ABSTRACT

COGNITIVE EVOKED AUDITORY POTENTIALS AND NEUROPSYCHOLOGICAL MEASURES FOLLOWING CONCUSSION IN COLLEGE ATHLETES

By Katherine Louise Baker

Over 800 athletes suffer from concussion in the United States each day, resulting in over 300,000 concussions each year. Recent data has revealed that the incidence of mild traumatic brain injury is on the rise for many different sports, placing athletes at higher risk. Damage is caused by the shearing of axons, which results in swelling and loss of limited function. Electrophysiologic techniques, specifically event-related potentials are one of the most frequently used cognitive assessments. Event-related potentials are a non-invasive method to gather a baseline of cognitive processes and to evaluate cognitive deficits. The current study investigated the sensitivity of event-related potentials in the identification of cognitive deficits following concussion in college athletes. Neuropsychological and electrophysiologic measures were collected from two groups of participants allocated by injury versus non-injury. Results from the study found important differences between non-concussed and concussed athletes using electrophysiological measures and neuropsychological test measures.
COGNITIVE EVOKED AUDITORY POTENTIALS AND
NEUROPSYCHOLOGICAL MEASURES FOLLOWING CONCUSSION IN
COLLEGE ATHLETES

A Thesis
Submitted to the
Faculty of Miami University
in fulfillment of
the requirements for a masters of art in
Speech Pathology
Department of Speech Pathology and Audiology

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2008

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DEDICATION

I would like to dedicate this paper to Libby Lou, Zero, Lyric, Airee and Pistachio.

To: the furry and feathered throughout the world.
ACKNOWLEDGEMENTS

I would like to thank Dr. Kathleen Hutchinson for spending many hours with me during the past year. She has been a wonderful inspiration to me throughout my graduate career and has put a lot of time and energy into helping me throughout the research process. I would also like to thank Dr. Fofi Constantinidou for her expertise in the area of neuropsychological measures and traumatic brain injury and Dr. J Brett Massie for his knowledge of college athletics and injury. Without the members of my committee, this thesis would not be complete.

I would like to thank my parents for all of their support. Thanks Mom for all of the wonderful meals and for listening to my constant chatter about research and thanks Dad for all of the questions! I would like to thank my brother, Kyle, for his intriguing yet unusual perspective. I would also like to thank my wonderful friends: Linda, Melanie, Callie and Sangeetha. Thank you for lending your ears and for helping me so much throughout these past two years! Finally, I would like to thank Stephanie Volker for taking me under her wing and teaching me so much about brain injury.
Cognitive Evoked Auditory Potentials and Neuropsychological Measures Following Concussion in College Athletes

Introduction

Event-related potentials reflect higher brain functions, such as attention, memory and processing speed. The principal measurement of event-related potentials is the P300 waveform, which occurs in a positive nature approximately 300 to 500 milliseconds after a stimulus is presented. The P300 measure has been used to assess cognitive deficits in neurological conditions as well as after brain injury, primarily using an oddball paradigm. A standard oddball task requires each subject to differentiate between the presentation of two separate stimuli, frequent and infrequent. The identification of infrequent stimuli will form the P300 waveform (Katayama & Polich, 1999; Lindin, Zurron & Diaz, 2005).

Evoked potentials mirror the process of physical stimulus, while event-related potentials mirror higher brain functions and mental state. Event-related potentials are important in the assessment of cognitive abilities and provide important information regarding changes after brain injury. As more research is completed in the area of electrophysiological assessment, especially the P300 waveform, clinicians will be able to augment evaluation techniques and more comprehensive assessments of cognitive impairment may be completed. The purpose of this study is to provide further data to existing research that incorporates the P300 waveform as a measurement tool to assess cognitive abilities to be used with neuropsychological measures after concussion in college athletes.

Literature Review

Athletes and Concussion

Over 800 athletes suffer from concussion in the United States each day, resulting in over 300,000 concussions in the United States each year (Kelly, 2000). Athletes are at risk for concussion, or mild traumatic brain injury, as an entire population. Recent data has revealed that the incidence of mild traumatic brain injury is on the rise for many different sports, placing athletes at higher risk. Recent data has also shown the rate of concussion is underreported and many athletes do not report symptoms of concussion at some point throughout their athletic career (Zillmer, 2003). Concussions are not well understood by many athletes due to the complexity of symptoms. Oftentimes it is easier
for an athlete to understand and accept an orthopedic injury rather than a concussion because there may be no physical indicators of injury following concussion; this may place the athlete at risk for further injury. Athletes that return to play before fully recovering from a concussion are placed at higher risk for receiving another concussion, resulting in cumulative permanent deficits.

Athletes that return-to-play shortly after suffering from concussion are at an increased risk for an additional concussion, resulting in Second Impact Syndrome. Brain swelling and axonal shearing occur after one concussion; therefore, additional damage results in severe brain swelling and increase in intracranial pressure. Second Impact Syndrome may have devastating results including permanent disability or even death. It is imperative that the consequences of Second Impact Syndrome are fully considered when deciding whether or not an athlete should return to play (Kelly, 2000).

Concussion is defined as an alteration in mental status, with confusion as the major warning sign. Damage is caused by the shearing of axons, which results in swelling and loss of or limited function. Post-concussive symptoms are indicators of mild traumatic brain injury and often include cognitive, motor and psychological deficits. Indicators may include the following symptoms: dizziness, headache, irritability, anxiety or depression. After concussion athletes may experience a gradual or sudden onset of symptoms, which may vary from mild to severe. Symptoms of concussion may persist for days to months, depending on the severity of concussion and how the brain was affected. During the time that symptoms are persistent, the athlete may struggle with academics and activities of daily living (Cobb & Battin, 2004; Kelly, 2000).

