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Head-Impact-Related Outcomes by Position in Retired NFL Football Players

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HEAD-IMPACT–RELATED OUTCOMES BY POSITION IN RETIRED NFL FOOTBALL PLAYERS

by

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ABSTRACT

This study examined how repeated head-impact-related traumatic brain injury experienced by retired NFL players impacts their neuropsychological functioning, as well as whether player position was a significant factor in the impairment experienced. Participants (N=142) were selected from an archival database gathered through the NFL Concussion Settlement belonging to the Neuropsychology Assessment Center of Nova Southeastern University.

One-Sample T-Tests indicated that the combined sample and the Skilled players group demonstrated significant differences in all neuropsychological measures, while the Linemen and Skilled Linemen evidenced impairment in most areas except in visual-spatial and non-timed language measures. Two-way ANOVAs indicated player position and ethnicity main effects, as well as interaction effects.

Findings indicate that the greatest impairments evidenced in executive functioning, processing speed, and verbal memory amongst this population. The memory difficulties noted were hypothesized to be further impacted and mediated by the impaired ability to come up at utilize organizational and compensatory strategies in order to create further structure can mediate and impact their performance in such tasks.

Regarding language abilities, it can be hypothesized that non-timed, non-memory-based language tasks, such as the WAIS-IV Similarities subtest and the Boston Naming Test are the least susceptible to being affected by diffused forms of brain injury experienced by all player position groups. The results in this study appeared to indicate that all player groups did not show significant impairment primarily in subtests measuring visual spatial functioning measures.

Significant differences were found between the player groups themselves, indicating that experiencing frequent and repetitive head injuries may lead to chronic neurological and neuropsychological impairment, which may lead to the continuous disruption of the recovery process and possible syndromes such as second impact syndrome. Additionally, these findings indicate that experiencing of repetitive subconcussive injuries can lead to significant neurological alternations as well. Significant differences related to ethnicity were further evident on the majority of measures. The present study suggests that the retired NFL players experience deficits that are significantly different from those evidenced in the general population. This research could further inform professionals and the general population about the potential long-term consequences of multiple brain injuries.

CHAPTER I

Statement of the Problem

Brain injuries experienced by professional athletes is a significant issue that is being explored in existing research and highlighted in the popular media. Specifically, more and more cases regarding athletes who received repeated injuries throughout their career and report long-term neurocognitive and psychological dysfunction are raising alarming concerns that need to be addressed. Despite multiple studies looking at different forms of brain injurie in athletes, as well as other populations, the existing research is yet to agree upon significant and consistent findings related to the diagnosis of concussions and subconcussive injuries, the resulting deficits and dysfunctions related to both single and recurrent injuries experienced by individuals, and any factors that may contribute to the acquirement and or worsening of sport-related brain injury. Therefore, this study attempts to extend the body of research on head-impact-related traumatic brain injury experienced by retired National Football League players by using neuropsychological assessment methods to possibly gain understanding of what the long-term effects of repeated concussive and subconcussive injuries are after retirement from the NFL. Specifically, this study will look at whether player position is a significant factor in neuropsychological impairment is experienced by this population.

CHAPTER II

Review of the Literature

Past Research and Definitions of Traumatic Brain Injuries

Traumatic brain injury (TBI) is an important public health problem in the United States and worldwide. Although there are many statistics supposedly reporting the number of people worldwide that have been hospitalized with one or more TBIs, the true proportion of those living with TBI-related disability is not known due to several reasons. For example, in the United States, national data does not include persons treated for TBI in settings such as hospital outpatient settings or physicians' offices (Finkelstein, Corso, & Miller, 2006), or military facilities both in the United States and abroad are not included (Langlois et al., 2006). Additionally, there are many individuals who receive medical care but the TBI is not diagnosed, or who sustain a TBI but do not seek care. Due to these reasons and more, it is impossible to understand the impact and consequences that TBIs have on individuals and communities worldwide.

What is known about TBIs, however, is that it is of special concern among certain groups of individuals. For example, studies have shown that as many as 87% of incarcerated persons in prison or jail report a history of head injury, such as TBIs (Langlois et al., 2006). Military personnel and rescue workers are also at a greater risk than the average individual to sustain a TBI (Langlois et al., 2006). A group that is of particular interest to this specific study is individuals engaged in sports and recreational activities. Research indicates that, among individuals 15 to 24 years of age, sports are second only to motor vehicle crashes as the leading cause of concussions (Marar et al., 2014). A past study by the Center of Disease Control and

Prevention estimated that approximately 300,000 TBIs and concussions specifically with accompanying loss of consciousness occur each year (Langlois et al., 2006). When taking into account such injuries that are not accompanied by loss of consciousness, that number is approximated to increase to a range of 1.6 to 3.8 million sport-related TBIs.

For many years, there was no consensus of what the definition of a concussion is. In recent years, the International Conference on Concussion in Sport defined a concussion as "complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces" (Meehan et al., 2013). The definition further identified the following clinical, pathological, and biomechanical injury constructs that may be used to define the nature of a concussive head injury: (1) a direct blow to the head, face, neck, or elsewhere on the body with an "impulsive" force transmitted to the head, (2) it typically results in the rapid onset of short lived impairment of neurological function that resolves spontaneously, (3) it may result in neuropathologic changes, but the acute clinical symptoms may largely reflect a functional disturbance rather than a structural injury, (4) it results in a graded set of clinical symptoms that may or may not result in a loss of consciousness, and that the resolution of the clinical and cognitive symptoms will typically follow a sequential course (although a small percentage of cases will evidence prolonged post-concussive symptoms), and (5) no abnormality on standard structural neuroimaging studies is seen in concussions.

Furthermore, when it comes to categorizing types of concussions, the Summary and Agreement Statement of the 2nd International Conference on Concussion in Sport provides two main categories: simple and complex concussions. Simple concussions are the most common form of concussions, and are categorized by the fact that, aside from the time in which a player is limited from playing or training while symptomatic, an athlete with such an injury will not require further intervention during recovery and will be able to resume playing without further complications (McCrory et al., 2004). For most athletes, a single concussion is typically a type of injury in which symptom resolution and neuropsychological recovery tends to occur in less than two weeks (Lovell et al., 2004; McCrea et al, 2003). Complex concussions, on the other hand, are categorized by the "presence of persistent symptoms which can be present with or without additional exertion, specific sequelae (such as concussive convulsions), prolonged loss of consciousness (more than 1 minute) or prolonged cognitive impairment after the injury" (McCrea et al, 2003). Complex concussion cases can also include athletes who suffer multiple concussions over time or where repeated concussions occur with progressively less impact force (McCrea et al, 2003). Due to the higher frequency of simple concussions, a majority of the research is focused on this type, and there is limited research on complex forms of concussions. However, increasing research in this area is needed, as research has shown that receiving a concussion has been linked to an increased risk of future concussions. For example, a study by Zemper (2003) has presented data which indicates that athletes have a 5.8 times greater risk of sustaining another concussion if they have had a previous concussion. Furthermore, those athletes which experienced more than three concussions tend to recover significantly slower from the consequences of concussions than athletes who experienced only one concussion (Guskiewicz et al., 2003).

Furthermore, it is becoming increasingly important to understand the effects of both a single and an accumulation of multiple concussions. So far, some existing research appear to indicate evidence that acquiring three or more concussions is associated with long term changes on one's neurophysiological, subjective reported symptoms, and neuropsychological test performance (i.e., memory deficits) (Gaetz, Goodman, & Weinberg, 2000; Iverson et al., 2004), as well as worse on-field presentations of their next concussion and slower recovery (Collins et al., 2002). However, the existing literature is highly varied in their results related to the possible accumulative effect, in that many studies have not found any significant findings. As a result, it is important to additionally take into consideration methodological limitations and possible alternate explanations surrounding each study.

Traumatic Brain Injuries in Sports

As previously stated, one of the populations that is significantly impacted by both single and recurrent concussions are athletes. In this population, the most commonly reported concussion symptom was headache (94.2%), followed by dizziness (75.6%) and concentration difficulty (54.8%). Other symptoms included confusion (45.0%), light sensitivity (36.0%), and nausea (31.4%) (Marar et al., 2014). Among football players in particular, a study by Marar et al. (2014) indicated that highest proportion of concussion in football injuries occurred during running plays (48.5%) and resulted from player-player contact (87.8%); the acts of tackling and being tackled were responsible for 62.5% of concussions. Furthermore, it was found that the overall rate of concussions was higher in competition games in comparison to practice games.

Existing research indicates that one factor that affects the likelihood of sustaining head impacts is playing position, which is believed to be due to different on-field responsibilities during a game. For example, offensive linemen and defensive linemen will engage in higher-frequency but lower-magnitude impacts on most plays as a result of starting on the line of scrimmage and engaging in blocking and rushing the quarterback in a short distance (Broglio et al., 2009). Offensive linemen additionally report higher frequencies of engaging in full-contact practices on a weekly basis in comparison to all other positions, thereby increasing their contact with players even outside of actual games (Baugh et al., 2015).Athletes involved in offensive and defensive skill positions, such as running backs, linebackers, defensive backs, wide receivers, and quarterbacks, will experience fewer but impacts of a higher-magnitude as a result of engaging in plays involving full-speed open field tackling (Broglio et al., 2009). On the other hand, some special team players, such as punters, kickers, and long snappers, are only involved in a small percentage of plats and will consequently receive less-frequent impacts in comparison to other positions. Existing research regarding position-specific differences have been explored using clinical data such as self-report methods and athletic trainer examination, as well as more objective measures, such as through the use of in-helmet accelerometers to measure the variation in the frequency and magnitude of head impacts. For example, a study using athlete self-report of symptoms found that linebackers and offensive linemen have the highest concussion rates per 1000 athlete exposures (Guskiewicz et al, 2003). In-helmet accelerometer studies have also been consistent with these findings, demonstrating measures that offensive and defensive linemen sustain the highest number of head impacts, although at a lower magnitude in comparison to other positions (Mihalik et al, 2007; Crisco et al. 2010; Crisco et al., 2011). In-helmet technology, such as using the Head Impact Telemetry (HIT) system can be used to accurately measure the frequency and magnitude of head impacts experiences as they do not interfere with normal plays unlike other technologies used.

Additional research by Baugh et al. (2015) found that, not only did football positions differ in frequency and magnitude, but in post-impact symptoms experienced; this article indicated that offensive lineman, for example, repeated more-frequent symptoms that are unlikely to be externally visible (such as headaches, concentration difficulties, and dizziness). The authors of this study interpreted this finding as the possibility that variables such as the frequency of impacts, linear nature of forces, and/or the total cumulative g force of the impacts sustained by lineman lead to the higher-frequency of these symptoms. Pellman et al. (2004) also proposed that linear accelerations to the head specifically can impact and increase the risk of concussion injury. This fascinating finding can be conceptualized as being consistent with existing research that states that an increase in total impacts can lead to small but measurable increases in neurological symptoms (Gysland et al., 2012).

Despite the possible consequences of concussions for athletes, research indicates that there is a high rate of failing to report the sustaining of a concussion or any relevant symptoms. For example, a 2004 study by McCrea et al. indicated that 47.3% of high school football players that sustained a concussion reported their symptoms. A study by LaBotz et al. in 2005 indicated that only 17% of collegiate-level athletes reported sustaining a concussion, even though approximately 48% reported the sustaining of a head injury that was followed by the signs and symptoms that are indicative of a concussion. In NCAA Division I football athletes, Baugh et al. (2015) found that certain player positions, such as offensive linemen, tend to report returning to play more frequently while still experiencing post-impact symptoms significantly more frequently, indicating that athletes that experience more frequent impacts might begin to consider head impacts a normal or routine aspect of their job and possibly feel less compelled to report resulting symptoms.

Furthermore, while the existing research is focused on studying athletes with diagnosed concussive injuries, there has been emerging interest in studying the effects of subconcussive injuries experienced by athletes. A subconcussive injury is defined as a cranial impact that does not result in known or diagnosed concussion on clinical grounds (Belanger et al., 2016). These types of injuries can occur with rapid acceleration-deceleration of the body or torso often seen in sports when athletes are hit, particularly when the brain is free to move within the cranium.

While these types of injuries do not result in a diagnosable concussion, they are still hypothesized to have an adverse long-term effect in some individuals. Such adverse effects include contributing to the development of depression, postconcussive syndrome, posttraumatic stress disorder, cognitive impairment, and dementia pugilistica (Bailes et al., 2013). Additionally, autopsy data evidenced in existing research have shown that there are subsets of athletes in contact sports who do not have a history of known or identified concussions but nonetheless have neurodegenerative pathology consistent with chronic traumatic encephalopathy (Bailes et al., 2013). Talavage et al. (2013), studied athletes with no readily observable symptoms but who instead exhibited functional impairment as measured by neuropsychological testing and fMRI studies, and found that neurological impairment occurred despite a lack of symptoms typically associated with a clinically diagnosed concussion. Subsequent work by the same investigators suggests that it is the accumulation of multiple blows to the head, rather than a single event, that can produce neurological impairments (Breedlove et al., 2012). Overall, their work implies that the sequence of blows experienced by a player can mediate the severity of the observed symptoms that lead to the clinical diagnosis or no diagnosis of concussion, and that the potential for accumulated damage would also probably involve biochemical factors of the period of cellular vulnerability, a hypermetabolic state, or vascular dysautoregulation, similarly to the pathophysiological mechanisms evidenced in mTBIs (Bailes et al., 2013).

Regarding position-based differences in subconcussive hits, existing research has evidenced significant differences amongst player positions and professional level. For example, A study by Broglio et al. (2012) examined 95 high school football players across four seasons by using a helmet telemetry system to record the total number of head impacts and the associated acceleration forces. Results showed that the average player sustained 652 impacts (range 5–2235 impacts) during a season, and that the linemen group had the greatest number of impacts per season (868); followed by tight ends, running backs, and linebackers (619); quarterbacks (467); and receivers, cornerbacks, and safeties (372). Additionally, Schnebel et al. (2007) used accelerometers embedded in the crown of helmets in both high school and collegiate football players and utilized a threshold in the range of 60–90g (mean 75g) for measuring possible concussions. These researchers found that while the expected number of high-speed, open-field collisions in skill position athletes, with forces in the range of 90–120g, linemen players incur impacts of 20–30g on nearly every play (Schnebel et al., 2007). Given that linemen have to lunge forward to immediately encounter their opposing player, head contact occurs on a constant and very frequent basis. Schnebel et al. (2007) also noted that linemen additionally experienced high impacts of up to 120g forces in 1 out of every 120 plays, indicating that they experience both subconcussive and concussive injuries on average.

As a result, understanding position-based differences in concussions and subconcussive hits could be used to inform strategies for risk reduction such as providing position-based education to the athletes and increased awareness and education to sport medicine clinicians about between position variability in symptom types experienced and tendency to report symptoms. Furthermore, these differences could be used to inform rule changes to reduce the frequency of impacts and possibly reduce resulting and persistent dysfunction.

Methods of Assessing TBIs and Relevant Findings

Since sport-related concussions can present with a mixture of cognitive, physical, emotional, somatic, and even sleep-related symptoms, it is recommended that a multifaceted approach to assessment should be taken to best accurately measure symptom presence, severity, and ongoing recovery. Among some of the proposed assessments are physical examinations, clinical interviews, self-report of symptoms, neurocognitive tests, and balance tests, among others. Despite the use of various methods, some have suggested that consistent findings related to concussive injury may be difficult to establish due to the varying nature of impact location, frequency of getting concussed, and the varying levels of magnitude. Therefore, multiple methods of assessing TBIs and their relevant findings will be discussed.

Neuropsychological Testing

Ideally, individuals should be provided with baseline assessments of cognitive functioning, as they provide an experimental control of an individual's premorbid functioning, as well as any individual differences between players of the same sport or even same position. Otherwise, any individual who otherwise just may have relative weaknesses in one or more cognitive domains or may simply perform more poorly that others overall might get incorrectly classified as injured. Currently, at the professional level, NFL players are administered the ImPACT measure. The Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) is the most popular of the computerized batteries used in sports today. In addition to a symptom checklist, the test generates four primary clinical composites: Verbal Memory, Visual Memory, Visual Motor Speed and Reaction Time. Studies have demonstrated that ImPACT is sensitive enough to indicate concussions in athletes. For example (a) high school athletes with grade I (''ding'') concussions showed a decline in memory one to three days after the injury as measured by ImPACT, followed by a return to baseline at 5–10 days after the injury (Lovell et al., 2004); (b) concussed athletes reporting headaches one week after the injury had slower reaction times and lower memory scores than concussed athletes who did not report headaches (Collins et al., 2003); (c) concussed athletes reporting perceived ''fogginess'' one week after the injury had slower reaction times, reduced processing speed, and lower memory scores than concussed athletes who did not report fogginess (Iverson et al., 2002). Expanding on findings related to impaired memory performance, it was found that multi-concussed athletes were 7.7 times more likely to show a drop in memory performance in the acute phase immediately following injury than concussed athletes with a history absent of past concussions (Iverson et al., 2005).

The use of formal neuropsychological assessment tools has been shown to be reliable and valid in the detection of a concussion, and they have been utilized to document and make objective decisions on an injured athlete's ability to return to play, track recovery curves, and possibly protect against multiple-concussion or second impact syndrome-related injuries through the implementation of serial assessments (Barth et al., 2011). Once an athlete has received a head injury that could be suspected to be a concussion, immediate post-concussion sideline assessments are able to be used. One such measure currently used by the NFL is the Sideline Concussion Assessment Tool (SCAT-5). The SCAT-5 can be used by professionals in the evaluation of individuals 13 years or older who are suspected of having sustained a sport-related concussion. This most recent version contains an immediate/acute assessment section which includes indications of emergency management and signs of a possible concussion. The SCAT-5 also now has a section which includes affirmation that the SCAT5 was used or supervised by a healthcare professional, whether a concussion was diagnosed, and that written clearance by a healthcare professional is needed prior to returning to play/sport. As in previous versions, this measure further includes a symptom checklist, a brief cognitive evaluation [the Standardized Assessment of Concussion (SAC)] (McCrea, 2001) the Maddocks questions (Maddocks & Dicker, 1989) and a and a rapid neurological screen. It additionally includes a Glasgow Coma Scale and signs of concussion (loss of consciousness, balance dysfunction). The SAC component is comprised of four components meant to assess orientation, immediate memory, concentration, and delayed memory. Validity studies conducted on the SAC indicate that this measure can accurately classify concussed athletes with 95% sensitivity and 76% specificity (Barr & McCrea, 2001; McCrea, 2001). Using this measure, it has been found that concussed athletes demonstrate deficits in immediate memory and delayed recall, as well as decreased performance in comparison to individual baseline performance. However, sideline assessments such as the SAC provide only a gross indication of an athlete's cognitive abilities or deficits, and as such, return-to-play decisions should not tend to be based on these decisions (Collins, Lovell, and McKeag, 1999).

Yet another of the most popular methods of assessing concussion-related deficits is through the administration of the Post Concussion Symptom Scale (PCSS). The PCSS is a symptom inventory containing a total of 22 symptoms which athletes can then rank on a scale from 0 (indicating that an athlete is not experiencing a given symptom), to 6, (indicating a symptom as "severe"), leading to a possible total score that can range between 0-132. Aside from helping assess current concussions, this tool has been able to be used to identify previously undiagnosed concussions through retrospective interviews with individuals that previously suffered head trauma but were not formally diagnosed with a concussion. A relevant and important finding related to this measure is that athletes who reported sustaining a previously undiagnosed concussion were more likely to have lost consciousness and have a higher mean PCSS score with their current injury than athletes without previously undiagnosed concussions (Meehan et al. 2013). Additionally, higher mean PCSS scores tend to be associated with an increased likelihood of loss of consciousness and increased symptom duration with a recurrent injury (Guskiewics et al., 2003; Castile et al., 2012).

