or two previous self-reported concussions on neuropsychological performance or symptom reporting. Likewise, a recent study by Collie et al. (2006) found no effect of up to four or more previous concussions and current cognitive performance in Australian rules football players. Guskiewicz et al. (2002) reported no difference in performance between soccer players with up to two previous concussions, and those with no concussion history. Similarly, a study of professional football players showed no difference between athletes with a history of three or more concussions and those with fewer than three injuries on a traditional neuropsychological test battery (Pellman et al., 2004). Finally, a recent study by Broglio et al. (2006) reported no differences between groups with zero, one, two, or three past concussions on computerized neuropsychological test performance[5].

Strengths of the Current Study

The current study possesses a number of strengths that differentiate it from many of the concussion studies hitherto in the literature. First, the three groups were statistically well matched on a number of important participant variables and potential confounds, including gender, age, GPA, alcohol consumption, depression, current symptoms (somatic, cognitive, emotional), and time since last concussion. Second, the unselected nature of the current sample (recall that participant selection was based on the occurrence of injury rather than the expression of any post-concussion symptoms) served to effectively safeguard against an over-estimation of concussion effects. Indeed, it was concluded in recent meta-analysis that sample selection type (clinic-based vs. unselected)

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An important distinction between these studies and the current investigation is that the former evaluated athletes as opposed to a more general university undergraduate population. While many of the concussions reported in current study were sports-related, participants were not classified as being athletes or non-athletes; it is assumed that the current sample was heterogeneous in this regard. However the distinction might not be all that important, since it was recently demonstrated that outcome from mild traumatic brain injury is comparable for athletes and non-athletes (Belanger & Vanderploeg, 2005).

moderates concussion outcome. Specifically, participants who were selected on the basis of actively seeking treatment for concussion-related sequelae (clinical samples) were significantly more likely to demonstrate cognitive, emotional, and somatic problems in the post-acute stage of recovery than individuals who were selected solely on the basis of having sustained a concussion (unselected samples). While it remains contested why some individuals experience significantly more severe and prolonged symptoms following concussion than others, it is hardly surprising that the former tend to seek more treatment and perform worse on tests of neuropsychological performance. As such, the current study addresses the recently articulated need for more investigations involving unselected samples. Finally, an additional strength of the current study is the robust and challenging nature of the psychophysical judgment task, and the inclusion of measures to assess meta-cognitive awareness.

Limitations of the Current Study

A number of methodological weaknesses, however, limit the usefulness and generalizability of the findings. First, participants were drawn from an undergraduate university population, ostensibly a high-functioning cohort of individuals. It is reasonable to assume that university students are not representative of the concussion population in general. Furthermore, data collection for the current study took place entirely during the winter semester; it is feasible that significant problems related to concussion would increase an individual's probability of dropping out during first year (or not even enrolling in the first place), potentially biasing the sample. Second, the number and severity of previous concussions was based on participant self-report. This poses several problems. One is the tendency of diffuse brain injury to interfere with memory function proximate in time to the trauma (e.g. retrograde or anterograde amnesia). Another problem concerns the general reliability of self-report, which has frequently been called into question. When an individual is asked to recall specific details about an injury that inherently affects memory, the reliability of their report is all the more tenuous.

To compensate for some of the problems associated with diagnosing concussion retrospectively from self-report, a stringent inclusion criteria was used to group participants in the current study. Recall that traumatic brain injuries are classified as either severe, moderate or mild. Yet mild traumatic brain injury (concussion) also represents a continuum of injury. Loss of consciousness was once -- and sometimes still is -- assumed to be a necessary condition for its diagnosis. While loss of consciousness following a blow to the head (or the head impacting an object) is almost certainly indicative of a brain injury, so too is any immediate alteration of consciousness (i.e. being dazed, stunned, confused, or amnesic). The numerous grading scales for concussion attest to the fact that the injury is heterogeneous and need not involve a loss of consciousness. However, in the current study, participants were assigned to groups contingent on the number of self-reported head injuries involving unconsciousness of up to 30 minutes in duration. This conservative approach to grouping was utilized because LOC is the most unambiguous sign of a concussion, and as such possesses the most utility for retrospective diagnosis. Use of this criteria likely reduced the probability of attributing spurious concussions to participants, however by the same virtue, the actual number of concussions was probably underestimated in the analysis. A possible implication is that participants with previous non-LOC concussions (e.g. AAN grade 1 and 2 concussions, which are much more common, but also more difficult to diagnose retrospectively) could have undermined within-group homogeneity and the practical distinction between groups. Even for concussions involving a LOC, it is very difficult to retrospectively assess injury severity based on the evidence typically available (e.g. reported duration of unconsciousness). Thus, even strictly defined grouping criteria does not adequately safeguard against the limitations of self-report and the general difficulties involved in grading concussion severity.

The current study is also limited by its retrospective, quasi-experimental design. For practical reasons, however, it was not feasible to prospectively investigate the chronic and cumulative effects of concussion, since this would take many years to accomplish. Finally, small sample size limited statistical power in the current study. It is of note, however, that the self-reported incidence rate of multiple concussions involving a loss of consciousness was approximately 6% among first year undergraduate psychology students who completed mass testing during the 2006/2007 academic year. Many of the aforementioned limitations -- representativeness of the sample, retrospective design, small sample size, and reliance on self-report -- are common among studies examining the post-acute effects of concussion.