An increase in awareness of the effects of concussion has occurred in recent years. Improved evaluation techniques has occurred with more research in the area of concussion and better protection, including new rules and regulations for many sports (Belanger & Vanderploeg, 2005). The use of neuroimaging, neuropsychological assessment and electrophysiological techniques are currently being used to assess the effects of concussion. Research is currently being completed to fully define concussion, risk factors for mild traumatic brain injury and the deficits associated with the diagnosis of concussion (Gaetz & Bernstein, 2001). Utilizing current knowledge with future research should result in safer playing conditions and opportunities for all athletes.
**NeuroCognitive Assessments**

The use of neuroimaging has become prevalent in the medical field and as a means to evaluate cortical damage after traumatic brain injury (Kelly, 2000). Both magnetic resonance imaging (MRI) and computed tomography (CT) have been used to objectively evaluate damage to the cerebral cortex. These evaluation techniques are expensive and cannot effectively assess damage caused by mild traumatic brain injury. MRI scans are much more effective than CT scans when identifying damage to small vessels and acute axonal injury. However, the primary neuropathology in the uncomplicated mild sports-related concussion results in widespread neuronal metabolic imbalance, which is not detected by the traditional neuroimaging tools like the MRI or the CT scan.

Historically, there has been a lack of objective evaluation techniques for mild traumatic brain injury; therefore, several methods have been utilized to evaluate concussion. One particular method is presently being used to evaluate cognitive deficits based on symptoms reported by injured athletes. The report technique lacks reliability and may place athletes in danger for further damage. There has been a need for objective evaluation techniques to identify mild traumatic brain injury. This has led to further advances in the field of Neuropsychology, including the development of the relatively new field of Sports Neuropsychology.

Neuropsychological measures are currently believed to be the most sensitive measures to quantify deficits after concussion (Kelly, 2000), although neuropsychological assessments rely on full participation from subjects and do not rule out other cognitive disorders such as depression or learning disability. Neuropsychological assessments are still widely used by many organizations including the National Football League, National Hockey League and the NCAA. Many versions of neuropsychological measures are being used including abbreviated assessments to extensive assessment batteries, along with paper and pencil tests to computer-based tests.

Although neuropsychological measures provide objective information in the assessment of cognitive abilities, limitations are present. If no baseline data exists for an athlete, neuropsychological measures may not be able to detect deficits due to the subtle effects of sports-related concussion. Another probable limitation in concussion
assessment occurs when athletes fail to report their symptoms so they may return to play (Echemendia & Candu, 2003). This can result in dangerous playing conditions for the individual and increased risk of injury. Understanding that limitations exist, has encouraged the pursuit to improve current concussion assessment techniques; therefore, event-related potentials may be a useful tool in addition to neuropsychological assessment in the evaluation of concussion in making return to play decisions.

Most assessments are sensitive in the detection of change in mental status, including the Pittsburgh Steelers Neuropsychological Battery (PSNB). The PSNB is designed to specifically detect changes in memory, mental fluency, motor speech and dexterity, processing speed and verbal memory. It was first implemented in the 1990s and is now used for return to play decisions for the NFL, NHL and NWL. Table one lists each subtest of the PSNB and the cognitive abilities evaluated by each test.

Table 1
Pittsburgh Steelers Neuropsychological Battery

<table>
<thead>
<tr>
<th>Test</th>
<th>Ability Evaluated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hopkins Verbal Learning Test (HVLT)</td>
<td>Memory for words (verbal memory)</td>
</tr>
<tr>
<td>Trail Making Test</td>
<td>Visual scanning, mental flexibility</td>
</tr>
<tr>
<td>Controlled Oral Word Association Test</td>
<td>Word fluency and retrieval</td>
</tr>
<tr>
<td>Digit Span (from Wechsler Memory Scale-Revised)</td>
<td>Attention span</td>
</tr>
<tr>
<td>Symbol Digits Modalities</td>
<td>Visual scanning, visual motor speed</td>
</tr>
<tr>
<td>Grooved Pegboard Test</td>
<td>Motor speed/coordination</td>
</tr>
<tr>
<td>Delayed Recall (from Hopkins Verbal Learning Test)</td>
<td>Delayed memory for previously learned word list</td>
</tr>
</tbody>
</table>

Electrophysiological Measures

One of the most frequently used assessments of brain function is electrophysiologic techniques, specifically event-related potentials. Electrophysiological measures evaluate sensory pathways, while event-related potentials evaluate cortical cognitive processes. Event-related potentials are a non-invasive method to gather a baseline of cognitive processes and to evaluate cognitive deficits in neurological disorders or after brain injury (Gaetz & Bernstein, 2001). Event-related potentials are
used to measure cognitive function, such as attention, memory and processing speed and as a means to accompany neuropsychological assessments.

**P300 Waveform**

The P300 waveform was first described in 1965 as the most positive-going component of an evoked potential (Sutton, Braren, Zubin & John 1965). It has quickly become the most analyzed waveform of event-related potential measures, resulting from cognitive processes following a specific task-related event and corresponding stimuli. Use of the P300 waveform varies from measurement of attention to analysis of cognitive deficits in many neurological disorders or after traumatic brain injury. The main use of P300 is to serve as a cognitive marker over time. The P300 waveform is named because it typically occurs between 250-350 milliseconds in young adults (Comerchero & Polich, 1998; Fjell & Walhovd, 2003). It is also endogenous, occurring in response to stimuli and is not affected by physical parameters of the stimuli presented. The P300 waveform can be elicited through various stimuli and is normally collected using auditory, visual or somatosensory stimuli.