Post-injury, traditional paper-and-pencil assessments are utilized in combination with computer-acquired baseline data, particularly when the athlete in question has a complex concussion history or if their computerized cognitive baseline is considered to be suboptimal or invalid. Regarding paper-and-pencil measures, there is currently a test battery implemented by the NFL which resulted from the collection of data from 1996-2001. This battery evaluates multiple aspects of cognitive functioning, including attention, visual scanning, information processing and psychomotor speed, visual and verbal learning and memory and verbal fluency (Lovell & Solomon, 2011). The current battery includes the Hopkins Verbal Learning Test-Revised (HVLT-R), Brief Visuospatial Memory Test-Revised (BVMT-R), Trail Making Test (TMT; Parts A and B), Symbol Digits Modalities Test (SDMT), Controlled Oral Word Association Test (COWAT), and Digit Span (Forwards and Backwards). Both the HVLT-R and the BVMT-R assess for both immediate and delayed forms of the respective type of memory they assess (verbal or visual), and they both have six equivalent forms, which minimizes practice effects and makes them ideal for use with athletes who are likely to undergo evaluation on multiple occasions throughout the course of their careers. The TMT consists of two parts and requires the athlete to use spatial scanning, speed, and cognitive flexibility skills. The inclusion of the COWAT further allows for the measuring of verbal fluency. Furthermore, the Digit Span task allows for both the measuring of attention through the forwards component and working memory through the completion of the backwards task. Lastly, The SDMT requires the use visual scanning and processing speed to match a series of numbers and symbols within a timed component. It is important to note that while some of the included tasks have alternate versions that can be used to prevent test-retest effects, tasks such as the TMT, the SDMT, and the COWAT demonstrate significant practice effects. For example, a study by Lovell and Collins

(1998) reported mean improvements of 2 seconds on TMT-B in a sample of 40 nonconcussed college football players tested at the beginning and end of the season.

A study by Lovell and Solomon in 2011 analyzed the baseline data of 513 athletes who completed all of these neuropsychological tests and in order to better understand determining whether the norms obtained on the various tests used in the NFL paper and pencil battery were similar to normative values for the general population reported in the literature. Their results indicated that the NFL players' scores were lower on HVLT-R Total and Delayed Recall when compared with normative values published in the HVLT-R manual, and that the scores on COWAT, TMT-A, and TMT-B were about 0.5 standard deviations lower than the average scores reported by Heaton et al. (2004) when compared with Caucasians ages 20 to 34 years old and with 16 years of education, but scores on COWAT and TMT-A were essentially equivalent to the average scores when compared with the norms of African Americans ages 20 to 34 years old and with 16 years of education (Lovell & Solomon, 2011). The NFL players' scores on TMT-B were 0.8 standard deviations above the average reported by Heaton et al. (2004) when compared African Americans ages 20 to 34 years old and with 16 years of education (Lovell & Solomon, 2011). Regarding the BVMT-R, scores were found to be identical to the average scores obtained by individuals ages 24 to 30 years old (Lovell & Solomon, 2011). These results suggest that when assessing NFL players, the normative data presented in this aforementioned article should be used for comparative purposes on the HVLT-R, and that ethnicity may be a relevant factor and should be controlled for when assessing an NFL player's performance on COWAT, TMT-A, and TMT-B.

Due to the findings that the NFL population may perform differently that the general population on standard paper-and-pencil testing, another study by Solomon et al. in 2015 reviewed and summarized the existing literature at the time to ascertain the available published neuropsychological data for professional football players. Regarding active players, the study found that NFL players score similarly to scores reported on the test manual for both immediate and delayed scores on the BVMT-R, as well as for the COWAT (Solomon et al., 2015). However, for the HVLT-R, players mean score was slightly lower in both immediate and delayed memory in comparison to the population scores (Solomon et al., 2015). This study additionally looked at computerized testing data from the ImPACT and found normative data for both active players and draft pick groups. The mean scores for both active players and draft picks demonstrated similar test results (Solomon et al., 2015). Regarding retired players, the same study found that the retirees scored 0.5 SDs lower than general population normative values on BVMT-R immediate (but not delayed) recall (Solomon et al., 2015). However, scores from the TMT and the COWAT appeared to be similar to those of the general population (Solomon et al., 2015). When looking at computerized testing, ImPACT scores fell in the average to low average range when controlled for age (Solomon et al., 2015).

Overall, the results of this literature review evidenced that there is adequate normative data for active and draft pick players for both paper-and-pencil and computerized measures. As a result, a "hybrid model" may be a valuable approach to assessing current active players.

The argument for the use of computerized assessment types include that they are less labor-intensive, can be done more quickly, and can potentially alleviate financial burdens related to traditional neuropsychological assessment. The costs and time requirements of these personnel demands often place such testing out of reach of school districts and many sports organizations. Moreover, it is hypothesized that computer administrations are more objective and standardized than traditional neuropsychological assessments, which can be impacted by same-rater or different rater reliability. Therefore, using computerized assessments could potentially allow for more valid results to be compared. Lastly, research indicates that concussions can show deficits in processing speed that might be too subtle for a human evaluator to measure. For example, Bleiberg et al. (1998) demonstrated that concussed individuals have been shown to significantly differ from nonconcussed individuals on tests of reaction time by margins of 100 milliseconds or less. Currently, some computerized batteries available to measure concussions are the Immediate Measurement of Performance and Cognitive Testing (Maroon et al., 2000), the Concussion Resolution Index (Erlanger et al, 1999), and CogSports (CogState, 1999).

However, computerized test batteries also come with its own set of limitations. Firstly, they can be limited in their ability fully assess memory and are largely limited to recognition memory, and additionally limited in the assessment of receptive auditory processes and verbal abilities. The further limit interaction between athlete and examiner, which reduces the observation of behavior and problem-solving strategies, and it impacts the assessment and management of effort, motivation and distractions are less effectively assessed and managed using group administration formats.

In an effort to acquire the benefits of both forms of assessment, a hybrid model of blending traditional and computer-based tasks can be utilized. A typical example of the Hybrid model is that used by the NHL and NHL Players' Association (NHLPA) Concussion Evaluation and Management Program. In 2006, the ImPACT test was added to the their paper-and-pencil battery. At present, the NHL approach uses ImPACT at baseline and a combination of ImPACT and P&P tests to evaluate players post-injury. ImPACT post-injury test data are compared to a player's individual baseline data whereas the P&P post-injury test scores are compared to a robust NHL-specific normative database that is stratified by a player's language of origin. A player just then undergo post-injury cognitive testing with a neuropsychologist prior to return to unrestricted play, as well as undergo a clinical interview and review of their medical records through a neuropsychologists in order to determine if a player has returned to baseline levels of cognition (Echemendia et al., 2020)

A study by Echemendia et al. in 2020 further explored the hybrid model of testing and utilized factor analysis techniques in order to assess whether the utilization of both types of assessments each contributed to the overall results and were independent of each other, or whether they shared too many common variances are could be seen as overall redundant. Their combined factor analyses of the ImPACT and P&P tests provided support for the unique contributions of P&P and computerized measures and hence the Hybrid model. Five factors (Verbal Learning and Memory, Visual Learning and Memory, and Processing Speed/Executive Functioning) were identified that appeared to be relatively independent of each other (Echemendia et al., 2020). The factors were mainly related to the paper-and-pencil measures without any significant loadings from the ImPACT composites. However, the Cued/Recognition Memory and Reaction Time factors were largely related to the ImPACT composites, except for SDMT Memory (Echemendia et al., 2020). These findings demonstrate the usefulness of each type of assessment, while at the same time demonstrating limitations that clinicians must be mindful of, such as those of the ImPACT as related to assessing memory functions while recognizing the relative efficacy of ImPACT in assessing processing speed.

Despite variability in assessment methods, it has been found that mild TBIs, including concussions, can cause long-term cognitive problems that affect a person’s ability to perform daily activities and return to work (Pellman et al, 2004). One neuropsychological domain that has been researched throughout many studies has been attention, in which it has been indicated that concussed individuals have demonstrated deficits on most tests of attention in comparison to normal controls, and that these differences were found to still be significant even when emotional disturbances and processing speed were controlled for (Chan, 2002). For example, the ability of individuals with post concussive symptoms to sustain attention was found to be impaired in comparison to normal individuals were measured through the use of Digit Span and the Sustained Attention to Response Task (Chan, 2002). Furthermore, these patients also evidenced a higher number of commission errors, as well as differing response styles in committing such errors. Specifically, whereas normal individuals will demonstrate a tendency to slow down their reaction time after committing an error, concussed patients will not demonstrate such a strategy and will keep responding to the task without adjusting accordingly (Robertson et al., 1994). Patients suffering from post-concussive symptoms appear to additionally exhibit increased distractibility when assessments such as the Stroop Word-Color test were used (McLean et al., 1983), as well as deficits related to divided attention when measured through the PASAT and Symbol Digit Modalities Test, for example (Chan, 2002). Lastly, concussed individuals have been found to have impaired attentional control processing and task switching abilities, which has been shown to be related to a higher proportion of dysexecutive behaviors in everyday lives (Chan, 2002). One assessment that has been found to measure this domain is the Six Elements Test. Once again, these findings were found to still be significant after controlling for any emotional disturbances or concerns.

However, there are also many studies which do not conclude the same findings as the previously mentioned findings. Some limitations related to neuropsychological studies include the number of previous concussions, information on time since injury, and severity of injury often being based on athlete self-report. Therefore, issues such as the grade of concussion, duration of time between concussion, and time taken to return to play can often not be significantly analyzed statistically. Additionally, testing an athlete can have obvious lingering effects from a previous concussion that one might have received even before baseline testing (Iverson et al, 2006).

Yet another significant consideration regarding neuropsychological testing limitations is not taking into account ethnicity-based differences. While Black Americans make up approximately 13.2% of the US population , their representation in concussion-risk sports is substantially higher, as the National Collegiate Athletic Association (NCAA) estimates the prevalence of Black athletes in concussion-risk, revenue-producing sports (i.e., football, men's and women's basketball) to be 49.2% (Wallace et al., 2018). Differences between Caucasian and African American individuals and their performance in neuropsychological testing have been documented in multiple studies. A study by Wallace et al. in 2018 demonstrated that significant differences could be found between Black and White athletes college athletes at the baseline testing level. Specifically, they found significant differences on the player's visual motor processing speed and reaction time, in which the Caucasian players performed better. Additional research by Manly et al. in 1998 looking at cognitive performance differences between older Caucasians and African Americans without neurodegenerative disorders evidenced significant ethnic group differences on measures of figure memory (BVRT recognition), abstract reasoning (WAIS-R Similarities), language, executive functioning (category fluency), and visuospatial ability (Rosen Drawings Test and BVRT matching) remained, even after matching participants by education level, occupation, or history of medical conditions such as hypertension and diabetes. Such significant differences in so many domains are highly indicative on one of the salient problems regarding neuropsychological testing, as traditional neuropsychological assessment is usually based on skills that are considered important within majority culture. However, these same skills may not be salient or valued within the African American culture, or other minority cultures. Therefore, differences in salience of cognitive skills, exposure to items, and familiarity with certain problem-solving strategies could have affected the performance of African Americans on the neuropsychological battery. Cultural variability in response set, participant examiner interactions, test taking attitudes, and motivation during the testing session may also account for the ethnic group differences found on tests of both verbal and nonverbal ability (Manly et al. 1998). Furthermore, research has shown that there are even significant differences in how African Americans categorize information, such as word lists, pictures, and situations, differently than the majority Caucasian culture, leading to significant differences in attention, memory, and abstraction tasks (Manly et al. 1998). Therefore, culturally influenced variability in organization and information analysis (e.g., holistic versus detail-oriented, functional versus descriptive) may explain the ethnic group differences on this measure, regardless of whether the education level is expected to be equal (Manly et al. 1998).

Despite the reporting of both acute and chronic post-concussion symptoms among athletes, there is continuing controversy regarding additional factors that could impact the reporting of such symptoms. One factor that appears to be of particular concern is the possibility of malingering, especially in athletes or individuals involved in litigation. One possible explanation for this concern is that objective measures meant to correlate with post-concussive symptoms will often not be consistent and significant throughout studies. However, studies such as one conducted by Sterr et al. (2006) have attempted to rule out this concern by excluding participants involved in litigation of any kind and selecting volunteers that were currently employed or currently studying, and that did not report significant emotional distress. With this participant sample, they were still able to find that the severity of symptoms was related to the level of performance across a range of cognitive tasks.

Vestibular and Ocular System Assessment

Due to the findings that vestibular and ocular system-related symptoms, such as dizziness, is reported in approximately 50% of concussed athletes and that the presence of such a symptom is associated with a 6.4 times greater risk in having a recovery period greater than 21 days (Lau et al., 2011), it is important to utilize methods that measure vestibulo-ocular system functioning. Damage to this system can additionally lead to visual instability and disrupted balance, as well as blurred vision, diplopia, impaired eye movements, ocular pain, and impaired visual-based concentration. One particular assessment that allows for a more thorough evaluation of this system is the Vestibular/Ocular Motor Screening (VOMS) Assessment. In this assessment, patients are asked to perform behaviors that allow for the assessment of smooth pursuit, horizontal and vertical saccades, convergence, horizontal vestibular ocular reflex (VOR), and visual motion sensitivity (VMS), and then asked to verbally rate changes in symptoms compared to their preassessment scores to determine whether symptoms were provoked or worsened (Mucha et al., 2014). Research has shown that the VOMS was able to distinguish concussed from non-concussed athletes, as patients that were concussed scored significantly higher on all VOMS items than the control participants. Researching measuring the significance of the VOMS demonstrated that the specific components of the VOMS such as the VOR, VMS, and NPC distance components are especially useful and provide practical cutoff scores for the accurate identification of concussed individuals. For example, assuming an initial 50% probability that a person is concussed (chance probability), any individual VOMS item resulting in a score of two or greater symptoms increase the probability of being concussed by at least

46%; an NPC distance of 5cm or greater increases the concussion probability of a concussion by at least 34% (Mucha et al., 2014). Overall, this measure provides a positive prediction rate of .89 for the identification of concussed individuals.

Neurological Studies

Sport-related concussions have yet to demonstrate a consistent injury pattern that is detectable in neuroimaging studies. In past research, a great majority of CT studies conducted on boxers, for example, failed to positively indicate lesions or damage, with only the most severe case showing some form of cerebral atrophy (Jordan et al., 1988). MRI studies have also been able to demonstrate few lesion detections (Newton et al., 1992). More advanced neuroimaging techniques, such as fMRI, have demonstrated atypical activation patterns in concussed versus non-concussed athletes even months after the injury, especially when engaging on a working memory task (Chen et al., 2008). In regard to PET and SPECT studies that assess mild TBIs, results tend to most consistently indicate frontotemporal region impairments, although results overall can vary greatly (Chen et al., 2003).

Electrophysiological- and metabolic-based methods of assessing brain dysfunction, such as using event-related potentials (ERP), transcranial magnetic stimulation (TMS), and magnetic resonance spectroscopy (MRS) appear to detect differences between concussed and non-concussed athletes in a more consistent manner. ERPs, for example, are averaged electrical brain responses that allow one to determine the time course of higher-level processes such as attention and memory updating in the human brain, as it represents the average EEG signal time-locked to a presented stimulus (Coles & Ruggs, 1995). Multiple studies have indicated that both symptomatic and asymptomatic concussed athletes have altered auditory and visual processing well after the acute post-injury phase (Gosselin et al., 2006). An additional study by

DeBeaumont et al. (2007) using ERPs particularly found that persistent alterations in the N2pc component negatively impact an athlete's visual-spatial attention, which is a fundamental skill needed to achieve high levels of performance in contact sports such as football. The cumulative effects of multiple concussions on the latency and amplitude in the P3 wave in the brain of concussed athletes has additionally been demonstrated (Gaetz et al., 2000; DeBeaumont et al., 2007).

Regarding subconcussive injuries specifically, existing research using staining for amyloid precursor protein have shown that these subconcussive impacts reliably produce tearing of axons and the formation of axonal retraction bulbs in the brainstem-level descending motor pathways (Bailes et al., 2013). Research further shows that that the forces related to subconcussive injuries were imparted to the deep midbrain and brainstem structures level near the head's center of gravity, occurring 10 msec following impact (Pellman et al., 2003). Injuries related to concussive injuries and related symptomatology appear to demonstrate that the forces are mainly imparted to the mesencephalon, corpus callosum, and fornix, and as such, experiencing forces in these areas may be related for concussion symptoms, such as LOC, amnesia, and cognitive dysfunction (Pellman et al., 2003).

Regarding the proposed effect of multiple concussions or subconcussive injuries on the brain, Giza and Hovda (2001) have presented the hypothesis of a metabolically vulnerable brain, in which it is proposed that a second mTBI or injury can lead to "catastrophic damage to the mitochondrial energy metabolism depending on the lag time between two traumatic events". To gain understanding of the duration of that lag time, both animal and human studies have been conducted. For example, Vagnozzi et al. (2007) conducted a study investigating the possible existence of a temporal window of brain vulnerability in rats that underwent repeated mTBIs that were delivered at increasing time intervals. The results of this study found that, in rats, that maximum metabolic vulnerability, as defined by the highest decrease of NAA and other energy-related metabolites were recorded in animals receiving a second mTBI approximately from 3 days apart (Vagnozzi et al., 2007). Their proposed explanation is that the recovery process of energy-dependent cell functions is at their maximal intensity approximately 3 days after the initial mTBI, and the cells are at minimal capacity to counteract the metabolic effects that result. Since the time scale of metabolic events in rats has been found to be much shorter in rats than in humans, however, it is expected that the lag window in humans is longer lasting. Despite the difference in actual lag time, this hypothesis allows to explain why receiving multiple concussions in the same match or game does not have the same effect as two mTBIs that occur days or weeks apart, as the recovery efforts have not yet reached maximum level. If additional mTBIs do occur during the vulnerability window after the hypothesized time period, however, it is expected that the metabolic effects will become dangerously cumulative, and the resulting damage might be hard to later reverse.

In humans, a particular way of eliciting a P3 response is through the use of 'oddball tasks', which is a task that involves the presentation of two stimuli and the ability to discriminate an infrequent target stimulus by responding to the target. Research has shown that P3 amplitude is correlated with the amount of attentional resources allocated to a particular task and with better performance on memory tasks, whereas shorter P3 latency is associated with better processing speed and the allocation of attentional resources for memory processing (Polich, Howard, & Starr, 1983; Reinvang, 1999). More importantly, this finding related to P3 amplitude has been found to still be significant and measurable even on asymptomatic multiple-concussion athletes who sustained their last concussion about 3 years prior to testing (on average), which indicates both the chronic nature of this dysfunction as well as the efficacy of this assessment method.

Research using TMS has found a positive correlation between altered intracortical inhibition in concussed athletes with the numbers of concussions sustained, which suggests a possible long-term and cumulative effect in the motor system (DeBeaumont et al., 2007). Additionally, the use of MRS allows for the in vivo detection of several brain metabolites, such as creatine-phosphocreatine (a general energy marker); choline-containing compounds (markers of neuronal damage and membrane turnover); myoinositol (a glial marker), glutamate (a principal excitatory neurotransmitter); and N-acetylaspartate (a marker of neuronal integrity) (Henry et. al, 2010). Using these markers can indicate neuron damage, such as diffused axonal injury, because they are indicative of changes in the neuronal composition (Toga and Mazziotta, 2002). Past studies using this method have found a decrease in N-acetylaspartate particularly in the frontal lobe in some, but not all, concussed athletes in the acute phase (Cimatti, 2006; Vagnozzi et al., 2008). Henry et al. (2010) additionally found correlations between decreased N-acetylaspartate levels and cranial symptoms of concussion such as headaches, pressure in the head, and sensitivity to light and noise. Vagnozzi et al. (2008) additionally tracked the time it takes for N-acetylaspartate levels to return to typical levels, and it was found that it takes approximately 30 days post-injury. Regarding other metabolites, Henry et al. (2010) found depressed M1 in addition to depressed N-acetylaspartate, even with neurological test performance within normal limits.