Conclusion

That the current investigation found some evidence -- but not overwhelming evidence -- for a cumulative effect of concussion is intriguing in light of recent findings that suggest that if a cumulative effect exists, it is probably very subtle. Groups in the current study did not differ significantly on the Paced Auditory Serial Addition Task, a well established traditional neuropsychological test, but they did differ on the psychophysical judgment measure that is proposed to be more sensitive to subtle cognitive deficits. In this light, the current findings, rather than constituting inconclusive evidence, favor the hypothesis that chronic neurocognitive deficits resulting from the cumulative effect of concussion do exist, but are extremely subtle and difficult to detect. However, it remains to be determined whether the observed decrease in discriminative accuracy for the multiple concussion group was an effect of injury, or simply the implication of a differential speed-accuracy trade-off strategy employed by this group.

Thus for the most part, the results paint a positive picture for MTBI prognosis in the chronic stage of injury, even in the case of multiple concussions. With one exception, the current groups performed similarly on all measures of performance, despite the rigorous and challenging nature of the tasks. Additionally, it is quite remarkable that the multiple concussion group, despite their history of brain injury, demonstrated no significant impairment in meta-cognitive ability; this finding constitutes an important addition to the literature.

The present findings hence justify the term 'mild' as a realistic descriptor of injury for the current sample. However, a replication of the current study is needed to assess the reliability of these findings, and it is suggested that a measure of impulsivity be included to further investigate the result of reduced proportion correct in the multiple concussion group, especially in light of their unexpectedly quick response times. Since the most significant limitations of this and other cumulative effect studies stem from the inherent liabilities associated with retrospective design and the reliance on self-report for assessing injury parameters, a prospective design entailing a more objective procedure to identify and diagnose concussions would further contribute to the resolution of this highly salient and enduring debate.

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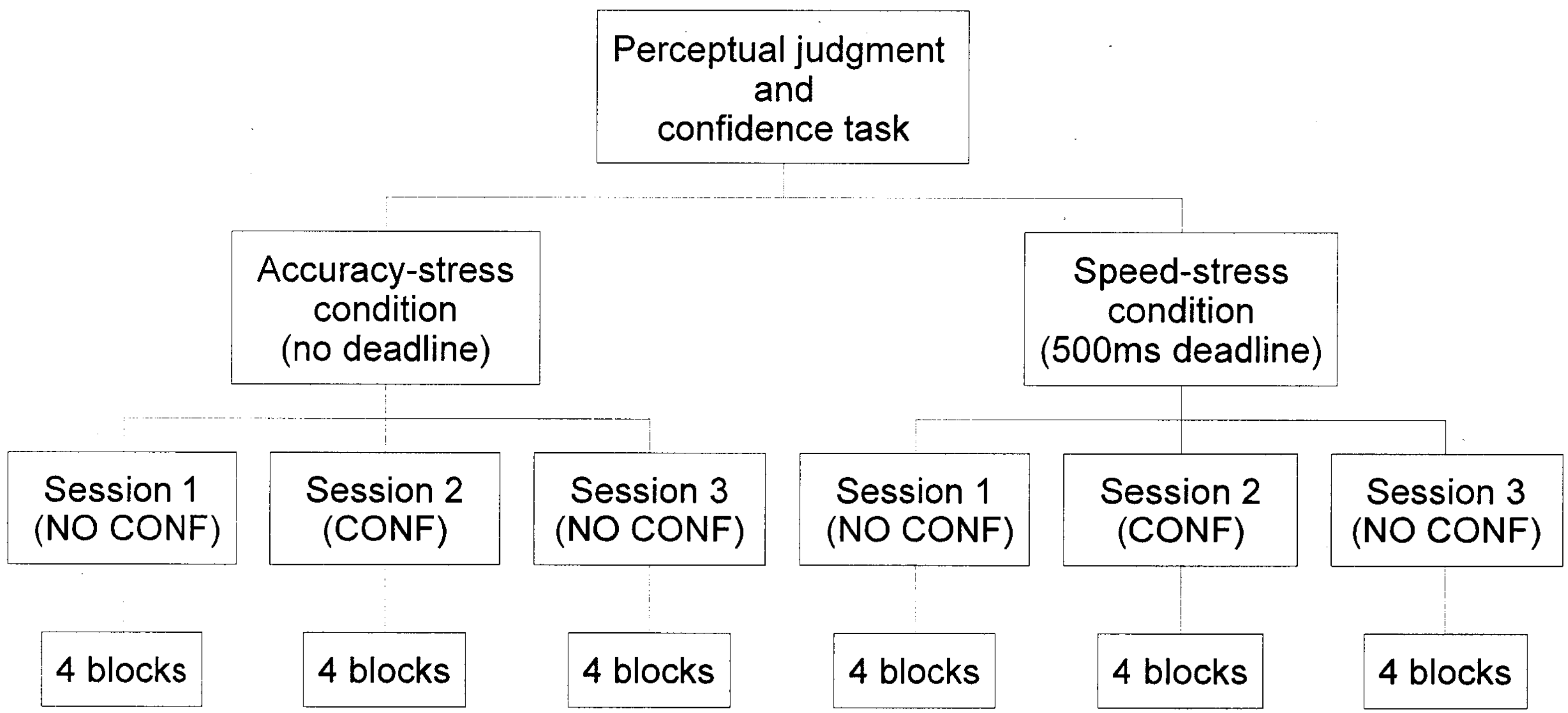
Appendix A


Perceptual judgment and confidence task
Accuracy-stress condition (no deadline)
Speed-stress condition (500ms deadline)
Session 1 (NO CONF)
Session 2 (CONF)
Session 3 (NO CONF)
Session 1 (NO CONF)
Session 2 (CONF)
Session 3 (NO CONF)
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