The third positive waveform following auditory stimuli in electrophysiological collection is the P300 waveform, which typically has a latency of 300 milliseconds. It is relatively large with amplitude of 5-20 microvolts and is evoked by an odd-ball paradigm. The odd-ball paradigm involves presentation of two stimuli, one frequent and the other infrequent (Aleksandrov, Polyakavoa & Stankevich, 2005; Fjell & Walhovd, 2003; Sutton et al., 1965). Infrequent stimuli are presented randomly during the task and each subject must identify the stimulus through a cognitive or motor response: silent counting or tapping. Frequent stimuli typically occur during 80% of the task, while infrequent stimuli occur during only 20% of the task. The ideal result is reduced latency and increased amplitude of the P300 waveform, indicating active brain function.

Some intrinsic factors can affect the latency and amplitude of the P300 waveform such as subjects’ age and attention level as well as frequency of stimuli, intensity of stimuli and rate of presentation. Each factor can change the morphology of event-related potential measures; therefore, normative data may vary depending on test parameters used. The P300 waveform’s appearance can also be altered depending on subject’s history of neurological disorders and history of substance abuse. Gaetz and Bernstein
(2001) reported the P300 waveform is a response to information processing and involves many different areas of the brain including the hippocampus, superior temporal sulcus, intraparietal sulcus and more. Just as information processing is affected by mild traumatic brain injury and requires activity throughout the cerebral cortex, the P300 response occurs secondary to activity throughout the brain; therefore the P300 is an appropriate and effective measure of cognitive deficits in mild traumatic brain injury.

**Latency**

Latency of the P300 waveform peak is a direct reflection of cognitive processing time; therefore, decreased latency demonstrates rapid processing speed (Fjell & Walhovd, 2003). This corresponds to task difficulty, as demonstrated by short latency with easy tasks and long latency periods with more difficult tasks. Latency has been found to be a better indicator of cognitive deficit than P300 amplitude (Gaetz & Bernstein, 2001). Latency is one of the most important diagnostic indicators of cognitive function when analyzing P300 waveforms.

**Amplitude**

Amplitude of the P300 waveform is an indicator of cognitive function. Although amplitude is not as useful as latency as a diagnostic measure, it remains an important measure of event-related potentials. Typically, amplitude will increase with ease of task and will increase with amplified stimuli due to better subject arousal. Attention and arousal of each subject is required during presentation of stimuli to receive accurate results; therefore, louder auditory stimuli may produce better quality results of the P300 waveform (Katayama & Polich, 1999). Greater neural activity within subjects will increase amplitude and may require more difficult discrimination tasks than recognition of infrequent stimuli.

**Electrophysiologic Sites**

The P300 waveform may be generated using many different sites on subjects’ scalp. Some of the most successful sites include the central-parietal area, parieto-occipital area, temporal lobe and temporal-parietal junction (Katayama & Polich, 1999). These areas provide access to greater information processing, resulting in stronger, consistent P300 measures. Other, more controversial, sites include the hippocampus
region and limbic structures because these areas are used for many other processes, but making it difficult to measure P300 waveform (Frodl et al., 2001).

Historically, animal models have been used to explore new generator sites for the purposes of electrophysiological measures. A study using the monkey was conducted by Arthur and Starr (1984) utilizing the Cz, Fz and Pz receptor sites. Other research has been completed using animals models, including research on both the rat and cat (Arthur & Starr, 1984). Although animal models are helpful in the development of event-related potential design, results do not always generalize to the human model.

Applications

The exact origin of the P300 waveform has not been found to date, although professionals have widely accepted that the P300 waveform is an indicator of high-level cognitive function (Fjell & Walhovd, 2003). Quantifying cognitive impairment can be an important and objective way to measure change in mental status over time. Use of P300 measures may become an invaluable tool, replacing more subjective measures such as behavioral screening measures. Although behavioral screening measures may remain helpful as a clinical tool, P300 waveforms are estimated to be more sensitive; therefore, P300 waveforms may identify subtle changes, while behavioral screening measures may neglect to identify important change (Gaetz & Bernstein, 2001).

The P300 measure has been used across a variety of disorders to indicate cognitive change over time. Several populations include subjects with alcoholism, depression, dementia and other neurological and psychological disorders (Aleksandrov, Polyakova & Stankevich, 2005; Lindin, Zurron & Diaz, 2004). Decreased mental function is most easily identified by increased latency of the P300 waveform and can also be identified by decreased amplitude of the P300 waveform, indicating decreased processing time.

Elicitation

Many paradigms exist to elicit the P300 waveform. It is important to incorporate task difficulty and type of stimuli into consideration when deciding on an elicitation technique. The P300 waveform can be elicited using auditory, visual or somatosensory stimuli. An odd-ball paradigm can be utilized with auditory stimuli or picture stimuli can be identified by each subject to form the P300 waveform; therefore, it is imperative for
researchers to consider their subject population and which stimuli would be most appropriate for the task presented. The appearance of the P300 waveform can be altered in many ways, as latency and amplitude are affected by the elicitation technique chosen (Comerchero & Polich, 1998; Katayama & Polich, 1999).

**Parameters**

Subject parameters include elicitation techniques, age, artifact, and skull thickness, all of which can affect P300 results (Fjell & Walhovd, 2003; Frodl et al, 2001). Elicitation techniques may be chosen based on each subjects’ mental and physical abilities. Younger subjects or subjects with disabilities may simply push a button when an infrequent stimulus is produced and the device will total the number of infrequent stimuli presented. Older subjects may silently count the number of infrequent stimuli presented. Both techniques produce the same result with no difference in latency or amplitude of the P300 waveform.