A possible explanation for the ability of these methods of studying the brain to better assess differences in concussed and non-concussed athletes is the possibility that there are micro-structural or metabolic changes that lead to persistent alterations in electrophysiology, but that are not being picked up by additional neuropsychological test batteries being used in these studies. Therefore, it is possible that the use of these alternative methods of assessment provides added sensitivity to the long-term effects of sports concussion. On the other hand, some might argue that the inability to find overt neurocognitive changes in asymptomatic concussed athletes undermines the clinical significance of these neurological changes, and that the subtle alterations in brain activity could be interpreted as irrelevant for the athlete's cognitive function. Therefore, further research in all possible methodologies would be suggested in order to further increase the overall knowledge regarding mTBI and sport-related brain injury diagnosis and implications.

Concussions and Psychological Symptomatology

Existing research has indicated that TBIs can lead to increased risk for other heath conditions. For example, it has been found that people who suffered a TBI are 1.8 times more likely to report binge drinking and 11 times as likely to develop epilepsy (Zemper, 2003). Regarding neurological and psychological conditions, research has shown a 1.5 increased risk of depression and a 2.3-4.5 increased risk of Alzheimer's disease depending on the severity of TBI suffered. These findings, as well as many others related to functional impairment post-concussion can be partially explained by Kay et al.'s (1992) proposed neuropsychological model of functional disability post-mTBI, in which they noted that multiple factors can complicate a recovery from concussions, such as neurological findings (i.e, axonal shearing or premorbid injury affecting structural integrity of brain), physical factors (i.e., pain, sleep disturbances, peripheral injury), psychological, personality, and psychosocial factors. Montgomery (1995) additionally proposed his own multidimensional model of disability post-brain injury, which states that personal factors (such as the presence of negative cognitions, attention-arousal, physical symptoms and fatigue) and situational factors (rapid processing demands, need for complex cognitive attention, and external distraction) can impact overall neuropsychological disability.

Regarding psychological factors, it has been found that psychological distress can additionally impact cognitive functioning by suppressing attention, mental efficiency, learning, and memory (Broschek, De Marco, & Freeman, 2014). Experiencing these cognitive impairments have been found to additionally lead to stress, frustration, anxiety, and depression. As a result, this psychological distress can accumulate over time and may become more disabling that symptoms related to the original injury. Personality factors, such as being an overachiever and setting high achievement goals for oneself can affect the way an individual interprets their symptoms and overall recovery.

While evidence suggests that psychological distress can arise due to adjustment difficulties (such as removal or possible retirement from play and limited support from their team and coaches), research does demonstrate evidence of neurobiological changes associated with brain injury, regardless of the severity level (Chen et al., 2008). For example, Mayberg's cortical-limbic model of depression suggests that the onset of depressive symptoms is not generally due to a resulting injury to a particular cortical area or neurotransmitter system, but it is instead due to a multi-dimensional disruption of underlying functional pathways, as well as the failure of reciprocating systems to maintain "homeostatic emotional control" (Mayberg, 2003). Specifically, this model suggests that depressive symptoms and sadness are mediated by increased bloodflow in the ventral limbic and paralimbic regions, and decreased bloodflow in neocortical and limbic regions. Past research has further indicated that frontal-limbic-subcortical pathways have been linked to the pathophysiology of depression. For example, one study using diffusion tension imaging found alterations with the default mode network, which involves a network of cortical regions associated with self-referential activity, as well as within the frontal-thalamo-caudate network.

Given that individuals who experience traumatic brain injuries, such as mTBIs and subconcussive injuries, can experience intracranial abnormalities that involve the frontal and temporal lobes, as well as fronto-limbic-subcortical structures that are often implicated in depression, it is not surprising that depression is a commonly-observed consequence of TBIs of all severities (Dikmen et al. 2004). A study which specifically used an athlete sample reported differences in the dorsolateral prefrontal cortex, dorsal anterior cingulate cortex, insular cortex, thalamus, and striatum, as well as differences in gray matter volume, in athletes that reported depressive symptoms relative to both concussed athletes without depression-related symptoms and controls (Chen et al., 2008). As a result, the authors of this study concluded that, while the structural abnormalities observed were likely secondary to the concussion, the depressive symptoms themselves were mainly attributed to the medial prefrontal dysfunction related to the head injury.

Yet another common psychological disturbance reported after acquiring a brain injury (such as a sport-related TBI) is anxiety. As previously stated, these types of injuries often involve damage to the prefrontal cortex, ventral frontal lobe, and anterior temporal lobe, which are areas that are heavily implicated in the recognition of emotionally-relevant stimuli, as well as the regulation of one's reaction to such stimuli (Etkin et al., 2010; Rauch, Shin, & Phelps, 2006). Regarding available models, Etkin's limbic-medial prefrontal model indicate that anxiety-related emotions such as fear are associated with the hyperactivation of the amygdala and insula, as well as subcortical structures like the hypothalamus and periaqueductal grey (Etkin et al., 2010; Rauch, Shin, & Phelps, 2006). Furthermore, the ventromedial prefrontal cortex has been found to play a critical role in regulating amygdala activity, and that hypoactivity in this area can lead to negative mood states due to this region not providing its expected regulatory role (Motzkin, 2014). Therefore, it can be suggested that structural/functional changes related to a brain injury can lead to a greater risk of developing both depression and/or anxiety-related symptoms, especially if they sustain repetitive injuries. This finding is currently partially supported by existing research which has found that a history of repeated concussions can place individuals at a higher risk for the development of depression or anxiety later in life than individuals without a concussion history (Motzkin, 2014).

Chronic Traumatic Encephalopathy (CTE)

While the previously discussed consequences can be found in both single and repetitive concussions, existing research has increasingly investigated a particular disorder known as chronic traumatic encephalopathy, otherwise known as CTE. CTE is defined as a progressive neurodegeneration triggered by repetitive mild traumatic brain injuries and characterized by the widespread deposition of hyperphosphorylated tau (p-tau) as neurofibrillary tangles (McKee et al., 2013). Past research indicates that CTE was originally reported by 1928 by Harrison Marland, who initially described clinical aspects of a progressive neurological deterioration that occurred after repetitive brain trauma in boxers; this deterioration was known as being ‘punch drunk’. In 1937, Millspaugh coined the term ‘dementia pugilistica’ to describe this condition, but after studies found this development of symptoms were observed in activities other than boxing, terms such as progressive traumatic encephalopathy and, eventually, CTE, were developed and more widely used.

Regarding symptomatology, CTE is clinically associated with the presence of symptoms such as irritability, impulsivity, aggression, depression, short-term memory loss, and heightened suicidality that usually begin approximately 8-10 years after experiencing mild repetitive traumatic brain injury (McKee et al., 2013). As this disorder progresses, further neurological changes are said to develop, such as dementia, gait and speech abnormalities, and parkinsonism, to the point that late-stage CTE can be clinically mistaken for Alzheimer's disease or frontotemporal dementia (Gavett et al., 2010). However, CTE can be distinguished from other tauopathies such as Alzheimer's due to distinctive neuropathological changes, including generalized tauopathies of the cerebellar cortex, medial temporal lobe, diencephalon, and mammillary bodies, and enlarged ventricles (McKee et al., 2013). Additional findings include extensive p-tau neurofibrillary tangles in the frontal cortex, temporal cortex, cerebral sulci, limbic regions, diencephalon and brainstem nuclei, extensive degeneration of axons and white matter fiber bundles, and a relative absence of amyloid-B peptide deposits (McKee et al., 2013).

Currently, the Center for the Study of Traumatic Encephalopathy at Boston University School of Medicine has a brain bank available which maintains the brain and spinal cords of athletes, military veterans, and civilians that experienced repetitive mild traumatic brain injury. Through this data, 4 main stages of CTE have been identified. Stage I is characterized by focal epicenters of p-tau neurofibrillary and astrocytic tangles, mainly in the sucal depths and the superior and dorsolateral frontal cortices; clinical symptoms related to this stage include loss of attention and concentration, short-term memory difficulties, aggressive tendencies, depression, executive dysfunction, and explosivity (McKee et al., 2013). In stage II, more epicentres are noted and localized spread of neurofibrillary pathology to more superficial layers are observed; clinically, similar symptoms are reported, as well as some cases of more severe executive dysfunction, impulsivity, language difficulties, and suicidality (McKee et al., 2013). In Stage III, p-tau pathology is further widespread into frontal, insular, temporal and parietal areas of the brain, and neurofibrillary pathology is observed in the amygdala, hippocampus, and entorhinal cortex; common presenting symptoms in this stage include memory loss, executive dysfunction, explosivity, attention and concentration deficits, depression, mood swings, visuospatial difficulties and aggression (McKee et al., 2013). Lastly, in Stage IV, severe p-tau pathology is noted to affect most cerebral cortex regions, sparing the calcarine cortex in all most the most severe cases; aside from the previously mentioned symptoms, individuals will also report paranoia, severe memory loss, and dementia, as well as an increased prevalence of suicidality (McKee et al., 2013). A study by McKee et al. (2013) indicated that approximately 31% of individuals in this stage had reported being suicidal and some point in their disease progression.

Furthermore, when specifically looking at professional American football players, this study found that, out of a sample of 35, three had Stage I, three had Stage II, nine had Stage III, and seven had Stage IV CTE, with only one individual showing no disease. Furthermore, 94% were symptomatic, with the most common symptoms being short-term memory loss, executive dysfunction, attention difficulties, and concentration loss (McKee et al., 2013). The mean age at symptom onset was 54.1 years of age, with a range of 34-83 years. This study additionally looked at position specific differences and found that positions positive for CTE included "offensive linemen (26%), running backs (20%), defensive linemen (14%), linebackers (14%), quarterbacks (6%), defensive backs (6%), tight ends (6%) and wide receivers (6%). However, statistical analyses indicated that both the position played was not statistically significant to CTE severity (McKee et al., 2013).

Clinical Relevance

The lifetime costs of TBIs in the United States, including medical costs and lost productivity, is estimated to cost approximately $60 billion annually. Additionally, this cost does not even begin to address the indirect impact on friends, families, and caregivers and the community. Since particular populations, such as professional athletes, are at a higher risk of acquiring brain injuries, it is of utmost importance to investigate related factors that might impact the acquirement of brain injury, and how any factors impact subsequent presentation. Diagnoses related to sport-related diagnoses, such as CTE, are now being further investigated, but many factors such as how much head trauma, what type of trauma, and how frequently the trauma is experienced and considered to be causative of significant and impairing symptoms, what type of trauma is causative, is yet to be fully understood. Therefore, it is imperative for future studies to focus on the identification of such impairments and any related factors (such as player position) can lead to possibly devastating long-term consequences.

Purpose

The purpose of the proposed study was to extend the body of research on head-impact-related traumatic brain injury experienced by retired National Football League players. Concussion and subconcussion-related impacts sustained in American football have been associated with both short- and long-term neurological impairment; however, further research is needed to understand exactly what the long-term effects are after retirement from the NFL. Furthermore, differences in head impact outcomes across playing position as a key risk factor for neuropsychological impairment in football players. Therefore, this study compared neuropsychological differences between groups of football players on the following domains: attention and processing, learning and memory, visual-perceptual skills, language, and executive functioning. The groups will be categorized based on position played and will be defined as following: “Linemen” (Offensive and Defensive), “Skilled Linemen” (Offensive Backfield, Tight End, and Linebacker), and “Skilled Players” (Quarterback, Wide Receiver, and Backfield

Defenders). These groups were defined as so due to similarities in position responsibilities and expected brain injury frequency and magnitude.

Hypothesis One

It was hypothesized that the combined sample of retired NFL players would demonstrate impairment in test scores when compared to a population norm of a T-score of 50 and a standard deviation of 10. Furthermore, each of the three previously defined groups (Linemen, Skilled Linemen, and Skilled players) would individually demonstrate impairment in scores when compared to the same population T-score and standard deviation norm. Existing research has indicated that experiencing multiple concussions can lead to long-term impairment due to chronic neurological damage and degeneration, particularly in the areas of attention/processing speed, learning and memory, and executive functioning. Therefore, it is expected that the entire sample, as well as each individual player position group will demonstrate lower scores indicating impairment in functioning when compared to normal statistical population norms.

Hypothesis Two

Should significant differences be revealed among the combined sample group, it would then be hypothesized that differences would be found between the three groups. More specifically, the Linemen group would perform more poorly in comparison to the Skilled Linemen and Skilled Players, and that the Skilled Linemen would perform more poorly in comparison to the Skilled Players on all cognitive measures. Existing research has indicated the Linemen group suffer more frequent head impacts and post-impact symptoms than other playing positions, as well as having a higher rate of returning to play while symptomatic or engaging in full-contact practices. Skilled Linemen, on the other hand, experience fewer, but often higher-magnitude, impacts which result from activities such as full-speed open-filed tackling. Skilled

Players, lastly, tend to be involved in a small percentage of plays and will consequently sustain the least-frequent impacts during the game. Studies have additionally shown that experiencing multiple past concussions has led to findings of worse performance. Therefore, it is expected that the Linemen group will perform more poorly in comparison to the Skilled Linemen, and that the Skilled Linemen will perform more poorly in comparison to the Skilled Players.

CHAPTER III

Method

Participants

The participant sample in this study consistent of 142 male adult individuals who were selected a de-identified, archival, databases gathered through the NFL Concussion Settlement belonging to the Neuropsychology Assessment Center of Nova Southeastern University.

Table 1. *Group Demographics*

Variables	**Combined Sample**	**Linemen**	**Skilled Linemen**	**Skilled Players**
N	142	39	44	59
Mean Age	48.86	52	50.09	43
Age SD	10.70	11.40	11.24	9.09
Age Range	31-83	34-77	32-83	31-74
African American	108 (76.1%)	22 (56.4%)	37 (84.1%)	49 (83.1%)
Caucasian	33 (23.2%)	17 (43.6%)	7 (15.9%)	9 (15.3%)
Associate's Degree (2 Years of College)	0.7%	0%	0%	1.7%
3-5 Years of College (No Degree)	29.6%	25.6%	22.7%	37.3%
Bachelor's Degree	55.6%	53.8%	63.6%	50.8%
Post-Bachelor's/Masters'	13.4%	20.5%	13.6%	8.5%

were included in the study if they were between the ages of 25 and 90 and played in the NFL for at least one season. Participants were further divided into three groups, defined as following: "Linemen", "Skilled Linemen", and "Skilled Players". This database included demographic information and different neuropsychological assessment scores. The individuals within the sample included those with different psychiatric and neurologic disorders as well as those who were bereft of diagnosis.

The “Linemen” group (n=39) included in the present study was found to have a mean age 52 (SD= 11.40). The sample was predominantly African American (56.4%), and also consisted of Caucasian participants (43.6%). The average level of education that the sample achieved was a Bachelor’s Degree (53.8%), followed by 3-5 years of college without a degree (25.6%), and a post-Bachelor’s or Master’s Degree (20.5%).

The “Skilled Linemen” group (n=44) included in the present study was found to have a mean age of 50.09 (SD=11.24). The sample was predominantly African American (84.1%), and additionally included Caucasian participants (15.9%). The average level of education that the sample achieved was a Bachelor’s Degree (63.6%), followed by 3-5 years of college without a degree (22.7%), and a post-Bachelor’s or Master’s Degree (13.6%).

The “Skilled Players” group (n=59) was found to have a mean age of 46.02 (SD=8.99). The sample was predominantly African American (80.3%), with 18.0% of the remaining participants identifying a Caucasian; 1.6% did not specify their ethnicity. The average level of education that the sample achieved was a Bachelor’s Degree (50.8%), followed by 3-5 years of college without a degree (36.1%), a post-Bachelor’s or Master’s Degree (9.8%), and an Associate’s Degree or 2 years of college (1.6%).

Analyses of Covariance (ANCOVA) analyses were completed in order to assess for possible significant differences among the groups for education and ethnicity. No differences were found regarding education among the groups [F(2, 2, 140), p=.122]. In order to assess for statistical differences in ethnicity composition amongst groups, a Pearson Chi-Squared Analysis was conducted. The relation between player position and ethnicity was significant, X^2 (8, N =

141) = 45.18, *p*< .001. As such, ethnicity will be included as secondary fixed factor in future analyses.

Measures

Wechsler Adult Intelligence Scale, Fourth-Edition (WAIS-IV)

The Wechsler Adult Intelligence Scale – Fourth Edition is a measure of general intellectual functioning. The WAIS-IV measures intelligence from the perspective of both intelligence as a global, singular factor, as well as the combination of unique aspects that differ in their levels of functioning.The WAIS-IV was standardized on a group of 2,200 adults ranging from 16 years of age to 90 years of age (Lezak, Howieson, Bigler, & Tranel, 2012). The use of the WAIS-IV in a neuropsychological battery is important not only for the wide range of cognitive abilities it assesses, but also for the behavioral observations it can provide for the examiner as an initial test within a battery (Lezak, Howieson, Bigler, & Tranel, 2012). There are 10 core subtests of the WAIS-IV which are administered per the instructions of the administration manual. Although the manual follows the test order as presented in protocols, the order of WAIS-IV subtest administration can be altered for the benefit of the client (Lezak, Howieson, Bigler, & Tranel, 2012). However, the order of the tests is intentional in that they alternate between visual and verbal tasks in order not to fatigue the client (Lezak, Howieson, Bigler, & Tranel, 2012). Interpreting the WAIS-IV is best accomplished by examining the indices and Full Scale IQ for variations. Understanding where these variations develop from individual subtests is also important in order to best understand specific skills and weaknesses. As with most neuropsychological data, it is recommended that the any scores or deviations be interpreted in the context of other tests and client background information (Lezak, Howieson, Bigler & Tranel, 2012). The scores that were used in these analyses will be the Block Design, Digit Span, Arithmetic, Letter-Number Sequencing, Coding, Symbol Search, Cancellation, Visual Puzzles, Matrix Reasoning, and Similarities T-scores.

Block Design.

Block Design is a core perceptual reasoning subtest designed to measure the ability to analyze and synthesize abstract visual stimuli. In this task, an individual is asked to view a picture (or a model and a picture) and utilize red-and-white blocks to recreate the design within a specific time limit. Studies have also found that completing this task involves the use of nonverbal concept formation and reasoning, broad visual intelligence, fluid intelligence, visual perception and conceptualization, simultaneous processing, visual-motor coordination, learning, and the ability to separate figure-ground in visual stimuli (Carroll, 1993; Groth-Marnat & Baker, 2003).

Digit Span.

Digit Span is a core working memory subtest composed of three tasks: Digit Span Forward, Digit Span Backwards, and Digit Span Sequencing. In Digit Span Forward, the examinee is read a sequence of numbers and recalls the numbers in the same order. This task requires rote learning and memory, attention, encoding, and auditory processing (Wechsler, 2008). In Digit Span Backwards, the examinee is asked to recall the numbers provided in the reverse order. This task involves working memory, transformation of information, mental manipulation, and visuospatial imaging (Wechsler, 2008). In Digit Span Sequencing, the examinee is asked to recall the provided numbers in ascending order from the smallest to largest number. It also involves the use of working memory and mental manipulation (Wechsler, 2008)

Arithmetic.

Arithmetic is a core working memory subtest consisting of 22 total items, in which the examinee must mentally solve a series of arithmetic problems within a given time limit. This task involves mental manipulation, concentration, attention, short- and long- term memory, numerical reasoning ability, and mental ability (Wechsler, 2008). Studies have also indicated that this task may involve sequential processing, quantitative knowledge, and fluid, quantitative, and logical reasoning (Groth-Marnat & Baker, 2003).

Letter-Number Sequencing.

Letter-Number Sequencing is a supplemental working memory subtest in which the examinee is asked to recall a sequence of numbers and letters in ascending and alphabetical order. The examinee is taught this task in a stepwise manner, in that he or she is taught to first repeat numbers before letters, and then to sequence the repeated numbers and letters. This subtest involves multiple neuropsychological functions, including sequential processing, mental manipulation, attention, concentration, memory span, and short-term auditory memory, as well as information processing, cognitive flexibility, and fluid intelligence (Wechsler, 2008).

Coding.