Subject age and attention level can impact the results of event-related potential measures. If a subject is drowsy or does not pay attention to the presentation of infrequent stimuli, the P300 waveform may decrease in amplitude or it may not appear at all during test procedure (Comerchero & Polich, 1998). An overall increase in latency and decrease in amplitude is observed as adults age; therefore, it is important for researchers to compare data collected to norms by age. Collecting a normative sample is the best way to ensure reliability of results and to provide a definitive comparison for the clinical population being researched.

Artifact can greatly impact the appearance of a P300 waveform; therefore, it is essential to control all extraneous artifacts. This can be done by asking each subject to close his or her eyes during the test procedure. If high artifact does occur, additional stimuli can be presented to lower the percentage of overall artifact in the sample. It has been suggested that samples must contain less than 10% artifact to be considered acceptable; therefore, artifact rejection systems are available on many auditory evoked potential software programs (Comerchero & Polich, 1998; Fjell & Walhovd, 2003).

A study completed by Frodl, Meisenzahl, Muller, Leinsinger, Juckel, Hahn, et al. (2001) reported that scalp thickness has no apparent effect on P300 results, although skull thickness may impact P300 measures. This study provides additional factors to consider.
when utilizing the P300 waveform as a measurement of cognitive change. It is difficult to control for differences in skull thickness between subjects in a sample; therefore differences in skull thickness should be taken into consideration when measuring the reliability of results.

Paradigm Variations

A two-tone odd-ball paradigm is frequently used to elicit the P300 waveform, although other paradigm variations exist. A study of a three-stimulus paradigm was completed using an additional infrequent stimulus. Both infrequent stimuli were randomly presented within the presentation of frequent stimuli. The results did not reveal a significant difference between a two-tone odd-ball paradigm and a three-tone odd-ball paradigm when forming the P300 waveform (Katayama & Polich, 1999). Other studies have been completed researching the effectiveness of the one-tone paradigm. Results revealed that the one-tone paradigm, consisting of silence with a presentation of a single tone, is similar in effectiveness to the traditional two-tone odd-ball paradigm.

Evoked Potentials and Concussion

Many individuals who suffer from a mild traumatic brain injury or concussion, exhibit a variety of cognitive deficits in the areas of attention, memory processing speed, problem solving, initiation and planning. Research in the areas of brain injury and event-related potentials has increased in recent years. Professionals and researchers have identified a correlation between neuropsychological measures and event-related potentials in the area of traumatic brain injury (Potter, Bassett, Jory & Barrett, 2001). Studies have been completed comparing neuropsychological results to electrophysiological results in older adults. Both measures presented similar results for subjects, identifying a correlation between neuropsychological and electrophysiological techniques.

Neuropsychological measures have existing limitations; therefore, seriousness of brain injury may be underestimated, placing the athlete in danger. Studies have identified that neuropsychological measures do not always identify subtle cognitive deficits. Maeshima, Okita, Yamaga, Ozaki and Moriwaki (2002) completed a study using both neuropsychological measures and event-related potentials. Results suggested that both measures should be used collectively to reliably identify cognitive changes within
individual subjects. Due to the increased risk of suffering additional concussions after suffering one concussion, return-to-play decisions should be made with great caution. Second Impact Syndrome and long-term effects may result from further damage caused by additional concussions; therefore it is imperative that appropriate, objective screening measures are utilized when making return to play decisions.

A model was developed to categorize important factors when making return-to-play decisions. Several factors identified include patient report, medical history, personality, manner of play and neuropsychological test results. Researchers concluded that neuropsychological test results play an important role in making return to play decisions, although return to play decisions require a complex model (Echemendia & Cantu, 2003). Event-related potentials, specifically the P300 measure, can be incorporated into the complex model of return to play decisions to monitor recovery following mild traumatic brain injury. In conclusion, integrating electrophysiological measures into the complex model of return to play decisions can enhance assessment methods, improve the evaluation of recovery over time and facilitate decision making efforts concerning return to play for college athletes that have suffered from mild traumatic brain injury.

The current study investigated the sensitivity of event-related potentials in the identification of cognitive deficits following concussion in college athletes. Event-related potential measures and neuropsychological data were collected to identify any cognitive deficits following concussion in college athletes. Results of this study could benefit athletes, athletic trainers, coaches and physicians in the management and prevention of concussion. Following are the research questions and hypotheses:

1. Are the event-related potential measures sensitive in the detection of cognitive deficits following onset of mild traumatic brain injury? It is hypothesized that P300 waveforms will be a reliable measure of cognitive decline following mild traumatic brain injury. It is also hypothesized that latency will be increased, as amplitude of the P300 waveform is decreased.

2. Do binaural ERP measures correlate with averaged individual waveforms? It is hypothesized that there will be a significant difference between binaural and averaged individual waveforms within both groups due to interactive stimulation effects.
3. Are neuropsychological measures sensitive in the detection of cognitive deficits following onset of mild traumatic brain injury? It is hypothesized that neuropsychological test results will reveal cognitive decline following concussion in college athletes and will be comparable to results from previous research.

4. Do significant differences exist between male and female athletes when comparing non-injury versus injury? It is hypothesized that significant differences will exist between male and female athletes across all trials and female athletes will present with shorter latency times than male athletes.
Methods

Subjects

Participants included in this study are members of a varsity sports team at Miami University. Two groups of participants were allocated by injury versus non-injury. Baseline data was collected for each athlete including neuropsychological and electrophysiological measures. Baseline testing of neuropsychological measures is required by the Concussion Management Program at Miami University. Electrophysiological measures were voluntarily collected from athletes. Group assignment and additional neuropsychological and electrophysiological testing was completed following concussion on all injured college athletes. Subjects tested participate in women’s field hockey, men’s football, men’s hockey, men’s basketball, women’s softball and women’s soccer.