Coding is a core processing speed subtest, in which an examiner has to copy symbols that are paired with numbers within a specific time limit. This task measures processing speed, and involves short-term visual memory, learning ability, psychomotor speed, visual perception, visual-motor coordination, visual scanning, cognitive flexibility, attention, concentration, and motivation (Wechsler, 2008). In order to best measure processing speed specifically, various changes were made to this subtest from the previous version, including replacing more complex symbols with four new and simpler symbols, utilizing each number twice within each row to maintain equal item difficulty, enlarging the symbols and numbers to reduce visual acuity demands, and increase the sizes of the boxes used to record responses in order to reduce fine motor demands (Wechsler, 2008).

Symbol Search.

Symbol Search is a core processing speed subtest, which asks the examinee to scan a search group and indicate whether one of the symbols in the target group matches within a specific time limit. This task measures processing speed and involves short-term visual memory, visual-motor coordination, cognitive flexibility, visual discrimination, psychomotor speed, speed of mental operation, attention, and concentration (Wechsler, 2008). According to research, this task also involves auditory comprehension, perceptual organization, fluid intelligence, and planning and learning ability (Groth-Marnat & Baker, 2003). Similarly to changes done to the Coding subtest, the Symbol Search subtest was changed to best allow for the measuring of processing speed by enlarging the symbols so as to reduce visual acuity demands (Wechsler, 2008).

Cancellation.

Cancellation is a supplemental processing speed subtest in which the examinee is asked to scan through a structured arrangement of shapes and mark only the target shapes provided. Aside from measuring processing speed, this task also involves visual selective attention, perceptual speed, and visual-motor ability (Wechsler, 2008). Additionally, this measure allows for an examiner to assess visual neglect, response inhibition, motor perseveration, and decision-making (as the task requires the examinee to discriminate both the color and shape of the stimuli) (Wechsler, 2008).

Visual Puzzles.

Visual Puzzles is a 26-item core perceptual subtest in which an examinee views a completed puzzle and selects three options that reconstruct the puzzle when placed next to each other. This task measures nonverbal reasoning, as well as the ability to analyze and synthesize abstract visual stimuli (Wechsler, 2008). It additionally involves spatial visualization and manipulation, as well as broad visual intelligence and fluid intelligence (Groth-Marnat & Baker, 2003).

Matrix Reasoning.

Matrix Reasoning is a core perceptual reasoning subtest, in which the examinee is asked to view an incomplete matrix and select the response option that completes it out of a total of five possible options. Furthermore, explicit instructions are given to the examinee in order to learn the problem-solving strategy necessary for successful performance. According to studies, this task involves fluid intelligence, broad visual intelligence, classification and spatial ability, knowledge of whole-part relationship, simultaneous processing, and perceptual organization (Groth-Marnat & Baker, 2003).

Similarities.

Similarities is a core verbal comprehension subtest. In this task, the examinee is asked to define words that are presented both visually and verbally. Picture items are also available if reversal criterion is met, and the examinee is then asked to name the object that is visually presented. This task measures word knowledge and verbal concept formation (Wechsler, 2008). Other abilities that are thought to be measured by this task are crystallized intelligence, fund of knowledge, learning ability, long-term memory, degree of language development, auditory comprehension, and verbal expression (Groth-Marnat & Baker, 2003).

Wechsler Memory Scale, Fourth Edition (WMS-IV)

The Wechsler Memory Scale – Fourth Edition (Wechsler, 2009) is a test of an individual's visual and verbal memory functioning. This fourth edition is considered to be a significant revision of the previous versions as it eliminated six subtests from the previous versions and added three new ones. Furthermore, the three subtests that remained from the previous version were modified in some way so that it is not able to be compared to previous versions. The WMS-IV subtests that are the most similar to those found in previous versions are Logical Memory, Verbal Paired Associates, and Visual Reproduction. For Logical Memory, both content and administration procedures differ significantly from previous versions, while the changes related to Visual Reproduction centered mainly around the scoring criteria, as opposed to changes in content and administration. The new subtests added to this version are Design Memory I and II, Spatial Addition, and Symbol Span, which are all considered to be visual memory tests, as the test creators believed that the previous versions needed improvement regarding their ability to measure visual memory. Furthermore, the number of memory indices overall were reduced from eight to five. The new indices are Auditory Memory (comprised of Logical Memory and Verbal Paired Associates), Visual Memory (Visual Reproduction and Design Memory), Visual Working Memory (Spatial Addition and Spatial Span), Immediate Memory (immediate recall trials of the four core subtests), and Delayed Memory (delayed recall trials of the four core subtests).

The normative sample for the WMS-IV standard battery consisted of 900 people ranging from 16 to 69 years of age. These individuals were further divided into 9 age bands. The fourth version additionally has normative data available for older adults whose age ranges between 65 to 90, in addition to the previously available normative data for individuals aged 16 to 69. The

Older Adult battery was normed on 500 people whose age ranged between 70 to 90. An equal number of males and females were included in the age groups up to age 64, in which the number of females then increased in the older age groups in a proportional manner to the 2005 census. The racial composition and education levels were also proportional to the 2005 census (more than 70% of individuals identified as White; approximately 80% had a high school diploma or above). When used in conjunction with the WAIS-IV meaningful comparisons between intellectual ability and memory functions can be made. For this study, the scores that were used in this study will be Logical Memory I, Logical Memory II, Verbal Paired Associates I, Verbal Paired Associates II, Visual Reproduction I, and Visual Reproduction II T-scores.

Logical Memory I and II.

The Logical Memory I subtest varies slightly depending on whether the Adult battery or the Older Adult battery is administered. In the Adult battery, the examinee hears two stories, which are only each presented once, of similar length and complexity. However, in the Older Adult battery, there is only one story which is presented twice. This difference allows for a sufficient floor to be obtained for both the immediate and delayed versions of logical memory (Wechsler, 2009). Logical Memory II, however, indicates one's ability to recall information with minimal prompting after a 20- to 30- minute delay.

Low scores on this task indicate difficulty recalling conceptually organized and semantically related verbal information (Wechsler, 2009). Furthermore, when administering the Adult battery, low scores may indicate that the examinee has difficulty recalling information after only one exposure. It is important to note that Logical Memory does not measure the ability to retell a story, but the ability to recall specific story elements. Also, while presenting information in an organized and meaningful way is expected to ease recall, it does not necessarily suggest that specific details will be recalled as a result of remembering other parts of the story. Regarding Logical Memory II, one's performance on this task is related to the level of information acquired at the initial presentation, rather than a direct measure of forgetting.

Verbal Paired Associates I and II.

The Verbal Paired Associates subtests measure the examinee's ability to recall both novel and semantically related word associations. Verbal Paired Associates I measures the immediate cued recall for word associations, and is presented in a multi-trial learning format. Therefore, it is expected that recall should improve after each exposure to the list. Low score in this task may indicate difficulties with learning new associations or failure to improve memory performance after multiple learning trials (Wechsler, 2009). Regarding Verbal Paired Associates II, this task measures the ability to recall verbal associations after a 20- to 30- minute delay. Low scores on indicate difficulties retrieving word associations from long-term memory (Wechsler, 2009).

Visual Reproduction I and II.

Visual Reproduction I measures an examinee's ability to recall and draw designs immediately after being exposed to the design for 10 seconds. Visual Reproduction II measures the ability to recall and draw the designs after a 20- to 30- minute delay, and the examiner may draw the previous designs in any order. While tasks are meant to measure visual memory, they also require visual-constructional abilities, as the examinee is required to recall the size and relative spatial relationship among elements (Wechsler, 2009). Also, elements can be named (i.e., triangle, square, dots), which may facilitate encoding if the examinee utilizes this strategy.

Halstead Category Test

The Halstead Category Test measures higher order cognitive functions of a nonverbal nature and the ability to determine general principles from sets of specific stimulus items. This test is a complex visual abstraction concept-formation assessment tool that requires the utilization of abstract concept formation, cognitive flexibility, and aspects of visual-spatial functioning and memory. The task consists of a presentation of 208 individual items. There are no time limits. There are six item sets, each organized on the basis of different principles (number, shape, size, color, intensity, and location), followed by a seventh set made up of previously shown items which require recall of previously learned ‘rules’ from earlier sets. The patient’s task is to deduce the principle presented in each set and indicate which one of four target stimuli correctly adhere to the current rule. The total number of errors across subtests is used as a measure of abstract reasoning ability. Correct performance requires the selection of a correct response based upon the stimulus and positive or negative feedback given, maintenance of the response pattern, and shifting of cognitive set, when appropriate. Of the other subtests from the Halstead Neuropsychological Battery, the Category Test is the most sensitive to neurological insult regardless of the location of insult (King & Snow, 1981; Cullum & Bigler, 1986), indicating that it is sensitive to damage in areas beyond the frontal lobes. The test is sensitive to the effects of age and education; Heaton, Grant, and Matthews (1991) devised correction factors for age, education and gender based upon a large normative sample. For the purposes of this study, the Number of Errors T-score was used in the analyses.

Trail Making Test

The Trail Making Test measure cognitive flexibility, sequencing ability, and visual-motor speed. The Trail Making Test (parts A and B) are a subtest from the Army Individual Test (1944) used as measures of attention, scanning, visual-motor tracking, divided attention, and set-shifting abilities. Trails A is a measure of visual scanning and motor speed. In Trails A, the patient is given a page with a set of numbered circles scatters about the page and is asked to draw a line between consecutive numbers. Trails B is considered to be a more specific measure of executive functioning as it requires reasoning ability other higher-order processes (Golden, Espe-Pfeifer, & Wachsler-Feider, 2000; Kortte, Horner, & Windham, 2002). In Trails B, the patient is given a sheet with randomly distributed circled numbers and circled letters and asked to draw a line connecting A-1, B-2, C-3, and so forth in a sequencing pattern. Scores are based on total time to complete task, and the number of errors made. Cut-off scores were used in the original interpretation of the test (Reitan and Wolfson, 1985), but contemporary practitioners favor the sensitive of the use of *t*-scores based normative groups established by Heaton in 2004 (Strauss, Sherman, & Spreen, 2006). Test reliability is acceptable but there is significant variability across studies using different samples (Strauss, Sherman, and Spreen, 2006). For the purposes of this study, the Trails B time T-score was used in this analysis.

Controlled Oral Word Association Test (COWAT or FAS)

The Controlled Oral Word Association test consists of three word-naming trials. Since the first set of letters that were used were F-A-S, this test is oftentimes referred to as the "FAS" test. The letters were selected on the basis of the frequency of English words that begin with these letters, in that words beginning with the letter F have a relatively high frequency, words beginning with the letter A have a somewhat lower frequency, and words beginning with S have a still lower frequency. Other English-based versions include the letters C-F-L and P-R-W. Additionally, there are multilingual batteries available for French, German, Italian, and Spanish Speakers. For example, in French, the letters P-F-L have valuables that are comparable to the English version (Lezak et al., 2012). To give the test, the examiner asks the subject to say as many words as they can think of that begin with the given letter of the alphabet, while excluding proper nouns, numbers, and the same word with a difference suffix. The score is then calculated by summing all acceptable words produced in the three one-minute trials and are then adjusted for age, sex, and education. Rule violations such as non-words, proper nouns, and repetitions (including variations of the same word) are not included in the final sum. The adjusted score can then be converted to percentiles. Regarding normative data, contemporary practitioners favor the use of normative groups established by Heaton in 2004 (Strauss, Sherman, & Spreen, 2006). For the purposes of this study, the FAS T-score was used.

Category Naming Fluency (Animals)

In comparison to letter fluency, category fluency has been found to be less difficult. In this task, individuals are simply asked to name as many animals that they can think of, without being given any other cues or restrictions. Healthy subjects have been found to produce more animals than FAS words per minute, even those subjects that are well into their 80s. Individuals with disorders such as those affecting the temporal lobe, on the other hand, have demonstrated category deficits that are greater than those in letter fluency deficits. Temporally-based disorders such as Alzheimer's Disease, demonstrate this pattern, which can be attributed to a breakdown in sematic knowledge about different categories. This pattern differs from those who suffered frontal damage, in which the pattern demonstrates equivalent deficits in both letter and category fluencies. Regarding normative data for the Category Naming test, such data is further stratified by age, sex, and education. Like the FAS test, contemporary practitioners favor the use of normative groups established by Heaton in 2004 (Strauss, Sherman, & Spreen, 2006). Additional normative data has also been created for Spanish speakers living in the United States (Acevedo et al., 2000). For the purposes of this study, the Category T-score was used.

Boston Naming Test

Boston Naming Test (Kaplan, Goodglass, and Weintraub, 1983) is a test of verbal expression and naming. This test consists of 60 large ink drawings of items ranging in familiarity from common items at the beginning of the test, to less common items towards the end of the test. Adult examiners begin with item 30 and will continue to advance unless they make a mistake in the initial 8 items administered to them, in which case they must reverse until 8 items are consecutively answered correctly. If examinees are unable to independently state the name of the presented item, a semantic cue can be provided to him or her. If the semantic cue is unsuccessful, an additional phonemic cue is provided. The testing is discontinued after six consecutive failed responses. An item review of possible responses from 1,383 adults with ages ranging from 17-97 indicated that alternative responses were the most common for 4 particular items (mask, pretzel, harmonica, and stilts) when the participants differed in age, education, race, and geographic region of the United States (Goldstein et al., 2000). Pedraza et al. (2009) additionally identified 12 of the items from items 30-60 between older African American and Caucasian examiners. Regarding normative data, there are a number of studies which offer data for varying populations. Scores related to this study were calculated using the previously mentioned Heaton norms. The score that was used for this study was the T-score.

CHAPTER IV

Results

Preliminary Analysis

Prior to conducting analyses, the dataset was examined for outlier data. Individuals with statistically discrepant scores (scores greater than three standard deviations from the sample

Table 2. Descriptive Statistics for Linemen Group

Test Scale	Mean	SD	Skewness	Kurtosis
WAIS-IV Digit Span	44.18	12.51	.33	-.84
WAIS-IV Arithmetic	42.92	11.05	.70	-.50
WAIS-IV Letter-Number Sequencing	43.30	8.09	.72	1.96
WAIS-IV Symbol Search	39.85	10.38	.03	-.38
WAIS-IV Coding	37.95	9.48	.15	-.29
WAIS-IV Cancellation	39.65	10.30	.79	1.46
WSM-IV Logical Memory I	39.74	10.57	.01	-.84
WMS-IV Logical Memory II	38.54	11.06	.33	.34
WMS-IV Verbal Paired Associates I	41.54	10.54	.37	0.60
WMS-IV Verbal Paired Associates II	41.13	10.59	.41	-.06
WMS-IV Visual Reproduction I	42.33	10.87	.18	-.16
WMS-IV Visual Reproduction II	45.85	9.79	-.15	-.04
WAIS-IV Block Design	43.23	9.48	-0.25	.03
WAIS-IV Matrix Reasoning	49.54	13.09	.11	-1.21
WAIS-IV Visual Puzzles	45.15	10.12	1.01	.61
Boston Naming Test	39.13	10.58	1.07	2.77
Category Fluency (Animal Naming)	36.97	15.18	-.01	-.73
BDAE Complex Ideational Material	32.89	17.05	-.24	-1.16
Verbal Fluency (FAS)	40.64	11.67	.20	-.09
WAIS-IV Similarities	45.38	11.36	.43	-.23
Trails Making Test- Part B	39.41	10.86	-.36	.56
Category Test	37.82	11.58	-.60	-.12

mean) could be considered to not represent the wider population of interest. To determine whether the models deviate from normality, cut off scores between -3 and 3 were employed for skewness and kurtosis.

Regarding the Linemen group, the examination of the descriptive statistics indicated that none of the scores displayed a normal distribution. Descriptive statistics are listed in Table 2.

Table 3. *Descriptive Statistics for Skilled Linemen Group*

Test Scale	**Mean**	**SD**	**Skewness**	**Kurtosis**
WAIS-IV Digit Span	45.18	9.59	-.03	.60
WAIS-IV Arithmetic	43.73	8.44	.79	.34
WAIS-IV Letter-Number Sequencing	45.68	7.28	.55	3.44
WAIS-IV Symbol Search	45.34	11.71	.59	.90
WAIS-IV Coding	43.59	9.12	.54	-.22
WAIS-IV Cancellation	46.24	11.71	.46	.68
WSM-IV Logical Memory I	40.05	9.13	.44	-.28
WMS-IV Logical Memory II	39.32	9.28	.57	-.41
WMS-IV Verbal Paired Associates I	42.82	6.94	.17	-.24
WMS-IV Verbal Paired Associates II	42.30	7.30	.33	.27
WMS-IV Visual Reproduction I	43.93	11.43	-.21	-.47
WMS-IV Visual Reproduction II	46.32	9.14	-.33	1.68
WAIS-IV Block Design	45.34	8.43	.55	-.43
WAIS-IV Matrix Reasoning	46.34	10.52	.41	-.09
WAIS-IV Visual Puzzles	45.34	10.76	.46	1.74
Boston Naming Test	36.98	8.90	.64	.00
Category Fluency (Animal Naming)	42.36	10.40	-.28	-.81
BDAE Complex Ideational Material	32.48	16.66	-.14	-.86
Verbal Fluency (FAS)	44.11	12.22	.39	-.32
WAIS-IV Similarities	47.07	8.14	-.02	-.09
Trails Making Test- Part B	46.95	10.03	.53	.35
Category Test	40.68	9.05	.07	.46

Regarding the Skilled Linemen group, the examination of the descriptive statistics indicated that none of the scores displayed a skewness or kurtosis less than -3 or greater than 3, indicating a normal distribution. The descriptive statistics are listed in Table 3.

Regarding the Skilled Players group, the examination of the descriptive statistics indicated that none of the scores displayed a skewness or kurtosis less than -3 or greater than 3,

Table 4. *Descriptive Statistics for Skilled Players Group*

Test Scale	**Mean**	**SD**	**Skewness**	**Kurtosis**
WAIS-IV Digit Span	43.83	10.78	.43	1.37
WAIS-IV Arithmetic	41.08	10.23	.19	.07
WAIS-IV Letter-Number Sequencing	44.24	8.95	.05	2.33
WAIS-IV Symbol Search	40.97	12.76	.23	-.11
WAIS-IV Coding	39.98	9.95	.14	.32
WAIS-IV Cancellation	40.88	10.95	-.00	-.16
WSM-IV Logical Memory I	36.58	11.16	.64	-.05
WMS-IV Logical Memory II	36.37	9.42	.55	1.51
WMS-IV Verbal Paired Associates I	39.31	8.08	1.46	4.11
WMS-IV Verbal Paired Associates II	40.76	9.37	.89	.94
WMS-IV Visual Reproduction I	41.97	10.73	-.28	-.74
WMS-IV Visual Reproduction II	47.14	10.07	.70	1.46
WAIS-IV Block Design	41.90	8.42	.12	.33
WAIS-IV Matrix Reasoning	44.25	10.26	.11	-.78
WAIS-IV Visual Puzzles	42.75	9.09	.73	.19
Boston Naming Test	35.10	10.30	1.07	2.64
Category Fluency (Animal Naming)	39.02	12.67	.00	-.22
BDAE Complex Ideational Material	30.22	17.91	.19	-1.23
Verbal Fluency (FAS)	43.29	10.68	.32	-.57
WAIS-IV Similarities	44.42	8.60	-.09	.45
Trails Making Test- Part B	41.44	10.71	-.37	.07
Category Test	41.57	10.86	-.41	-.31

indicating a normal distribution. The descriptive statistics are listed in Table 4.