P300 Protocol

Subjects completed all electrophysiological testing in an IAC sound-treated room within Miami University’s Speech and Hearing Clinic. Bio-logic Navigator PRO and ER-2A tubephones were used to collect all electrophysiological data. Equipment was checked for calibration before and after this study was completed to ensure reliability of measurements. All ERP data collection was completed by this author under the supervision of Kathleen Hutchinson, Ph.D., Department of Speech Pathology and Audiology, Miami University. Before the collection of P300 data, a screening was completed to ensure that each participant has hearing within normal limits. Screenings were completed by presenting a series of signals while each participant counts both frequent and infrequent stimuli. After passing the screening, P300 response was elicited by an oddball paradigm using two auditory tones randomly presented at 250 and 1,000 Hz by tone bursts set in rarefaction phase. Frequency Stimulus (FS) was set at 250 Hz and had 80% probability of occurrence. Infrequent Stimulus (IS) was set at 1,000 Hz and had 20% probability of occurrence.

A non-inverting electrode was used to record electrophysiological data at Cz (central temporal lobe) referenced to standard silver cup electroencephalogram (EEG) earlobe electrodes with the common or ground site location on the forehead. Electrode impedance should never exceed 6K ohms and was checked before and after each session.
to ensure test site stability. Artifact was detected and monitored by the Bio-logic Navigator PRO by amplifying electro encephalic (EEG) activity using a gain of 30,000 and input filters set at .10 and 30 Hz. If EEG activity exceeds 10% of the tones presented, Bio-logic Tester Navigator PRO automatically rejected the data and restarted the test session. Tones were presented at 65dB HL.

Each subject was examined by otoscope for any aural occlusions before completing electrophysiological testing. After passing the otoscopic exam, electrodes were applied to each subject in appropriate locations. Each subject was seated in a recliner with head resting back and legs up to reduce EEG activity. To reduce extraneous eye movement, subjects were asked to keep eyes closed throughout the assessment process. The test session took approximately thirty minutes to complete with five trials total. Subjects first completed a screening by triggering the counter for all frequent and infrequent stimuli. After passing the screening portion, subjects were asked to trigger the counter for all infrequent stimuli. One binaural, two right and two left trials were completed to guarantee waveform repeatability during testing.

**Neuropsychological Protocol**

The Sports Concussion Management Program at Miami University is conducted in the NeuroCognitive Disorders Laboratory of the Speech and Hearing Clinic. Fofi Constantinidou, Ph.D. and Kelly Knollman-Porter, M.S., CCC-SLP, Department of Speech Pathology and Audiology, Miami University, direct and supervise all neuropsychological data collection for the Sports Concussion Management Program. Trained graduate students from the Department of Speech Pathology and Audiology administered neuropsychological examinations to all athletes included in this study. All neuropsychological data was used in concurrence with electrophysiological data that was collected to analyze relationships between data.

**Procedures**

The entire data collection process took place at The Miami University Speech and Hearing Clinic. The process began in a private therapy room, when each athlete completed an Informed Consent Form, survey regarding previous concussion(s) and a Post-Concussion Rating Scale. A trained graduate student was present to answer any questions and to administer the neuropsychological test battery which consisted of either
paper and pencil assessment or ImPACT computer assessment, Controlled Oral Word Association Test (COWAT) and the Grooved Pegboard Test. All tests were administered by trained graduate students using written instructions; therefore, procedures were uniform. A Post-Concussion Questionnaire was completed by each subject to identify history of concussion and any neurobehavioral symptoms.

Confidentiality

Each subject was required to read and sign an informed consent form before participating in this study. Participation in this study was completely voluntary and a decision not to participate did not have an impact on grades in any class or impact athletic, grant or scholarship status. Subjects were permitted to withdraw from the project at any time during the research process. No compensation or payment was provided for participation. All identifying information was kept confidential through a letter/number code system. Only the student investigator and faculty advisor had access to identifying information.

Data Collection

Questionnaire

The questionnaire that was used in this study contained 28 questions addressing history of concussion. Greffen, Hinton-Bayre, and Greffen (1998) developed the original questionnaire as a standardized method to survey an athlete’s history of concussion. The questionnaire used in this study was modified for the needs of Miami University’s Sports Concussion Management Program by Dr. Fofi Constantinidou, Department of Speech Pathology and Audiology.

Post-Concussion Rating Scale

The post-concussion rating scale used in this study was a Likert Rating Scale, used to rate 21 symptoms associated with concussion. Lovell and Collins (1998) developed this rating scale as a standardized method to classify subjective symptoms after suffering from concussion. The rating scale used in this study was modified for Miami University’s Sports Concussion Management Program.
Results

Subjects

All subjects included in this study were both male and female athletes from Miami University. Twenty-eight male athletes and twelve female athletes participated in ERP data collection. Baseline neuropsychological data was available for all subjects and post-concussive neuropsychological data was available for subjects with history of concussion at Miami University. Baseline ERP measures were collected from twenty-three athletes, while two athletes returned for ERP testing within three days of sustaining a mild traumatic brain injury. Three athletes returned for ERP testing within six months post-concussion and twelve athletes returned for ERP testing an average of one year post-concussion to complete ERP measures. Subjects ranged in age from 17 to 22 years.

Table 2 provides demographic information for all of the participants in the study.

Table 2.
Demographic Information for All Participants

<table>
<thead>
<tr>
<th>Sport Played</th>
<th>No History of Concussion</th>
<th>History of Concussion (1 year prior)</th>
<th>Recent History of concussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Football</td>
<td>14</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Men’s Hockey</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Men’s Basketball</td>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Women’s Field Hockey</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Women’s Soccer</td>
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<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Women’s Softball</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>12</td>
<td>5</td>
</tr>
</tbody>
</table>

Data Analysis

Descriptive analyses and inferential statistics were completed to address each research question. A variety of statistical analyses were performed at $\alpha = .05$ to determine whether ERP measures are a reliable measure of cognitive change after onset of mild traumatic brain injury. P300 waveforms were compared by measurement of latency...
(milliseconds) and amplitude (microvolts). All N1 and P300 waveforms were elicited from one electrode site, Cz, on the scalp. Responses to infrequent stimuli were used in data analyses to make comparisons between non-concussed and concussed athletes.

ERP data was collected and analyzed in several different manners to ensure test-retest reliability. Data measurements included peak-to-peak amplitude, latency, absolute peak, and left and right weighted-add waveforms. Peak-to-peak amplitude is the measure of amplitude between the highest point and lowest point of a waveform; it was measured by the subtraction of N2 amplitude from P3 amplitude. ERP latency is the delay between presentation of the stimulus and the brain’s detection of the stimulus; it was measured by marking N1 and P3 and measuring the distance from zero. Absolute peak is the highest measure of amplitude of a waveform; it was measured by marking the P3 waveform at the highest peak and calculating the amplitude. Absolute peak voltage is calculated from the difference in mV baseline at the stimulus onset to the highest peak of the waveform. Multiple waveforms of the same type may be added together, or averaged, to provide a more accurate measure. Therefore; left and right weighted-add was completed by adding together both left waveforms and both right waveforms. This particular analysis is used clinically to allow for more reliable measurements of the collected data.

Research Question 1: Are the event-related potential measures sensitive in the detection of cognitive deficits following onset of mild traumatic brain injury?

Multiple analyses have been chosen to reliably evaluate sensitivity of types of measurements and types of waveform manipulation. N1 latency increased after onset of concussion, but with much variability. Table 3 depicts separate averages of the ERP data according to stimuli location; small increases in latency of the N1 waveform on certain trials were detected within the group of concussed subjects. Tests of binaural, left, right, left weighted-add and right weighted-add trials between non-concussed and concussed groups were analyzed using One-Way ANOVA of Variance. For all trials, there was insufficient evidence to indicate a significant difference between groups of the N1 waveform (Binaural t(1)=.061, p=.807, Left t(1)=.627, p=.434, Right t(1)=.015, p=.904, Left Weighted-Add t(1)=.094, p=.761, Right Weighted-Add t(1)=.179, p=.675). Figure 1
illustrates the differences between the latency of the N1 waveform between non-concussed and concussed athletes.

Table 3.  
N1 Waveform Latency

<table>
<thead>
<tr>
<th>Location of Stimulus</th>
<th>Binaural</th>
<th>Left</th>
<th>Right</th>
<th>Left Weighted</th>
<th>Right Weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Concussed</td>
<td>94.63(10.54)</td>
<td>89.47(12.26)</td>
<td>91.50(12.08)</td>
<td>95.67(12.12)</td>
<td>90.01(10.15)</td>
</tr>
<tr>
<td>Concussed</td>
<td>93.77(8.47)</td>
<td>92.73(10.58)</td>
<td>91.05(7.49)</td>
<td>96.97(11.99)</td>
<td>91.37(6.89)</td>
</tr>
</tbody>
</table>

*( )= Standard Deviation

Figure 1.  
N1 Latency of Non-Concussed and Concussed Athletes
Separate averages according to stimuli location revealed increased latency of the P300 waveform within the concussed group. The average latency of P300 in all conditions within the non-concussed group equaled 292.179 milliseconds, while the average latency of P300 in all conditions within the concussed group equaled 303.437 milliseconds. P300 latency increased after onset of concussion with much variability as seen in Table 4. Tests of binaural, left, right, left weighted-add and right weighted-add trials between non-concussed and concussed groups were analyzed using One-Way Analysis of Variance (ANOVA). For all trials, there was insufficient evidence to indicate a statistical difference between groups by P300 waveforms (Binaural $t(1)=.057, p=.812$, Left $t(1)=.810, p=.375$, Right $t(1)=.310, p=.582$, Left Weighted-Add $t(1)=.202, p=.656$, Right Weighted-Add $t(1)=.253, p=.618$). Figure 2 illustrates the differences in latency of the P300 waveform between non-concussed and concussed athletes across conditions.

Table 4.
P300 Waveform Latency

<table>
<thead>
<tr>
<th></th>
<th>Binaural</th>
<th>Left</th>
<th>Right</th>
<th>Left Weighted</th>
<th>Right Weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Concussed</td>
<td>268.53(38.09)</td>
<td>297.77(52.98)</td>
<td>293.01(47.46)</td>
<td>311.40(58.48)</td>
<td>286.97(49.17)</td>
</tr>
<tr>
<td>Concussed</td>
<td>272.47(59.51)</td>
<td>316.56(70.56)</td>
<td>303.62(65.45)</td>
<td>321.32(71.62)</td>
<td>296.56(63.46)</td>
</tr>
</tbody>
</table>

*( )= Standard Deviation
Peak-to-peak amplitude revealed higher amplitude of the P300 waveform within the concussed group on most trials. Table 5 provides averages across trials of P300 peak-to-peak amplitude between non-concussed and concussed athletes. Tests of binaural, left, right, left weighted-add and right weighted-add trials between non-concussed and concussed groups were analyzed using One-Way ANOVA of Variance. For all trials, there was insufficient evidence to indicate statistical differences between groups by P300 waveform peak-to-peak amplitude (Binaural t(1)=.603, p=.443, Left t(1)=1.05, p=.313, Right t(1)=.172, p=.681, Left Weighted-Add t(1)=.039, p=.846, Right Weighted-Add t(1)=.089, p=.767). Figure 3 illustrates the differences between the peak-to-peak amplitude of the P300 waveform between non-concussed and concussed athletes.
Table 5.
P300 Waveform Peak-to-Peak Amplitude