Hypothesis One

It was hypothesized that the three player groups combined would demonstrate impairment in scores when compared to the population norms for each test (mean of 50 and a standard deviation of 10 for all T scores). Results showed that the combined group evidenced

Table 5. *One-Sample T-Test for Combined Retired NFL Sample*

Test Scale	**T-test**	**df**	**Mean Difference**
WAIS-IV Digit Span	-6.94*	143	-5.69
WAIS-IV Arithmetic	-9.05**	143	-7.57
WAIS-IV Letter-Number Sequencing	-7.91**	137	-5.53
WAIS-IV Symbol Search	-8.06**	143	-7.97
WAIS-IV Coding	-11.60**	143	-9.40
WAIS-IV Cancellation	-8.22**	137	-7.84
WSM-IV Logical Memory I	-13.16**	143	-11.43
WMS-IV Logical Memory II	-14.85**	143	-12.13
WMS-IV Verbal Paired Associates I	-12.61**	143	-8.97
WMS-IV Verbal Paired Associates II	-11.30**	143	-8.57
WMS-IV Visual Reproduction I	-8.03**	143	-7.32
WMS-IV Visual Reproduction II	-4.25**	143	-11.46
WAIS-IV Block Design	-8.71**	143	-6.46
WAIS-IV Matrix Reasoning	-3.75**	143	-3.53
WAIS-IV Visual Puzzles	-6.83**	143	-5.66
Boston Naming Test	-15.82**	142	-13.18
Category Fluency (Animal Naming)	-9.87**	143	-10.51
BDAE Complex Ideational Material	-12.56**	142	-10.10
Verbal Fluency (FAS)	-7.49**	143	-7.13
WAIS-IV Similarities	-5.79**	143	-4.47
Trails Making Test- Part B	-6.90**	143	-6.24
Category Test	-11.08**	143	-9.72

***significance <.001*

significant differences in all measures. See Table 5 for results.

It was further hypothesized that the Linemen group would demonstrate impairment in scores when compared to the population norms for each test. Results showed significant differences in most subtests, with the exception of the WAIS-IV Digit Span, Matrix Reasoning, Visual Puzzles, Boston Naming Test, and Similarities subtests. See Table 6 below for results.

Table 6. *One-Sample T-Test for Linemen Group*

Test Scale	**T-test**	**df**	**Mean Difference**
WAIS-IV Digit Span	-2.91	38	-5.82
WAIS-IV Arithmetic	-4.00**	38	-7.08
WAIS-IV Letter-Number Sequencing	-5.04**	36	-6.70
WAIS-IV Symbol Search	-6.11**	38	-10.15
WAIS-IV Coding	-7.94**	38	-12.05
WAIS-IV Cancellation	-6.11**	36	-10.35
WSM-IV Logical Memory I	-6.05**	38	-10.26
WMS-IV Logical Memory II	-6.47**	38	-11.46
WMS-IV Verbal Paired Associates I	-5.02**	38	-8.46
WMS-IV Verbal Paired Associates II	-5.23**	38	-8.87
WMS-IV Visual Reproduction I	-4.40**	38	-7.67
WMS-IV Visual Reproduction II	-2.65**	38	-4.15
WAIS-IV Block Design	-4.46**	38	-6.76
WAIS-IV Matrix Reasoning	-0.22	38	-0.46
WAIS-IV Visual Puzzles	-2.99	38	-4.85
Boston Naming Test	-6.42	38	-10.87
Category Fluency (Animal Naming)	-5.36**	38	-13.03
BDAE Complex Ideational Material	-6.19**	37	-17.11
Verbal Fluency (FAS)	-5.01**	38	-9.36
WAIS-IV Similarities	-2.54	38	-4.61
Trails Making Test- Part B	-6.09**	38	-10.59
Category Test	-6.57**	38	-12.19

***significance <.001*

It was hypothesized that the Skilled Linemen group would demonstrate impairment in scores when compared to the previously described population norms. Results showed significant differences in most subtests, with the exception of the WAIS-IV Symbol Search, Cancellation, Matrix Reasoning, and Visual Puzzles subtests, as well as Trails B. The greatest impairments were noted in delayed verbal memory, and non-timed language-based measures. See Table 7.

Table 7. *One-Sample T-Test for Skilled Linemen Group*

Test Scale	**T-test**	**df**	**Mean Difference**
WAIS-IV Digit Span	-3.33**	43	-4.82
WAIS-IV Arithmetic	-4.93**	43	-6.27
WAIS-IV Letter-Number Sequencing	-3.80**	40	-4.32
WAIS-IV Symbol Search	-2.64	43	-4.66
WAIS-IV Coding	-4.66**	43	-6.41
WAIS-IV Cancellation	-2.05	40	-3.76
WSM-IV Logical Memory I	-7.23**	43	-9.95
WMS-IV Logical Memory II	-7.63**	43	-10.68
WMS-IV Verbal Paired Associates I	-6.87**	43	-7.18
WMS-IV Verbal Paired Associates II	-7.00**	43	-7.70
WMS-IV Visual Reproduction I	-3.52**	43	-6.06
WMS-IV Visual Reproduction II	-2.67**	43	-3.68
WAIS-IV Block Design	-3.67**	43	-4.66
WAIS-IV Matrix Reasoning	-2.31	43	-3.66
WAIS-IV Visual Puzzles	-2.87	43	-4.66
Boston Naming Test	-9.71**	43	-13.02
Category Fluency (Animal Naming)	-4.87**	43	-7.63
BDAE Complex Ideational Material	-6.98**	43	-17.52
Verbal Fluency (FAS)	-3.20**	43	-5.89
WAIS-IV Similarities	-2.39**	43	-2.93
Trails Making Test- Part B	-2.01	43	-3.05
Category Test	-6.83**	43	-9.32

***significance <.001*

It was also hypothesized that the Skilled Players group would demonstrate impairment in scores when compared to the previously described population norms. Results showed significant differences in all subtests, with the greatest impairments being in verbal memory, and both timed and non-timed language-based measures. See Table 8 below for results.

Table 8. *One-Sample T-Test for Skilled Player Group*

Test Scale	**T-test**	**df**	**Mean Difference**
WAIS-IV Digit Span	-4.50**	60	-6.24
WAIS-IV Arithmetic	-6.60**	60	-8.67
WAIS-IV Letter-Number Sequencing	-4.92**	59	-5.63
WAIS-IV Symbol Search	-5.58**	60	-8.97
WAIS-IV Coding	-7.80**	60	-9.85
WAIS-IV Cancellation	-6.51**	59	-9.08
WSM-IV Logical Memory I	-9.35**	60	-13.25
WMS-IV Logical Memory II	-11.47**	60	-13.61
WMS-IV Verbal Paired Associates I	-10.35**	60	-10.57
WMS-IV Verbal Paired Associates II	-7.52**	60	-9.00
WMS-IV Visual Reproduction I	-5.84**	60	-8.00
WMS-IV Visual Reproduction II	-2.14**	60	-2.77
WAIS-IV Block Design	-6.71**	60	-7.57
WAIS-IV Matrix Reasoning	-4.09**	60	-5.39
WAIS-IV Visual Puzzles	-5.84**	60	-6.90
Boston Naming Test	-11.31**	59	-14.80
Category Fluency (Animal Naming)	-6.87**	60	-10.97
BDAE Complex Ideational Material	-8.32**	60	-19.15
Verbal Fluency (FAS)	-4.85**	60	-6.59
WAIS-IV Similarities	-5.03**	60	-5.49
Trails Making Test- Part B	-4.22**	60	-5.75
Category Test	-6.15**	60	-8.43

***significance <.001*

Hypothesis Two

Given that significant differences were revealed among the combined sample group, it was further hypothesized that differences would be found between the three groups. More specifically, the Linemen group would perform more poorly in comparison to the Skilled

Table 9. *Test of Between-Subjects Effects for Measures of Attention/Processing Speed*

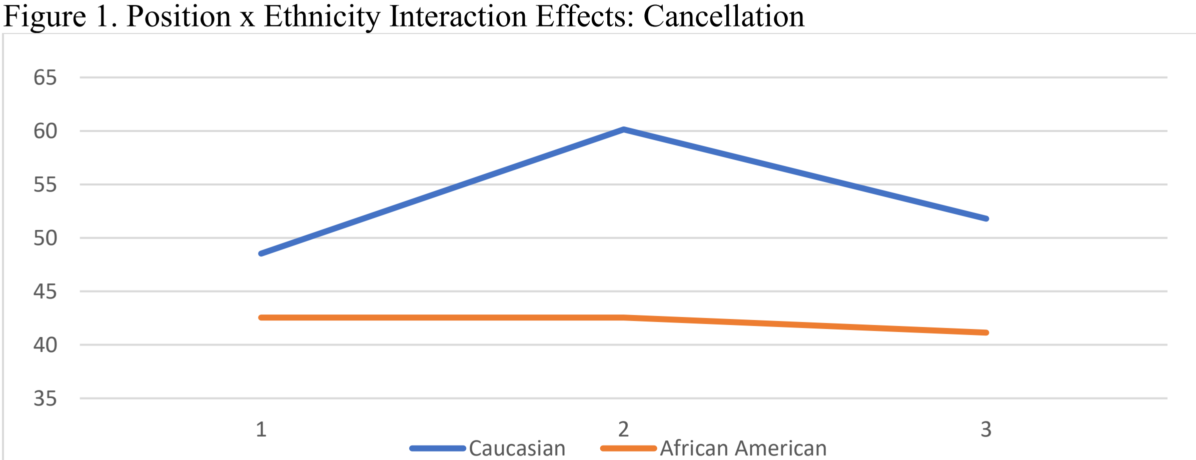
	F	df	Sig.
Digit Span			
Position Group	1.10	1	.332
Ethnicity	11.93	1	.001*
Position x Ethnicity	1.07	2	.345
Arithmetic			
Position Group	1.25	2	.290
Ethnicity	27.48	1	.000*
Position x Ethnicity	.31	2	.970
Letter-Number Sequencing			
Position Group	2.84	2	.062
Ethnicity	10.10	1	.002*
Position x Ethnicity	2.42	2	.090
Symbol Search			
Position Group	5.57	2	.005*
Ethnicity	20.26	1	.000*
Position x Ethnicity	2.02	2	.136
Coding			
Position Group	4.92	2	.009*
Ethnicity	9.03	1	.003*
Position x Ethnicity	.35	2	.703
Cancellation			
Position Group	8.52	2	.000*
Ethnicity	15.80	1	.000*
Position x Ethnicity	3.62	2	.029*

Linemen and Skilled Players, and that the Skilled Linemen would perform more poorly in comparison to the Skilled Players on all cognitive measures. To test the hypothesis, two-way ANOVAs were conducted at the $p<.05$ level to examine the effect of player position and ethnicity on mean differences of each of the cognitive measures that compose the battery. The model was constructed with the position group and the reported ethnicity as the fixed factors. The dependent variables will be each of the previously described tests.

Results evidenced statistically significant main effects related to position group on performance on the following measures of attention/processing speed: Symbol Search, Coding, and Cancellation. Main effects related to ethnicity were found on all measures, in which the Caucasian group performed better in all measures, as evidenced by higher mean T-scores. See Table 9.

There was also statistically significant interaction between the effects of player position and reported ethnicity in performance on the Cancellation measure. Although Caucasian

Figure 1. Position x Ethnicity Interaction Effects: Cancellation



*1=Linemen; 2=Skilled Linemen, 3=Skilled Players

ethnicity was related to superior performance on the Cancellation measure for all position groups, the magnitude of that relationship differed significantly between position groups amongst the Caucasian sample, while the African American participants demonstrated a more consistent performance amongst groups. Specifically, the difference between Caucasian and African participants was the largest in the Skilled Lineman group and the smallest in the Linemen group. See Figure 1 above.

Regarding learning and memory measures, there were no statistically significant main

Table 10. *Test of Between-Subjects Effects for Measures of Learning and Memory*

	F	**df**	**Sig.**
Logical Memory I			
Position Group	.61	2	.543
Ethnicity	6.72	1	.011*
Position x Ethnicity	.72	2	.488
Logical Memory II			
Position Group	.962	2	.385
Ethnicity	10.24	1	.002*
Position x Ethnicity	.11	2	.895
Verbal Paired Associates I			
Position Group	.12	2	.882
Ethnicity	2.98	1	.086
Position x Ethnicity	.99	2	.372
Verbal Paired Associates II			
Position Group	.37	2	.693
Ethnicity	3.15	1	.078
Position x Ethnicity	.38	2	.682
Visual Reproduction I			
Position Group	1.38	2	.254
Ethnicity	9.63	1	.002*
Position x Ethnicity	.746	2	.476
Visual Reproduction II			
Position Group	1.20	2	.304
Ethnicity	.77	1	.382
Position x Ethnicity	1.14	2	.323

effects related to position group on performance on these measures. However, main effects related to ethnicity were found on the following measures: Logical Memory I, Logical Memory II, and Visual Reproduction I, in which the Caucasian group performed better in those measures in comparison to the African American group, as evidenced by higher mean T-scores. No interaction effects were evident in these measures. See Table 10.

Regarding measures of visual-perceptual functions, there were statistically significant

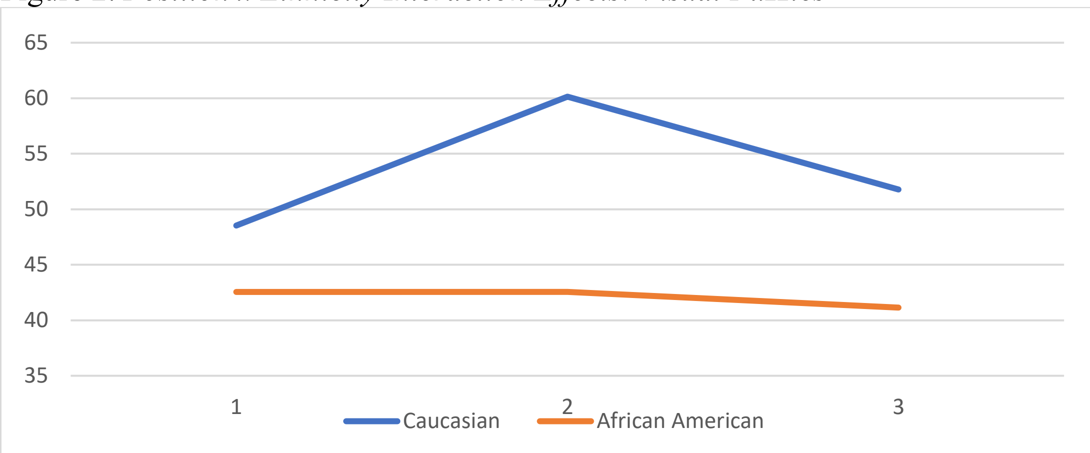
Table 11. Test of Between-Subjects Effects for Measures of Visual-Perceptual Function

	F	**df**	**Sig**
Block Design			
Position Group	3.22	2	.043*
Ethnicity	28.51	1	.000*
Position x Ethnicity	.51	2	.600
Matrix Reasoning			
Position Group	1.12	2	.329
Ethnicity	2.94	1	.089
Position x Ethnicity	.38	2	.680
Visual Puzzles			
Position Group	3.34	2	.039*
Ethnicity	36.66	1	.000*
Position x Ethnicity	3.12	2	.047*

main effects related to position group on performance on the Block Design and Visual Puzzles measures. Main effects related to ethnicity were additionally found on these measures, in which the Caucasian group performed better in Block Design and Visual Puzzles in comparison to the African American group, as evidenced by higher mean T-scores. See Table 11 below.

There was also statistically significant interaction between the effects of player position and reported ethnicity in performance on the Visual Puzzles measure. Although Caucasian ethnicity was related to superior performance for all position groups, the magnitude of that relationship differed significantly between position groups amongst the Caucasian sample, while the African American participants demonstrated a more consistent performance amongst groups.

Figure 2. *Position x Ethnicity Interaction Effects: Visual Puzzles*



*1=Linemen; 2=Skilled Linemen, 3=Skilled Players

Specifically, the difference between Caucasian and African participants was the largest in the Skilled Lineman group and the smallest in the Linemen group. See Figure 2.

Regarding measures of language, there were no statistically significant main effects

Table 12. *Test of Between-Subjects Effects for Measures of Language*

	F	**df**	**Sig.**
Boston Naming Test			
Position Group	.82	2	.444
Ethnicity	1.64	1	.203
Position x Ethnicity	1.74	2	.179
Category Fluency			
Position Group	2.43	2	.092
Ethnicity	1.66	1	.200
Position x Ethnicity	.78	2	.461
BDEA Complex Ideational			
Position Group	.16	2	.856
Ethnicity	4.03	1	.047*
Position x Ethnicity	.03	2	.970

related to position group on performance. Main effects related to ethnicity were found on the BDEA Complex Ideational measure, in which the Caucasian group performed better than the African American group, as evidenced by higher mean scores. See Table 12.

Lastly, regarding measures of executive functioning, there were statistically significant main effects related to position group on performance on Trails B. Main effects related to ethnicity were additionally found on the Similarities measures, in which the Caucasian group performed better in this measure in comparison to the African American group, as evidenced by higher mean T-scores. No interaction effects were evident in these measures. See Table 13 below.

Table 13. *Test of Between-Subjects Effects for Measures of Executive Functions*

	F	**df**	**Sig**
Verbal Fluency			
Position Group	.98	2	.988
Ethnicity	.23	1	.234
Position x Ethnicity	.10	2	.103
Similarities			
Position Group	1.13	2	.325
Ethnicity	9.94	1	.002*
Position x Ethnicity	.25	2	.775
Trails B			
Position Group	6.35	2	.002*
Ethnicity	3.73	1	.055
Position x Ethnicity	.336	2	.715
Category Test			
Position Group	3.00	2	.053
Ethnicity	1.71	1	.194
Position x Ethnicity	1.01	2	.367

Pairwise comparisons indicated that the Linemen group performed more poorly in comparison to the Skilled Linemen group in the Symbol Search, Coding, Cancellation, Block Design, and Visual Puzzle measures, as evidenced by lower mean T-scores. Pairwise comparisons also indicated that the Linemen group performed more poorly in comparison to the

Table 14. *Pairwise Comparison of Position Groups: Mean Differences*

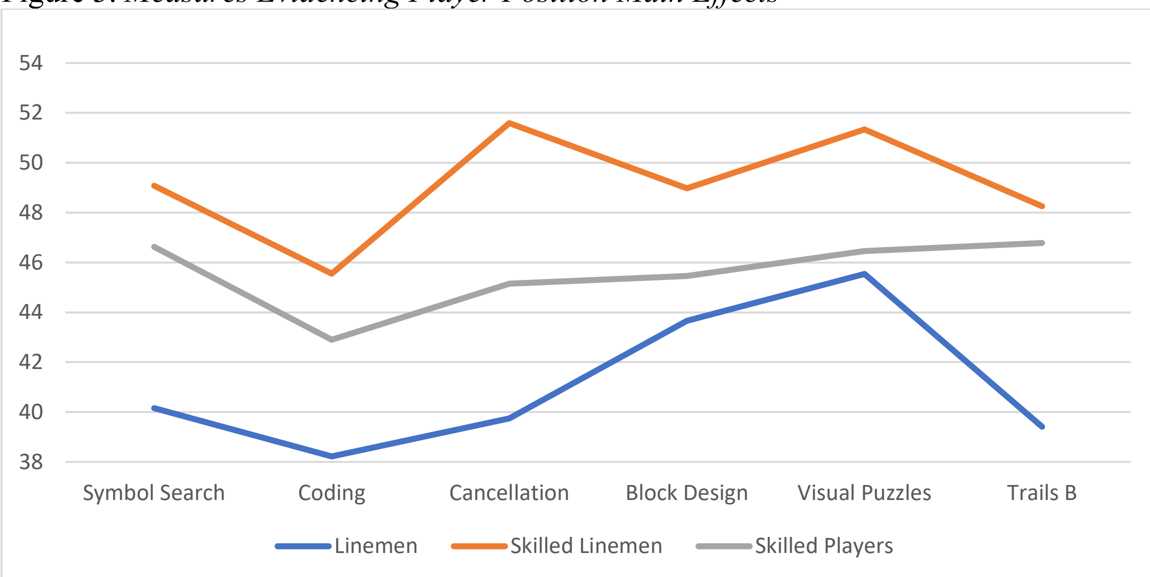
Measure	**Linemen – Skilled Linemen**	**Skilled Linemen-Skilled Players**	**Linemen-Skilled Players**
Digit Span	-3.27	-.11	-3.38
Arithmetic	-3.71	2.97	-.74
Letter-Number Sequencing	-2.38	1.59	-.79
Symbol Search	-8.92*	2.46	-6.46
Coding	-7.34*	2.65	-4.69
Cancellation	-11.85*	6.44	-5.41
Logical Memory I	-2.39	2.99	.59
Logical Memory II	-3.08	3.31	.23
Verbal Paired Associates I	-.97	1.04	.08
Verbal Paired Associates II	-1.56	-.13	-1.70
Visual Reproduction I	-4.59	2.12	-2.47
Visual Reproduction II	-.63	-2.90	-3.54
Block Design	-5.30*	3.51	-1.79
Matrix Reasoning	.96	3.02	3.98
Visual Puzzles	-5.81*	4.81	-.92
Boston Naming Test	3.28	-1.66	1.62
Category Fluency	-6.79	1.89	-4.89
BDEA Complex Ideational	-2.18	2.42	.24
Verbal Fluency	-3.47	.56	-2.91
Similarities	-3.25	3.27	.02
Trails B	-8.67*	1.47	-7.21*
Category	-2.86	-1.04	-3.90

**Significance <.05*

Skilled Linemen and Skilled Players group in Trails B. Pairwise comparison of the position groups did not evidence any statistically significant mean difference on measures of learning and memory or language. See Table 14 for all pairwise comparison results.

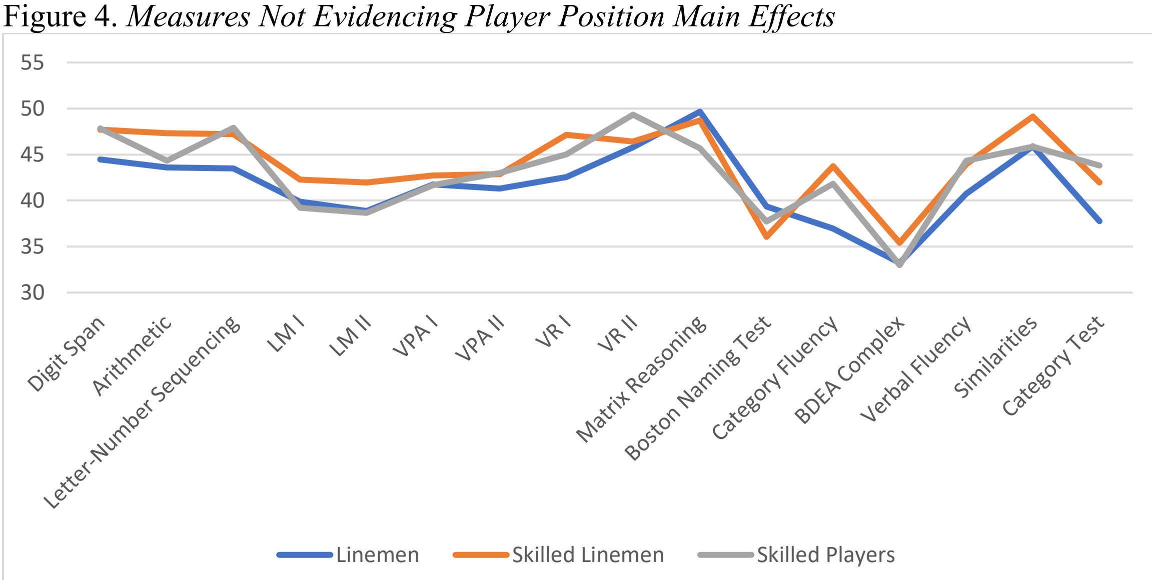
In summary, player position main effects were evident in 6 out of the 22 measures. The Linemen group was noted to evidence the poorest performance in all measures. See Figure 3.

Figure 3. *Measures Evidencing Player Position Main Effects*



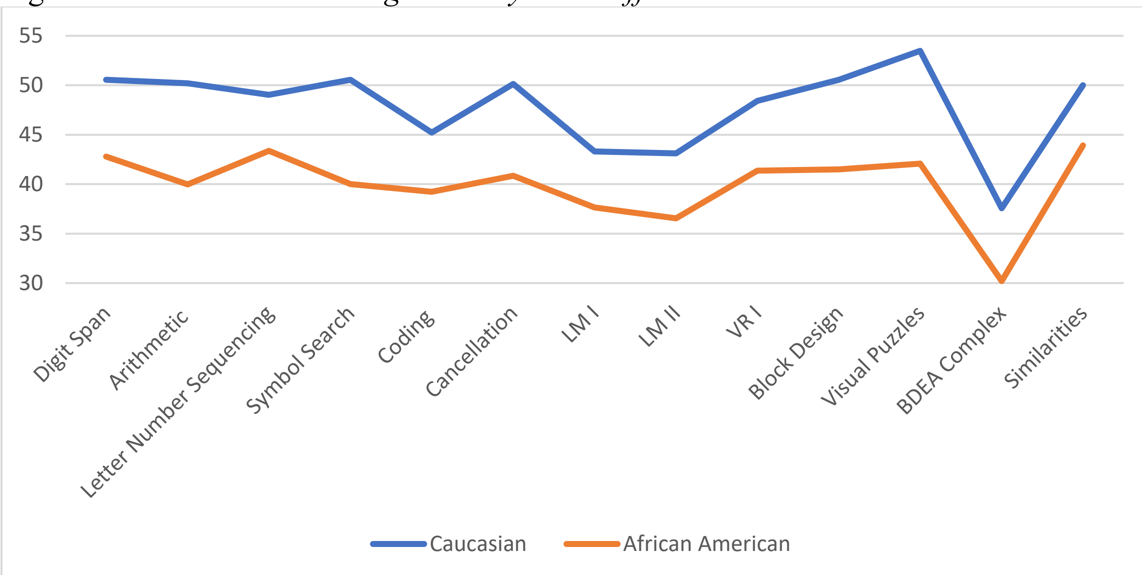
Player position effects were not significant in the remaining 16 measures. See Figure 4.

Figure 4. *Measures Not Evidencing Player Position Main Effects*



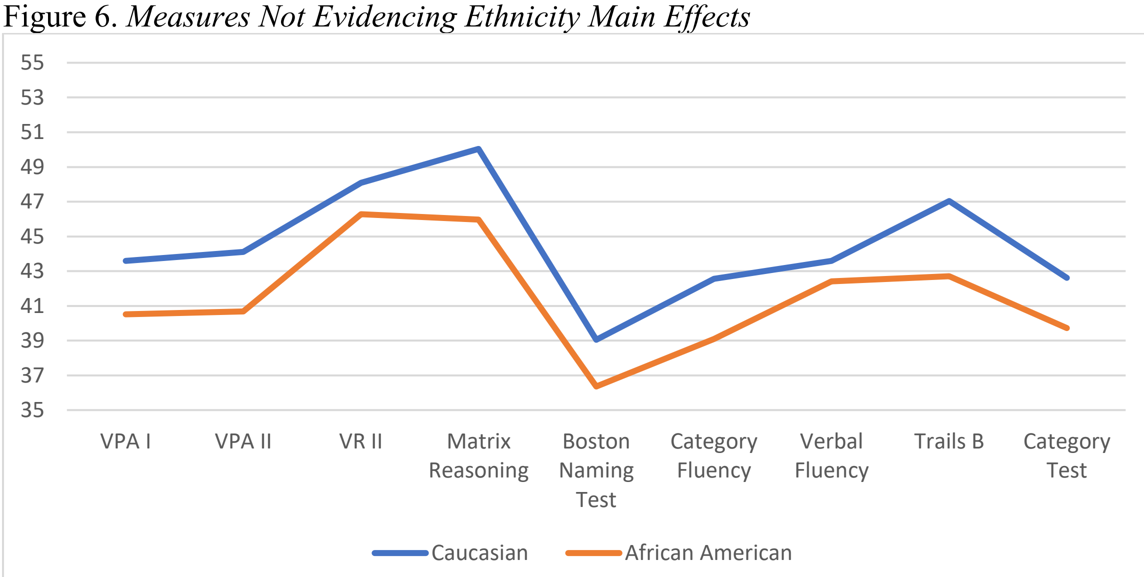
Reported ethnicity main effects were evident in 13 out of the 22 measures. The African American group was noted to evidence the poorest performance in all measures. See Figure 5.

Figure 5. *Measures Evidencing Ethnicity Main Effects*



Lastly, reported ethnicity main effects were not statistically evident in the remaining 9 measures. See Figure 6 below.

Figure 6. *Measures Not Evidencing Ethnicity Main Effects*



CHAPTER IV

Discussion

The purpose of the study was to extend the body of research on head-impact-related traumatic brain injury experienced by retired National Football League players. Concussion-related impacts sustained in American football have been associated with both short- and long-term neurological impairment, and this study sought to look at whether playing position in particular should be considered as a key risk factor for neuropsychological impairment in football players.

Hypothesis One

In Hypothesis One, it was hypothesized that the combined sample of retired NFL players would demonstrate impairment in test scores when compared to a population norm of a T-score of 50 and a standard deviation of 10. The three previously defined groups (Linemen, Skilled Linemen, and Skilled players) were also expected to individually demonstrate impairment in scores when compared to the same population T-score and standard deviation norm. Overall, both the combined group and each of the individually defined groups demonstrated impairments in the majority, if not all, assessments when compared to the population norms.

Beginning with the Linemen group, results showed that the majority of the included subtests were impaired when compared to normal functioning. One of the most impaired neuropsychological constructs among this group appear to be executive functioning. This can be evidenced, for example, in this group's overall performance of the Category test, as measured by a higher number of errors in this measure. This result suggests that these individuals may have difficulties learning a novel principle or task. While it is expected that an individual is going to make some incorrect responses at the beginning of each subtest in the Category test as they are attempting to learn criterion principle, making larger amount of errors may be indicative of inefficient learning abilities, such as being unable to pick out significant stimuli in order to formulate a possible rule or strategy. Furthermore, the current findings may be indicative of impaired problem-solving abilities for the Linemen group. An important component of problem-solving, is the ability to be flexible and adapt to a situation. The findings appear to indicate that this group may experience an inability to discover the underlying rule when presented with a novel task, especially when provided with little to no instructions from the examiner or test itself.

The implications surrounding a lack of problem-solving abilities in real world settings is crucial as individuals are often faced with situations in which they have never been in before, and the need to discriminate and decide on what is relevant and needed for the situation at hand is detrimental. Individual's may be faced with unexpected circumstances and therefore, need adequate flexibility to deal with changing circumstances. Consequently, individuals lacking these skills could face repercussions such as performing poorly their place of employment, experiencing difficulties in their social and romantic relationships, and even difficulties with initiating the proper response in any other situation. Therefore, understanding this component could lead to recommendations that could impact an individual's overall quality of life.

Significant results from this study also appear to be implying that factors relating to task-switching abilities could be impacted within this group. One finding that supports this theory is that the Linemen group additionally performed more poorly in Trails B, as measured by the length of time it took to complete the task. In this task, individuals with task-switching abilities will make errors such as going from one number to another number, instead of switching back and forth from number to letter or taking a long time due to experiencing difficulties with task switching. This construct is important to assess as it is one's ability to switch between two simultaneous tasks that allows a person to rapidly and efficiently adapt to different life situations.

Furthermore, impaired scores in category fluency can further support executive functioning difficulties within this group, as well as additional deficits in processing speed. In category fluency, an individual is asked to name items of a specific category (i.e., animals) within a time-limit. As a result, this task does not only require significant processing speed, but additionally demands executive functioning skills such as problem-solving and coming up with a strategy that will allow for the most efficient way to name as many items as possible. Impairments in this task can indicate that Linemen are further significantly impacted when having to problem solve a novel task while additionally being placed in a time constraint.

Tasks that further support the hypothesis of the Linemen group experiencing processing speed deficits is in the deficits noted within the WAIS-IV Coding, Symbol Search, and Cancellation subtests. In all three tasks, an individual must first attend to the rules and relevant stimuli presented to them, and then they must sustain that information in their mind and continuously attend the task for the total duration of the task. If one is unable to sustain attention during a timed task and process information as quickly as possible, this can consequently lead to poorer scores, as one will either begin to respond incorrectly or will not be able to get as many responses due to wasting time while having to continuously check on what the rule of the task was. If looking at the overall pattern of the previously mentioned constructs, one can further suggest that this group could be experiencing cognitive dysfunction particularly in the left frontal region. By understanding that the Linemen group is experiencing deficits in multiple executive functioning components, one can also understand how these impairments can lead to real world consequences, specifically how an individual is able to approach novel situations successfully in their real-world situations.

Yet another neuropsychological construct that appeared to be one of the most impaired is that of verbal (or auditory) memory functioning. In Logical Memory I, an individual is verbally told short stories and then asked to recall as many details of the story with as close to the same words as closely as possible. This task allows one to compare one's immediate auditory memory in a narrative context-based format. In Logical Memory II, an individual is expected to recall the previously presented information with as close to the same words as possible after a 20- to 30-minute delay period. Deficits in these tasks can indicate that not only can these individuals experience issues in organization of and integrating novel material into memory but can then additionally experience issues specifically in the delayed recall of declarative types of memories.

Other memory-based tasks, which are both verbal and non-verbal in nature, appear to be impaired within this group, though to a lesser extent than narrative context-based verbal functioning in relation to WMS-IV performance. In the Verbal Paired Associates task, for example, one is presented with a list of word pairs that may or may not be associated with one another for multiple trials. The inclusion of this task additionally allows to assess one's ability to learn through repetition. When compared to the Logical Memory subtest, it can be hypothesized that this is a less demanding task as it does not require the same amount of organization abilities that is required to make sense of a narrative format, and one gets the additive benefits of higher amounts of repetition. In regard to the remembering of this information after a delay period, it can also be expected that the same declarative memory deficits are noted in this task, though to a lesser extent as the repetition component allowed for greater learning of the material.

Nonverbal (or visual) memory functioning was further noted to be impaired as evidenced by the Linemen's performance in the Visual Reproduction I and II subtests, though not as much as that noted in verbal forms of memory. Visual memory was likely not as impaired as verbal memory due to preserved perceptual and visual-spatial skills, given the left frontal pattern of impairment seen across previously discussed tests. Therefore, players present with a relative strength in visual spatial skills, and this is reflected in performance on tasks involving any perceptual reasoning, including non-verbal or visual memory.

Overall, memory abilities are a crucial part in one's functioning and are often required to be able to complete both single and multi-step tasks in our daily lives. The ability to hold on to information in one's mind and manipulate in the form of working memory is also considered somewhat of an executive functioning ability, therefore relating these skills and exposing the need for memory in many executive functioning abilities. Furthermore, all forms of memory are important components of one's ability to learn and develop skills and abilities over time. As a result, this construct is a significant and crucial component in which most other cognitive abilities depend on, including executive functioning abilities, intelligence, cognitive, and achievement abilities.

Furthermore, findings demonstrated that working memory was also significantly impaired in the Linemen group. It was noted that the Linemen group demonstrated difficulties in both the WAIS-IV Arithmetic and Letter-Number Sequencing subtests. In both tasks, individuals are required to attend to orally presented letter-number sequences or word problems, temporarily retain the information in memory, and perform a required manipulation or operation. While the Digit Span subtest additionally measures working memory within the backwards and sequencing sections, it can be hypothesized that this task demands less complex working memory skills in comparison to the Arithmetic and Letter-Number Sequencing tasks, as it requires an individual to attend to and manipulate a less varied stimuli (only numbers as opposite to both numbers and letters or complex word problems with multiple components). As a result, the demands placed on this group of individuals might not be complex enough to demonstrate impairment within the Linemen group.

Lastly, findings indicate that the Linemen group did not show any impairment primarily in subtests measuring visual spatial functioning measures. In the Block Design, Matrix Reasoning, and Visual Puzzles subtests, individuals are required to manually or visually manipulate presented stimuli to recreate a desired response. These three subtests comprise the Perceptual Organization/Reasoning Index, in which it is meant to partially measuring the ability to solve novel tasks that are supposedly not dependent on formal schooling. This finding might therefore indicate that repetitive head impacts may not affect organizational skills on non-verbal material. The Linemen group additionally did not evidence significant deficits in non-timed, non-memory-based language tasks, such as the WAIS-IV Similarities subtest and the Boston Naming Test. In can be hypothesized that these types of language skills are the least susceptible to being affected by brain injury, as information such as the name and definition of common words and items tends to be highly practiced over one's lifetime, therefore becoming more crystallized form of memory.

When looking at the pattern evidenced in the Skilled Linemen group, there are a large number of similarities regarding the neuropsychological patterns previously described that is experienced by the Linemen. For example, the Skilled Linemen group evidenced significant impairments in executive functioning, as evidenced by impaired scores in category fluency, verbal fluency, and the Category test. This further supports the hypothesis that experiencing repetitive concussive impacts can affect a player's ability to come up with strategies for novel tasks and problem solve when provided with feedback that the task is being completed incorrectly. This difficulty is further noted to be evidenced in both time- and non-time-constrained situations.

Additionally, Skilled Linemen evidenced significant difficulties in the construct of memory, and similarly presented with slightly greater deficits in verbal memory and then impairments in visual memory to a lesser extent. As evidenced in the Linemen group, it appears as though the Skilled Linemen have perceptual and visuo-spatial skills that are more preserved and can mediate their performance on tasks that require both visual and memory skills. On the other hand, verbally-based memory tasks are much more significantly impacted as Skilled Lineme evidenced significant deficits in both memory and language-based tasks. For example, Skilled Linemen were found to experience the most impairment in language tasks such as the Boston Naming Test and the BDEA Complex Ideational task.

Furthermore, findings demonstrated that working memory was also significantly impaired in the Skilled Linemen group. However, findings how that this neurocognitive domain appeared to be impacted to a greater extent within this group, as it was noted that the Skilled Linemen group demonstrated difficulties in a greater amount of WAIS-IV attention/working memory subtests (Digit Span, Arithmetic, and Letter Number Sequencing). Whereas it was hypothesized that Digit Span was possibly not cognitively demanding enough for the Linemen group, the deficits within this domain for the Skilled Linemen group could be significant enough to also be identified by the structure of Digit Span.

Where this Skilled Linemen group differed the expectations of the impact of brain injury on neuropsychological domains is that motor-based processing speed tasks appeared to not be significantly impaired. For example, the WAIS-IV subtests of Symbol Search, Coding, and Cancellation all appeared to not be significantly impaired based on what is expected of the general population. Trails B, which is considered to be primarily an executive functioning task, is additionally highly dependent on an individual having adequate motor processing speed in order to complete the task. As a result, lack of significant findings on this measure could be indicative of the individuals that comprise this group of having relatively preserved motor processing speed abilities. However, tasks that require verbal processing speed skills still appear to be significantly impacted, once again demonstrating a significant deficit in left and frontally-mediated functions.

Regarding the Skilled Players group, impairments were evidenced in all subtests, with the greatest impairments noted in verbal memory, processing speed, and language-based skills. Regarding verbal memory, the Skilled Players evidenced the same pattern of performance regarding having the greatest impairment in narrative context-based memories, followed by verbal memory tasks that have the added benefit of further learning and repetition. Visual memory was additionally impacted, although once again to a lesser degree. Skilled players additionally evidenced significant deficits in both verbal and motor-based processing speed measures. This is consistent with the research indicating that processing speed is often one of the most susceptible neurocognitive domains impacted by brain injury.

A particularly interesting finding indicated in this research is that both the Skilled Linemen and Skilled Players of this study evidenced difficulties in non-timed language tasks, particularly as related to confrontational naming as evidenced in the Boston Naming Task. It can be hypothesized that, aside from possible player position differences in impact frequency and magnitude, it is the ethnic demographics of these groups are significantly different in comparison to a more equally diverse population, such as that evidenced in the Linemen group. Whereas the Linemen group is made up of approximately 54% of African American participants, the Skilled Linemen and Skilled Player groups are comprised of between 80-85% African American players. A study utilizing differential item functioning explored whether the conditional probability of responding correctly to individual BNT items differed between African American and Caucasian adults; results indicated that 12 items were shown to demonstrate differential item functioning, and that six of the 12 items ("dominoes," "escalator," "muzzle," "latch," "tripod," and "palette") demonstrated the strongest evidence for race/ethnicity-based differentiation (Pedraza et al. 2009). Therefore, the performance of African American individuals in this subtest could be a misrepresentation of their true confrontational naming abilities. These findings emphasize the importance of developing and using ethnically and culturally appropriate neuropsychological test norms as well as the risk of interpreting some Black individual's scores as below average when they likely are not.