<table>
<thead>
<tr>
<th></th>
<th>Binaural</th>
<th>Left</th>
<th>Right</th>
<th>Left Weighted</th>
<th>Right Weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Concussed</td>
<td>15.53(7.57)</td>
<td>11.53(3.63)</td>
<td>14.23(6.71)</td>
<td>11.80(4.85)</td>
<td>14.39(6.76)</td>
</tr>
<tr>
<td>Concussed</td>
<td>17.58(7.84)</td>
<td>13.10(5.48)</td>
<td>15.14(5.81)</td>
<td>12.12(4.53)</td>
<td>13.77(4.70)</td>
</tr>
</tbody>
</table>

*( )= Standard Deviation

Figure 3.
P300 Waveform Peak-to-Peak Amplitude of Non-Concussed and Concussed Athletes
Research Question 2: Do binaural ERP measures correlate with averaged individual waveforms?

Binaural waveforms were collected by stimulating central areas of the cerebrum, while individual waveforms were collected by stimulating each separate hemisphere of the cerebrum. Therefore, differences may occur between the location of stimuli arousal depending on the location and severity of concussion. Separate averages of N1 latency and P300 latency of binaural and individual waveforms, by group, revealed insufficient evidence of statistical differences by location of elicitation. Bivariate correlation of N1 latency was completed revealing a low correlation (Binaural and Left Weighted-Add p=.117, Binaural and Right Weighted-Add p=.131). While a Bivariate Correlation of P300 latency revealed a higher correlation (Binaural and Left Weighted-Add p=.481, Binaural and Right Weighted-Add p=.607). Research supports the higher correlation of individual and binaural P300 responses due to the more central location of stimulation and waveform etiology.

Research Question 3: Are neuropsychological measures sensitive in the detection of cognitive deficits following onset of mild traumatic brain injury?

Multiple analyses were conducted to determine the sensitivity of neuropsychological measures. Twenty-one non-concussed and 14 concussed subjects were compared using separate averages across trials. The average standard score of non-concussed subjects equaled 39.95 and the average standard score of concussed subjects equaled 39.00. No differences were revealed between non-concussed and concussed athletes on the Controlled Oral Word Association Test as seen in Figure 4 (t(1)=.091, p=.765). Non-concussed subjects scored higher on the Controlled Oral Word Association Test, than concussed subjects, indicating the negative effects of mild traumatic brain injury. Due to small subject size, statistical correlations were not possible between ERP data and neuropsychological measures. Visual trends were noted, revealing slight cognitive decline following concussion in college athletes with both event-related potentials and neuropsychological measures.
One assessment revealed significant differences between groups as seen in Figure 5. The Grooved Pegboard Test using the athletes' dominant hand measured processing and motor speed and revealed statistical differences between groups (t(1)=5.84, p=.021) demonstrating the negative effects of concussion on processing and motor speed. The mean standard score of 21 non-concussed subjects equaled 98.28, while the mean standard score of 14 concussed subjects equaled 89.62. Due to small subject size, statistical correlations were not possible between ERP data and neuropsychological measures.
Figure 5.
Grooved Pegboard Scores (Dominant Hand) of Non-Concussed and Concussed Athletes

Athletes entering Miami University’s program before August 2006, completed the Symbol Digit Modalities Test and the Trail Making Test A and B. Figure 6 illustrates differences between non-concussed and concussed scores. Averages from both the Symbol Digit Modalities and the Trail Making Test B revealed differences between groups, but with much variability (Symbol Digit Modalities $t(1)=1.66$, $p=.267$, Trail Making A $t(1)=.447$, $p=.54$, Trail Making B $t(1)=1.00$, $p=.374$) thus revealing cognitive decline following mild traumatic brain injury.
Research Question 4: Do significant differences exist between male and female athletes when comparing non-injury versus injury?

Data analyses were completed to determine statistical differences between genders. One-Way ANOVA of Variance was used to analyze data between males and females within the non-concussed group and within the concussed group. Results revealed nine trials with statistical significance in the non-concussed group (Binaural P3 Latency t(1)=5.25, p=.034; Binaural P3 Amplitude t(1)=11.94, p=.003; Binaural Peak-Peak t(1)=7.31, p=.014; Left P3 Latency t(1)=9.79, p=.006; Left P3 Amplitude t(1)=12.90, p=.002; Left Peak-Peak t(1)=5.71, p=.027; Right P3 Latency t(1)=7.75, p=.012; Right P3 Amplitude t(1)=8.72, p=.008; Right P3 Peak-Peak t(1)=10.48, p=.004). Great differences were found between male and female averages of P300 latency in the non-concussed group; an example is provided below in Figure 7. Statistical analyses of the concussed group revealed only one significant difference between gender (Right P3 Amplitude t(1)=5.22, p=.041).
As seen in Figure 8 below, both male and female subjects in the concussed group revealed increased P300 latency, with little difference between gender. Overall, non-concussed athletes demonstrated greater differences between gender than concussed athletes with greater increased P300 latency after concussion in females. Therefore, female subjects may be more sensitive to the effects of concussion than male subjects.

Figure 7.
Non-Concussed Gender Differences of Binaural P300 Latency
Discussion

**ERP Measures as Cognitive Assessment**

The purpose of the current study was to determine sensitivity of ERP measures in detecting cognitive change after concussion to improve the quality and reliability of sports concussion management programs. Kelly (2000) reported on the detrimental effects of Second Impact Syndrome that may result when an athlete suffers from multiple concussions causing severe damage to the brain and cognitive functions. Therefore, it is imperative that concussion management programs are improved to protect college athletes. Gaetz & Bernstein (2001) identified the need to determine deficits in current concussion management programs and measures.

Previous studies have reported that neuropsychological measures are the most sensitive measures in determining cognitive decline following concussion in college athletes (Kelly, 2000). This study found that neuropsychological measures found differences between non-concussed and concussed athletes. The present study included a
limited number of athletes who underwent neuropsychological testing and the results are inconclusive.

ERP measures were also used to determine cognitive change following concussion in college athletes. Both the N1 and P300 waveforms were studied by measurements of latency and amplitude in a variety of conditions: binaural, left, right and left/right weighted-add. The P300 waveform, as reported to be the most positive-going component of ERP data, was identified on all trials and was measured using latency in milliseconds and amplitude measurements in microvolts. There was delayed latency across trials in a small group of concussed athletes, thus revealing reduced processing speed following mild traumatic brain injury. Results were similar to information Gaetz and Bernstein (2001) who reported latency may be increased by cognitive decline. Although no significant differences were found between groups, latency of the P300 waveform consistently demonstrated change following mild traumatic brain injury in the concussed group.

Although statistical correlations could not be completed, similarities were found between neuropsychological assessment results and P300 latency. The Grooved PegBoard Test and P300 latency both measure processing speed. Both assessments demonstrated that athletes had slowed processing speed following concussion. This is an important finding for concussion management programs and it is consistent with previous research. It reveals specific deficits that can be easily identified when determining concussion severity and when making return-to-play decisions.

Statistically significant differences were found between male and female athletes in the non-concussed group, thus revealing gender differences between healthy young adults. Only one statistically significant trial was observed between male and female athletes in the concussed group. These findings demonstrate greater adverse effects in females following concussion than males. Concussed female athletes had a greater increase in mean P300 latency across trials, indicating a significant decrease in processing speed. Male athletes had only a slight increase in P300 latency, indicating only mild effects of concussion. This finding is important to concussion management programs because male and female athletes may require different criteria when making return-to-play decisions for each individual’s safety.
Implications

Findings from the current study may be used in the future to improve clinical practices and concussion management programs. The field of sports medicine is expanding and a need has been identified for additional research in the area of sports concussion. Data from the current study can be used to enhance return-to-play decisions. Previous studies have found that many athletes are poor self-reporters of symptoms and more objective measures must be used to ensure the safety of athletes. Currently, many athletic programs utilize rating scales and neuropsychological measures to make return-to-play decisions. Therefore, the addition of ERP measures would create a more comprehensive and reliable concussion management program.

Few studies collected ERP baseline measures from non-concussed college athletes. Results from the current study provide a representative sample of how normal college athletes perform on ERP baseline assessment and reveal significant gender differences before and after concussion. This information may be used to further define abnormalities and severity of abnormalities in the future. Overall, findings from the current study may provide implications for future research.

Limitations

Limitations of this study were identified in hopes to improve future research. One limitation of the current study was the small data sample of all athletes (n=40). Only new athletes entering Miami University’s athletic program completed the electrophysiologic baseline assessments during the 2007-2008 academic year and no athlete completing baseline assessment this year sustained a concussion. Therefore, it was not possible to make large group comparisons between baseline and post-concussion scores, which was the goal of the current study. While several athletes sustained concussions and received follow up neuropsychological testing, those athletes did not receive electrophysiologic testing due to scheduling and procedural challenges. It is expected that as the electrophysiological monitoring becomes part of the concussion management program, the aforementioned procedural challenges will be minimized.

Another possible limitation of the study is the timing of the baseline testing. Many athletes completed baseline testing during pre-season practices and were tired, fatigued and stressed, which may have created some variability in the baseline data.
Fjell & Walhovd (2003) discussed the impact of skull thickness on ERP measures. In this study, there was no specific or reliable way to determine skull thickness of each individual subject. Therefore, a variation between subjects exists that may alter the results of ERP testing based on skull density.

**Recommendations for Future Research**

Future research should focus on differences between individual subjects’ baseline and post-concussion scores to identify the direct effects of concussion on ERP data. Furthermore, the contribution of gender on electrophysiologic testing should be explored systematically. Post-concussion ERP testing should be conducted during the same visit as the neurocognitive testing to allow for improved monitoring and the ability to make reliable comparisons between ERP measures and neuropsychological performance.

In the future, ERP testing could manipulate task difficulty to better quantify the effect of the injury on electrophysiologic measures. This may be achieved by producing frequent and infrequent tones at a closer frequency. For example, the frequent tone could continue to be presented at 250 Hz, while the infrequent tone could be presented at 500 Hz. This paradigm change would make the task more difficult for subjects and may reveal more sensitive ERP findings. Previous research suggests that skull thickness may affect ERP results and could contribute to a gender effect. Future research should estimate skull thickness for each athlete during the baseline assessment by taking measurements of the skull and projecting thickness according to previously recorded averages. One of the challenges during the ERP testing in the present study centered on the athletes’ ability to maintain a stable head and minimize head movements. Therefore, the use of a neck collar or pillow may help stabilize the head and reduce artifact.

**Conclusion**

Effective sports concussion management requires a team effort. In the past 20 years, neuropsychological testing has played an integral role in this effort by providing an objective and sensitive method of quantifying the effects of concussion (Barth et al., 1983). The addition of ERP measures would contribute to the current concussion management protocols by providing additional objective information regarding the electrophysiology of brain neurons associated with specific cognitive areas. The combination of ERP and neurocognitive measures can aid athletic trainers and physicians
in making return-to-play decisions. More empirical evidence is needed at this time to determine if ERP measures have clinical value in baseline assessment and concussion monitoring in college athletes.
References