When looking at the overall player sample combined, the results indicated once again that all subtests were impaired when compared to the expected performance in these tasks. Further analyses of this pattern indicate that the greatest impairments were noted in the areas of processing speed, executive functioning, and verbal memory. These findings are consistent with the research that processing speed is one of the neuropsychological domains that is most susceptible to injury. Findings related to executive functioning deficits are also consistent with the existing research, as it has been found that concussed individuals have been found to have impaired attentional control processing and task switching abilities, which has been shown to be related to a higher proportion of dysexecutive behaviors in everyday lives (Chan, 2002). Lastly, the finding related to memory overall being impaired in this population, with greater impairment noted in verbal memory, further allows for the hypothesis to be made that repeated head impacts particularly affects functions found within the frontal and left regions of the brain. Therefore, these findings appear to indicate that players groups have experienced somewhat similar development of chronic neurodegenerative disorders as a result of repeated concussive insults. While all forms of TBIs are heterogenous in their injury characteristics and presentation, it is suspected that there are multiple neuropathological factors and consequences that individuals with TBIs evidence at the acute and chronic stages post-injury. These findings may perhaps suggest that all player positions are equally at risk to some form of chronic neurodysfunction despite their initial heterogenous presentation in terms of frequency and impact severity.

Overall, these results only allow for the implication of a possible pattern of significant impairment and overall neuropsychological performance related to these player position groups. Since no score can be definitive in its interpretation with varying statistical findings, clinical judgement would be necessary in order to analyze the patterns found in an actual individual case. These interpretations should be used with caution and must be taken in context with an individual's personal clinical history and behavioral observations, as well as any other results that arise from a more comprehensive neuropsychological assessment.

Hypothesis Two

In Hypothesis Two, it was further hypothesized that differences would be found between the three player position groups. More specifically, the Linemen group would perform more poorly in comparison to the Skilled Linemen and Skilled Players, and that the Skilled Linemen would perform more poorly in comparison to the Skilled Players on all cognitive measures.

Position-Related Main Effects.

The results demonstrated that the Linemen group demonstrated significantly poorer performance in comparison to the Skilled Linemen on six out of the twenty-two total measures (Symbol Search, Coding, Cancellation, Block Design, Visual Puzzles, and Trail Making Test-Part B). As it is believed that the Linemen group suffer more frequent subconcussive and concussive injuries than the other two groups (Guskiewicz et al, 2003; Mihalik et al, 2007; Crisco et al. 2010; Crisco et al., 2011), this pattern indicates that experiencing repeated head injuries may lead to chronic neurological and neuropsychological impairment. Existing research has demonstrated that both subconcussive and concussive injuries can lead to biomarker and metabolic changes that trigger apoptotic cascades and tau phosphorylation, among other consequences (Kawata et al., 2017). Furthermore, as the Linemen have been demonstrated to experience subconcussive and concussive injuries occur at a greater frequency (Bailes et al., 2013) the continuous disruption of the recovery process in this players could lead to syndromes such as the second impact syndrome, in which it is proposed that a second concussion or brain injury can lead to catastrophic damage to due to characteristic ionic fluxes, acute metabolic changes, and cerebral blood flow alterations that occur immediately after cerebral concussions. As, extracellular potassium concentration and resulting hypermetabolism can increase massively in the brain after concussion for up to ten days, a second sub-lethal insult of even less intensity can lead to the brain losing its ability to auto regulate intracranial and cerebral perfusion pressures (Bey & Ostick, 2009). This hypothesis may explain why receiving multiple hits in the same game does not have the same effect as two injuries that occur days or weeks apart, as the recovery efforts have not yet reached maximum level. If additional neurological injuries do occur during this window, however, it is expected that the metabolic effects will become dangerously cumulative, and the resulting damage might be hard to later reverse. Additionally, these findings indicate that it is not only concussion-level injuries that could lead to chronic injuries, but that the experiencing of repetitive subconcussive injuries can lead to significant neurological alternations such as axonal injuries, blood-brain barrier blood-brain barrier permeability, and evidence of neuroinflammation, all in the absence of behavioral changes, and especially if the injuries are repetitive (Bailes et al., 2013)

Furthermore, as all of the measures in which significant differences amongst the player position groups were noted have a timed component, this would suggest that processing speed is one of the most vulnerable domains to concussion-related injuries. It has been indicated that concussed individuals have demonstrated deficits on most tests of attention and processing speed in comparison to normal controls, and that these differences were found to still be significant even when emotional disturbances and processing speed were controlled for (Chan, 2002). Changes to neuropsychological functioning in areas of attention and processing speed in particular has been further supported in electrophysiological- and metabolic-based studies, which suggests a possible long-term and cumulative effect in the motor system that could impact processing speed in motor-based assessments (DeBeaumont et al., 2007). Further studies have additionally demonstrated that experiencing concussions leads to persistent alterations in electrophysiology that impact one's ability to attend to environmental stimuli, even on asymptomatic multiple-concussion athletes who sustained their last concussion about 3 years prior to testing (on average), which further indicates the chronic nature of this dysfunction (DeBeaumont et al., 2007).

Concussed individuals have been found to have difficulties related to task switching abilities, which has been shown to be related to a higher proportion of dysexecutive behaviors in everyday lives (Chan, 2002). As the Trails B task was also noted to be significantly impaired in the Linemen group, is can be hypothesized that experiencing more-frequent impacts can highly affect real-world situations such as having difficulties with task switching between two simultaneous stimuli under a time limit. Noting difficulties in task-switching neuropsychological measures is further meant to generalize and inform an individual's ability to switch between two or more tasks occurring simultaneously, thereby allowing someone to rapidly and efficiently adapt to different real-life situations, such as during their place of employment or home life. While research has demonstrated that active NFL players demonstrate a TMT-B score of about 0.5 standard deviations lower than the average scores when compared with Caucasians ages 20 to 34 years old and with 16 years of education and a score 0.8 standard deviations above the average when compared African Americans ages 20 to 34 years old and with 16 years of education, the retired Linemen group demonstrated approximately one standard deviation below the mean when compared to their own age, education, and ethnic group. This finding demonstrates that this player position group in particular evidences even greater impairment that what should be expected amongst NFL players in general. Therefore, this finding is indicating that continued subconcussive or micro-hits experienced by NFL players tends to significantly impacts frontal areas of the brain which allow for an individual to switch between alternate stimuli.

Furthermore, main effects were noted in two out of the three visual-perceptual tasks, in which the Linemen performed more poorly in the Block Design and Visual Puzzles measures in comparison to the Skilled Linemen group. In the Block Design task, an individual is asked to view a picture (or a model and a picture) and utilize blocks to recreate the design within a specific time limit, whereas in the Visual Puzzles measure, examinee views a completed puzzle and selects three options that reconstruct the puzzle when placed next to each other. Both tasks are meant to partially measuring the ability to solve novel visual-based tasks that are supposedly not dependent on formal schooling and additionally include a timed component. Concussed individuals will often demonstrate acute disruptions to their visual-spatial and perceptual skills as a result of symptoms such as visual instability, disrupted balance, blurred vision, diplopia, impaired eye movements, ocular pain, and impaired visual-based concentration (Lau et al., 2011). The results of this study, therefore, appear to be consistent with injuries often related to subconcussive injuries, such as axonal injuries to the mesencephalon in particular, which can significantly impair one's visual perceptual functioning (Bailes et al., 2013). As previously discussed, sustaining these injuries repeatedly and at a greater frequency could further lead to continuous metabolic changes and more consistent disruption to brain recovery during the most vulnerable period of recovery, leading to changes in brain functioning that became chronic over time.

The time-based component of these tasks additionally places a significant demand on these players, thereby giving them less time to compute the problem and analyze solutions or implement compensatory strategies. This is where the Matrix Reasoning task differs from the previously mentioned visual-spatial measures, as it does not have a strict time limit, and the implementation of a compensatory strategy could be easier to apply, as an individual only has to select one option out of a total of five possible stimuli. In such a task, a player can utilize strategies such as process of elimination and even guessing, and the likelihood of getting a successful response will be higher than in the Visual Puzzles task, in which all three correct pieces have to be selected within the time period provided, or the Block Design task in which the four or all total blocks must be placed in the accurate place and rotational pattern within a time limit as well.

It was found by this study that that no significant differences were found amongst the player positions on tasks of complex attention, learning and memory, language or non-timed executive functioning skills. The question then arises as to why these areas were not impacted at different severities if frequency or magnitude is hypothesized to be different amongst the positions. The results of this study appear to evidence that individuals who suffered repeated brain injuries could still engage in compensatory strategies when facing tasks that can are based on abilities typically learned in formal schooling, repeatedly practiced throughout one's lifetime, or can be more verbally mediated. For example, in the WAIS-IV Digit Span, Arithmetic, and Letter-Number Sequencing subtests, individuals are required to attend to orally presented letter-number sequences or word problems, temporarily retain the information in memory, and perform a required manipulation or operation. While these are novel stimuli that the individual would not have been exposed to prior to testing, the way in which these complex attentions and working memory tasks can be approached is often practiced during formal schooling. As all of the player position groups have demonstrated statistically similar levels of education, it can be expected that they are able to engage in similar compensatory strategies if difficulties are experienced.

Results further indicated that there were no statistically significant main effects related to position group on performance on measures of learning and memory. If looking at the groups' performance in measures of learning and memory, it was noted that all player groups demonstrated a similar pattern in evidencing difficulties in most memory subtests, with the greatest impairment noted in narrative contextually based verbal memory. When analyzing the characteristics of the verbally mediated memory subtests (Logical Memory and Verbal Paired

Associates), it can be hypothesized that their ability to come up at utilize organizational and compensatory strategies in order to create further structure can mediate and impact their performance in such tasks. For example, the use of repetition as a compensatory strategy may be beneficial across all player groups, as results demonstrated less impairment in Verbal Paired Associates when compared to the Logical Memory subtests, which involves being presented with four consecutive trials of the same word pairs. It can be hypothesized that this is a less demanding task as it does not require the same amount of organization abilities that is required to make sense of a narrative format, and one gets the additive benefits of higher amounts of repetition.

The utilized battery additionally included Visual Reproduction, which requires one to attend to and attempt to reproduce a visual stimulus presented to an individual for a limited time. Such a task has additional cognitive demands for an individual, such as visuospatial skills and executive functioning, particularly as related to what problem-solving approach one implements in order to organize and reproduce the material. Deficits in these tasks can there indicate that these individuals experience issues in organization of and integrating material into memory.

Overall, memory abilities are a crucial part in one's functioning and are often required to be able to complete both single and multi-step tasks in our daily lives. The ability to hold on to information in one's mind and manipulate in the form of working memory is also considered somewhat of an executive functioning ability, therefore relating these skills and exposing the need for memory in many executive functioning abilities. Furthermore, all forms of memory are important components of one's ability to learn and develop skills and abilities over time. The results of these hypothesis however indicate that, while they all performed at a lower level that what is expected, all player positions are either impacted at the same severity or that they may still access similar compensatory strategies, such as utilizing repetition and previously practiced memory strategies.

There were no main effects evident amongst the player position groups in measures of language, as they all evidenced similar level of impairment in these subtests. Within this study in particular, language components that were explored included receptive and expressive language (BDEA Complex Ideational), confrontational naming (Boston Naming Test), and semantic fluency (Category Fluency). While language is generally thought to be the domain that is least susceptible to injury, as information such as the name and definition of common words and items tends to be highly practiced over one's lifetime and becoming more crystallized form of memory, the player groups overall evidenced similar levels of impairment. This pattern once again appears to indicate that the player groups can implement similar compensatory approaches based on skills that have been highly practiced throughout one's lifetime.

Overall, the pattern of differences amongst the player position groups appears to indicate that the type of impairment that results from repeated impacts and the experiencing of metabolic disruptions while attempting to recover tends to most impact the ability to engage in novel, time-dependent tasks. However, players may be able to compensate in tasks which can be verbally mediated or are based on abilities typically learned in formal schooling or practiced throughout one's lifetime (such as language or engaging in memory strategies).

Ethnicity-Related Main Effects.

Results indicated that main effects were found on 13 of the total 22 measures across all domains. In all measures in which ethnicity-based differences were found, the Caucasian players demonstrated better performance in comparison to the African American players. No differences were evidenced on only 9 measures, which include the Verbal Paired Associates I and II subtests, Visual Reproduction II, Matrix Reasoning, Boston Naming Test, Category Fluency, Verbal Fluency, Trails B, and the Category Test.

Such significant differences in so many domains are highly indicative on one of the salient problem regarding neuropsychological testing, as traditional neuropsychological assessment is usually based on skills that are considered important within majority culture (such as completing tasks as quickly as possible and considering doing things quickly as a sign of intelligence). However, these same skills may not be salient or valued within the African American culture, or other minority cultures. Therefore, differences in salience of cognitive skills, exposure to items, and familiarity with certain problem-solving strategies could have affected the performance of African Americans on the neuropsychological battery.

Participant examiner interactions, test taking attitudes, and motivation during the testing session may also account for the ethnic group differences found on tests of both verbal and nonverbal ability. This is hypothesized to be particularly evident when the examiner is of a majority group. Furthermore, it can be hypothesized significant differences in how African Americans categorize information, such as word lists, pictures, and situations, differently than the majority Caucasian culture, both due to differences in education received and cultural upbringing within the home and their community can affect their overall results. Whereas someone that is Caucasian will often take a detail-oriented or functional approach, African Americans will generally take a more holistic and descriptive approach to analyzing and organizing information (Manly et al., 1998). As a result, this could lead to significant differences in attention, memory, and abstraction tasks. Therefore, culturally influenced variability in organization and information analysis may explain the ethnic group differences on this measure, regardless of whether the education level is expected to be equal.

In regards to subtests in which the ethnic groups were not significantly different in, it can be expected that, as seen in the differences between player position groups, differences amongst the ethnic groups can be explained through the utilization of compensatory strategies such as repetition or skills practiced throughout one's lifetime (such as language). Additionally, while differences in educational quality and community exposure could lead to differences in language acquisition, it can be expected that the language skills required in the tasks previously mentioned were simple enough to not lead to significant differences amongst the groups, particularly in this population in which the majority of participants achieved the same level of college education (naming common items and animals, knowing the alphabet).

Position and Ethnicity Interaction Effects.

Aside from the significant main effects seen related to both player position and ethnicity separately, there were also observed interaction effects on the Cancellation and Visual Puzzle measures. Although Caucasian ethnicity was related to better performance on all position groups, the magnitude of that relationship differed significantly between position groups for only these variables. Specifically, the Caucasian Skilled linemen group demonstrated better performance than the Caucasian Linemen and Skilled Players, as well as better performance amongst all African American players across all the player positions. The African American players demonstrated a consistently poorer performance across the board and did not evidence such significant differences in magnitude amongst the player positions. This pattern appears to highlight how the combination of being in a majority cultural group and experiencing less frequent impacts may lead to better performance in tasks that require both visual spatial skills and processing speed. As main effects were noted for ethnicity in these two measures as well, it is hypothesized that this effect does not allow for differences to be as significant amongst the players in the African American player groups.

In conclusion, the findings of this hypothesis highlight the importance of multiple concepts related to the understanding of repeated brain injury and their resulting effects. Firstly, the consistent finding that the Linemen group demonstrates the poorest performance in all measures found to be significantly different amongst the player positions demonstrate support for the significant damage that experiencing either subconcussive hits or concussions can have on an individual's neurophysiology and neuropsychological functioning, such as altered metabolic functioning and physical damage and tearing of axons (particularly in the deep midbrain region) that can remain chronically injured over time. Furthermore, as this group has been found to experience the greatest frequency of insults overall, whereas the majority of injuries are subconcussive in nature, these findings also appear to lead to the conclusion that experiencing these injuries at a greater frequency could lead to additional complications, such as interrupting important brain recovery during a critical period, leading to consequences such as second impact syndrome hypothesis, which can negatively impact an individual at the acute and cognitive level. Additionally, the findings particularly highlighted how traditional neuropsychological testing is based on a majority culture and may not accurately reflect the true performance of individuals from minority cultures, such as the African American culture. Lastly, the interactive effect of player position and ethnicity allows for more significant differences to be noted amongst Caucasian players, but not African American players, indicating that differences in timed measures of visual-spatial skills may not be adequately assessed for the players in different position groups in the African American population, and better assessed for the different player position groups within the Caucasian players.

General Discussion

This study sought to examine the pattern of neuropsychological impairment experienced by retired NLF players. Results evidenced that these players are significantly more cognitively impairment than what is expected of the general population. This finding applied to the majority of neuropsychological domains. This study also investigated if player position was a significant factor that could lead to differences in levels of impairment. Results did in fact indicate significant differences in levels of cognitive impairment between player positions. Lastly, the third outcome identified ethnicity as a significant factor that could be impacting neuropsychological performance results.

One of the main goals of this study was to explore the pattern of neuropsychological impairment of the retired NFL player sample overall in comparison to the general population in a context that would further contribute to the existing literature. Existing literature regarding long-term effects of brain injury in studies that utilized both active and retired player samples, particularly if repeated insults were acquired over time, suggested long-term impairments in processing speed (DeBeaumont et al., 2007; Lovell & Solomon, 2011; Solomon et al., 2015; Didehbani et al., 2020). Utilizing the current NFL-indicated neuropsychological battery, this study further revealed significant impairments in the areas of processing speed, as well as additional domains of impairment including executive functioning and verbal memory. Other neuropsychological domains such as visual memory and non-timed language measures were further noted to be impaired, though to a lesser extent. This study's results related to executive functioning abilities were also consistent with the research regarding TMT-B and verbal fluency performance, but other measures of executive functioning were often not evidenced in the existing literature thus far. Therefore, this study is contributing to the further understanding of executive functioning skills that may have not been explored prior (such as the abstraction or problem-solving abilities assessed by the Category Test or the WAIS-IV Similarities subtest).

Regarding verbal memory abilities, the findings of this study were consistent with the existing research, in which retired players performed at approximately one standard deviation below average (Lovell & Solomon, 2011; Solomon et al., 2015). However, the majority of the existing research appeared to utilize memory measures that were multiple trials-based and thus benefited from repetition, such as the HVLT and CVLT measures. While this study utilized the Verbal Paired Associates subtest of the WMS-IV, which differs in that pairs are remembered as opposed to single words, the level of impairment in this neuropsychological domain was consistent with those evidenced in studies that explored this domain with different measures. Furthermore, this study used contextual-based memory measures with the inclusion of the Logical Memory subtests, which has not been implemented in the existing retired NFL player research reviewed. Therefore, the inclusion of such measures is once again allowing for further expansion of our understanding of memory deficits that could be evidenced by this population.

Visual-spatial/perceptual abilities, however, were noted often to not be impaired in all football player samples, particularly when they were not time-dependent as well. This could be considered to be not consistent with the existing research that repeated brain injury often impacts visual functioning (Lau et al., 2011; Gaetz and Weinberg, 2006; Gosselin et al., 2006; DeBeaumont et al., 2002). It can be hypothesized, therefore, that methodological differences in the cited studies in comparison to the current study may have led to differences in findings regarding this neuropsychological construct. While the previous studies have appeared to focus primarily on assessing visual functioning through imaging and metabolic-based studies, almost no existing studies looked at studied visual perceptual skills through neuropsychological methods. It can therefore be hypothesized that the physiologically based visual difficulties experienced by this population may not generalize and impact neuropsychological testing, or that it can be mediated in some way, particularly if there is not a time-constraint during such as task. Additionally, the results of this study can indicate that the physiological differences between individuals that did or did not suffer sport-related repeated brain injuries may not be significant enough to impact their everyday functioning.

As noted in the previously presented literature, neuropsychological assessment is an integral part of diagnosing, treating, and providing recommendations for individuals that suffer from sport-related injuries. Neuropsychological insight can provide functional abilities or difficulties that are not evident by looking at brain imaging or metabolic studies. As a result, this study, which utilized a much larger battery than those included in the majority of the existing literature, may provide greater insight into more facets of neuropsychological functioning within this population. For example, the results of this study related to processing speed and executive functioning in particular indicate that individuals who played in the NFL and are now retired may experience issues with processing information in a timely fashion, problem solving, and engaging in multi-step tasks. Such instances can highly impact real-world situations such as having difficulties with completing time-dependent tasks while working, as well as in daily tasks such as driving or cooking a multi-step recipe. Furthermore, the results of this study indicate that, even when provided with feedback that a novel task is being done incorrectly, players may have difficulties up with strategies and problem solve further.

Memory deficits are often one of the most common reported symptoms by individuals impacted by brain injury. Therefore, understanding which forms of memory are being impaired and to what severity will lead to better recommendations for retired NFL players which are experiencing difficulties in this area. The pattern evidenced in this study could indicate to recommendations such as utilizing repetition to partially mediate memory difficulties, as well as then supplementing with other memory-assisting strategies, such as utilizing paper-and-pencil or electronic calendars or journals to notate appointments and other important daily information. If these individuals were to choose to continue working after retiring from the NFL, additional recommendations could include providing resources which they can easily refer to in order to complete their assigned tasks.

A second goal of this study was to explore significant differences among the player positions. The results indicated that significant differences were found between the player groups themselves. The Linemen players, those who experience a higher frequency of hits overall, experience further deficits above and beyond what other NFL players will experience. These deficits were noted in the areas of processing speed, timed visual-spatial abilities, and task-switching abilities. This was consistent with the existing research, as studies using clinical data such as self-report methods and athletic trainer examination, as well as objective measures such as in-helmet accelerometers, have demonstrated variations in the frequency and magnitude of head impacts, which were then expected to lead to significant differences in neuropsychological performance (Mihalik et al, 2007; Crisco et al. 2010; Crisco et al., 2011). Furthermore, the findings of the current study additionally present further support that these impairments can be found decades after retiring from the sport as well. While the research regarding retired NFL players is currently expanding, this pattern of impairment has been evidenced in existing research utilizing retired athletes of sports other than American Football (Hume et al., 2017). Therefore, the findings in this study are further expanding the research surrounding the chronic impairments experienced by retired players even decades after experiencing the actual injuries, while still being consistent with the findings evidenced in acute injury studies. Furthermore, as this study is additionally looking at player position type differences, the results evidenced in this study as opposed to those in the existing research can truly highlight how Linemen players evidence a level of impairment above and beyond the expected level of injury that NFL players in general experience. This therefore highlights the severity that subconcussive hits can have in long-term functioning, which is something that has yet to be fully explored in the existing research.

Repeated concussive and subconcussive injures has been demonstrated to lead to disruptions in the recovery process and the development of axonal injuries, neuroinflammation, and chronic injury to multiple white matter areas of the brain (Pellman et al., 2003). The findings of this study evidencing significant impairment in domains of processing speed, visual-spatial functioning, and executive functioning appear to be consisted with the pattern of injury present in discussed in the study by Pellman et al. in 2003. It is hypothesized that, as these injuries occur at a higher frequency, the continuous disruption of the recovery process in this players could lead to syndromes such as the second impact syndrome, in which it is proposed that a second concussion or brain injury can lead to catastrophic damage to due to characteristic ionic fluxes, acute metabolic changes, and cerebral blood flow alterations that particularly affect white matter areas related to these neuropsychological functions. The pattern of differences amongst the player position groups appears to indicate that the type of impairment that results from repeated impacts and the experiencing of metabolic disruptions while attempting to recover tends to most impact the ability to engage in novel, time-dependent tasks. However, players may be able to partially compensate in tasks which can be verbally mediated or are based on abilities typically learned in formal schooling or practiced throughout one's lifetime (such as language or engaging in memory strategies).

At the very least, the results of this study allows for current and future players of the NFL to be more aware of the significant risks of engaging in a contact-intensive sport, and even more so when selecting to play a position in which the frequency of hits is greater in comparison to others. Oftentimes, individuals are unaware of the severity of impairment which they can experience due to the illusion that wearing protective gear (and helmets in particular) can provide. Most importantly related to this study, many individuals make the assumption that only diagnosable concussions or concussions that lead to loss of consciousness are severe enough to have lasting effects. However, as more research emerges of the effects of repeated subconcussive hits in American football and other contact sports, individuals will now be better equipped to make informed decisions about whether they want to engage in the sport, and place greater emphasis in receiving continuous medical and psychological care during and after their NFL career.

Lastly, the results of this study truly highlighted the importance of developing and using ethnically and culturally appropriate neuropsychological test norms, as significant ethnicity-based effects were found in the majority of neuropsychological measures assessed. The results of this study appeared to be consistent with the existing literature overall, which has found neuropsychological result differences in Caucasian and African American individuals in both computerized and paper-and-pencil assessments, even when education and health-based factors were accounted for (Wallace et al., 2018; Manly et al., 1998).

Where this study did differ in some existing research related to ethnic and cultural differences between Caucasian and African American individuals was in not finding a significant difference related to ethnicity in the Boston Naming Test in particular. Existing research by Pedraza et al. in 2009 utilized differential item functioning to explore whether the conditional probability of responding correctly to individual BNT items differed between African American and Caucasian adults. However, these differences in findings could be hypothesized to be due to differences in the samples utilized for each study, as the aforementioned study gathered their sample from participants in their Mayo sites in Rochester, Minnesota, and Jacksonville, Florida, yet all of the African American adults were recruited from their Jacksonville location. It could be reasonably argued that their findings could be based upon geographic differences (i.e., north vs. south) rather than ethnicity-based factors. In the current study, participants were gathered from throughout the United States, thereby utilizing a more diverse sample and creating more generalizable results. Therefore, the simpler race identified of “Caucasian” and “African American” may not be the only cultural factor to take into account, as regional differences may also significantly impact results, particularly as related to confrontational naming.

The field on neuropsychology so far has had a universalistic point of view, which suggests that cognitive processes are fundamentally the same in humans, regardless of culture (Nell, 2000). While the intention behind this view can be seen as positive, as it attempts to not focus on racial and ethnic generalizations, which may have been based on inadequate and dangerous assumptions. However, not understanding these differences can lead to the inappropriate use of assessments which may not capture an individual’s true strengths and differences, as they are having methods seen by the majority culture as more important or valuable than those in one’s minority culture. This problem is highlighted in the existing literature in multiple assessments and neuropsychological domains, and is additionally evidenced in the result of this study. Therefore, while the field of neuropsychology is at least aware that this problem exists, it should additionally aspire to create updated and culturally-appropriate norms, as well as continue to create new assessments that are less based on stimuli that is more prevalent in the majority culture.

Overall, the results of this study evidenced the impairments that NFL players experience decades after retirement, which could greatly impact their ability to function in their day-to-day lives. The results in this study highlight the neurobiological and psychological consequences that all forms of sport-related repetitive injuries can have on an individual, whether it be subconcussive, concussive, or more severe forms of brain injury. Moreover, it is proposed that, as players experience a higher frequency of hits overall, they may experience physical neuronal injuries. However, players may be able to compensate in tasks which can be verbally mediated or are based on abilities typically learned in formal schooling or practiced throughout one's lifetime (such as language or engaging in memory strategies). Lastly, the results of this study truly highlighted the importance of developing and using ethnically and culturally appropriate neuropsychological test norms as well as the risk of interpreting some Black individual's scores as below average when they likely are not, as significant ethnicity-based effects were found in the majority of neuropsychological measures assessed. al injuries as well as metabolic disruptions during important periods of recovery.

Limitations

Overall, the medium size of the overall sample and the smaller size of the two separate groups, could impact the results by increasing the likelihood of Type-I error. In other words, the sample size could lead to the rejection of a hypothesis that is truly supposed to be null (also known as a "false positive" finding). This possible risk, however, was taken into account prior to conducting this study and, in order to attempt to reduce the possibility of making this type of errors, it was decided that a more conservative alpha of .001 to .05 would be used.

Another limitation of this study was that archival nature of the dataset and resulting sample. The use of archival data can be a positive in that it allows access to many variables taken from a wide range of individuals, which provides the opportunity to measure many constructs. It is hypothesized that using an archival dataset has prevented this researcher the ability to obtain a randomized sample. Using archival data prevents the use of a randomized sample because of the manner in which the study was completed. Due to the dataset being premade, the selection of participants was mainly made based on the number of participants available that could be used, rather than selecting randomly in order to better vary the groups. Because the sample was not randomized, some variables such as age, years of education, and gender, could influence the data and the results. However, this researcher attempted to control for two of the most common variables that tend to affect neuropsychological test results: age and race. Nevertheless, study is limited for having not accounted for all of these variables through the inclusion of these variables as covariates, as well as through using a randomized sample due to the sample size available in the archival data.

Furthermore, the use of archival data allowed for limited control over data entry and whether or not reported information was accurate. This risk could create problems such as outlying data if scores were entered incorrectly, or even missing numbers. As a result, any obvious mistakes in data entry were additionally deleted and participants with these errors were consequently removed. There is also limited information regarding client presentation and behavioral observations that could be obtained if the data were collected directly by the same technician. This could provide inconsistent results as performance across measures could be inconsistent due to a variety of participant combinations. Lastly, there could be significant variation in the assessment administration and scoring between and within psychometricians that could have impacted the results of the current study, which could have led to evidencing differences between the player groups and the expected normative statistics or the groups themselves.

A further limitation of this study is the large number of measures assessed. With the different types of assessment used for this exploratory research, it becomes difficult to interpret the individual results. There is a higher chance of finding results that have unusual data points, especially in individual measures that have many scores. Because the purpose of the present study, however, was to be an neuropsychological pattern comparison between the retired NFL players against a normative expectation of performance and amongst themselves, the large number of assessments was necessary in order to best gather a most comprehensive picture of possibly patterns that could further highlight this population's impairment pattern. This could impact the results because, when so many scores are measured, there is an increased likelihood of some scores being significant, which suggests a necessity to interpret some scores, such as in the personality measures with caution.

Additional research could focus on identifying or further adapting a core battery of paper and pencil and/or computerized neuropsychological tests for the assessment of active and retired NFL players in order to best compare studies and possible neuropsychological impairments and strengths with one another. Furthermore, this battery should include existing measures that can take into account significant factors such as cultural and ethnic differences, or be adapted as new measures that are more culturally-sensitive are available. Ideally, information such as concussion and subconcussion history, presence of diagnosed attention deficit spectrum disorder and/or learning disability, medical/psychiatric/substance abuse history, any available neuroimaging results or genotyping data, and length of retirement (if applicable), would additionally be gathered and presented in future research.

Yet another limitation that needs to be considered is the inability for this study to control additional variables that could have mediated the results. Such factors that could create greater impact into neuropsychological findings include individual characteristics such as genetic vulnerabilities/premorbid medical history, psychosocial factors, length of time since retirement, and other factors that were not analyzed in this study. Although age and education were assessed prior to analyzing the results and not found to be significantly different among groups, and race was significant and accounted for as significant variable, many of these other factors were not controlled for or even able to be assessed during the study.

Aside from individual biopsychosocial factors that were unable to be controlled for, being unable of getting an objective measure of the frequency and magnitude of the injuries experienced by each player was yet another limitation related to this study, a limitation often seen in retrospective concussion research. For example, an individual's prior mTBI/TBI and subconcussive history, including the type of injury that was sustained in each instance (i.e. acquiring a TBI through acceleration/deceleration vs. direct blunt force trauma), what neurological damage was sustained (i.e., diffuse axonal injury, focal sheer injuries, contusions, swelling), and the presence and duration of loss of consciousness and retrograde/anterograde amnesia are factors that could have significantly impacted the results of this study, yet were unable to be accurately accounted for. In neuropsychological studies, this information must generally be obtained through athlete self-report, which may not always be reliable. When an individual suffers as many incidences of subconcussions as these athletes do, follow-up with a medical professional after every instance is assumed to be unnecessary and the running tally is reduced to only the most remarkable. Furthermore, the lack of a strict definition of concussion means that each athlete must do a retrospective analysis of every hit that they may have experienced and self-determine whether it could be identified as a concussion.

While this study hypothesized that players engaged in different positions have, on average, exposure to different frequency and impact severity levels, it is impossible to retroactively track the specific characteristics evidenced in each injury experienced by each player and demonstrate a one-to-one correspondence between each concussive or subconcussive event and a specific level of measurable impairment. Furthermore, whereas the cumulative effects of a concussion have been shown in the controlled conditions of a lab, the circumstances under which one might sustain a concussion or subconcussive injury cannot be controlled during a real live game and the resulting outcomes cannot be predicted to present as similarly to that seen in experimental settings. Therefore, it is the role of a clinician to decide if the previously acquired injuries match the resultant net effect. Individuals who sustain a concussion should not be lumped together and treated with the same procedures. Similarly, a certain level of cognitive impairment cannot be assumed when assessing athletes with a history of multiple concussions.

Yet another limitation is the lack of a control group. While the study sample was compared against the mean and standard deviation that would be expected out of a normal group, the absence of a control group made up of real individuals makes it impossible to compare the group results to an uninjured population. The homogeneity of the sample (i.e. being made up of retired NFL players) also raises the question of whether or not these findings can be generalized to other populations that may experience repeated concussions or subconcussive hits. These athletes are unique in that many of these individuals have a history of risk-taking behavior, and may expect injury as a natural consequence. Thus, their lack of differences may only reflect variables unique to this population.

Overall, while there were many potential limitations to the present study, they can be discussed with the understanding that this study was exploratory in nature and using the most recent updates of different neuropsychological measures available based on the archival nature of the data. While the hypotheses of the current study presented mixed results, considering the limitations of the study could further explain the significant results as well as where future research can pursue this topic. If some limitations were able to be corrected, the hypotheses could have been more strongly supported by the results, although it may also have not been impacted in any significant manner. The limitations of this study do not warrant the results invalid, but rather indicate potential areas for improvement in research in the future.

Future Directions

The present study was considered an exploratory look at the neuropsychological profile of NFL players long after retirement and whether player position specifically could be considered a significant factor in its ability to impact any present impairment further. While this study took a broad approach and covered a large number of assessments, it provided interesting foundational information about what the population of interest is experiencing as far as impairment profile, as well as the function of a neuropsychological battery in order to assess and track these resulting impairments. Results were mixed in regard to supporting all portions of the hypotheses presented, but nonetheless provided information about patterns of assessment and what the variable is intended to measure, as well as what else it could measure.

Firstly, future research could further investigate complex concussions overall. Complex concussions can be categorized by “presence of persistent symptoms which can be present with or without additional exertion, specific sequelae (such as concussive convulsions), prolonged loss of consciousness (more than 1 minute) or prolonged cognitive impairment after the injury, as well as suffering multiple concussions over time or where repeated concussions occur with progressively less impact force (McCrea et al, 2003). Due to the higher frequency of simple concussions, a majority of the research is focused on this type, and there is limited research on complex forms of concussions. Additionally, there exists limited research regarding the long-term consequences of concussions past a few months or one year post-injury. As a result, the later-life clinical and neurological outcomes associated with repeat concussions are less understood. As highlighted in this study, even less research focuses on subconcussive injuries, which are now being understood as leading to short- and long-term consequences, particularly if they occur on a frequent basis. Many may be surprised that a large amount of what we know about sports-related concussion has evolved from research conducted over the past few decades.

Future research should look more extensively at populations who sustain a large number of concussions and subconcussions, and the differences between those who report persistent post-concussion symptoms and those who do not. In addition, the development and utilization of a universally accepted standard for defining concussion injuries is of the utmost importance. Currently, the utilization of the concussive syndrome definition is not proving to be the most effective, as the word ‘syndrome’ implies a consistent combination or pattern of symptoms that occur together and is indicative of a specific condition or disease process. However, even at the individual level, a single individual can sustain multiple concussive or subconcussive injuries and have different symptom presentation with each event. Furthermore, the severity of symptoms and recovery time also vary by individual and by event. It is because of the wide range of possible presentations that the concept of post-concussion syndrome has been debated, considering the amount of variability involved in the symptom presentation (McAllister & Arciniegas, 2002). More research is also needed on expectations and symptom reporting, in order to help clinicians offer more appropriate interventions for their patients or athletes that can suffered concussions. When patients are not fully informed about the common symptoms of concussion and the expected pattern of recovery, it can lead to persistent and debilitating complaints. Accurate diagnosis leads the way to properly informing patients about what they may or may not experience and better informing treatment plans.

Yet another possible focus that future research can focus is the ecological validity of the findings in the present study or any other studies looking at athletes who have suffered multiple concussive and subconcussive hits. The lack of ecological validity has been another criticism for traditional neuropsychological tests, as seen by the fact that individuals that perform within a normal range in certain measures within a controlled testing environment will then still experience deficits and complications within their real-life environments. In a controlled testing environment, individuals are given experimental tasks that demand relatively simple responses to events presented to them in comparison to what one experiences in their real life. More complex multi-step tasks in daily life may require more complicated series of responses to achieve, such as figuring out one's goals, prioritizing possible steps needing to complete such goals, triggering prospective memory to initiate these identified steps when the conditions for them are at their most ideal, and inhibition of irrelevant and inappropriate actions to different steps. Therefore, most of the conventional experimental tasks only tackle issues at the impairment level but cannot reflect a true picture beyond the levels of true function or dysfunction. As a result, future research should focus on assessing these significant patterns and see if they are able to be found or replicated in real-life situations and challenges experienced by this patient population.

Understanding position-based differences in concussions, subconcussions, and brain injury overall could be used to inform strategies for risk reduction such as providing position-based concussion education to the athletes and increased awareness and education to sport medicine clinicians about position variability in symptom types experienced and tendency to report symptoms. Furthermore, the public would benefit from becoming further informed about differences between player positions and whether engaging in one position versus another will lead to differences in impairment in the future. Currently, players and family members are primarily utilizing traditional and social media sources in order to make significant decisions. While the media could be considered a valuable resource in drawing attention to the effects of a concussion, efforts need to be made so that that the public is aware of the right information, including uncertainties about long-term risks of adverse outcomes. Social media particularly is becoming more prominent as an education tool, and future research could look at how this resource can be utilized to assess knowledge gaps in the general population in order to identify and develop more effective education strategies. Aside from educating the general public, future research could look at how to best educate referees, administrators, parents, coaches and healthcare providers must be educated regarding the detection of concussions, its clinical features, assessment techniques and principles of safe return to play. Methods to improve education, including web-based resources, educational videos and international outreach programs, are important in delivering the message.

Furthermore, these differences could be used to inform rule changes to reduce the frequency or magnitude of injuries that results from a single or repeated impacts and possibly reduce resulting and persistent dysfunction. Research looking at the changes made in equipment and concussion management over time has indicated that the earlier adaptations focused more on preventing skull fractures more so than concussions, such as the implementation of the face mask in 1956, improvements in the plastic utilized in the exterior to decrease shattering in the 1960s, and the addition of air bladders in "energy absorbing helmets" and four-point chin straps during the 1970s (Harrison, 2014). It was not until 2002 that a new official helmed design for the NFL was created, which was advertised as "intended to reduce concussion". Furthermore, the clinical treatment of concussion has not seemed to advance too much rest, reduction of sensory stimulation, and symptom management—similar recommendations to those available in the early decades of the 20th century.

Moreover, future research should continue to explore possible ethnic and cultural biases amongst currently existing measures, and aspire to adjust their present stimuli or create new assessments altogether. While it might be impossible for a measure to account for every possible variation in an individual's cultural/ethnic background, neuropsychologists should continue to aspire to reach this goal in order to better serve the diverse population that we are meant to serve. By doing so, results would be able to be better personalized and applied for that specific individual's needs and goals.

Overall, present study provides numerous starting points for future research, and gives information regarding the potential impairments experienced by NFL players long after retirement. As this was considered an exploration of the neuropsychological pattern of each player position group and the sample as a whole, there were many interesting results which could be explored and defined in more detail. The importance of the present study is that it suggests that the retired NFL players experience deficits that are significantly different from those evidenced in the general population. Understanding how these deficits interact with one another to produce difficulties in an individual's comprehensive level of functioning in their real life is important as a future direction of this information. This research could further inform professionals and the general population about the potential long-term consequences of multiple brain injuries, which ultimately and hopefully raises the standard of care. Future research can progress from the current understanding of repeated injury and putting these findings into use within the clinical world.

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