OXFORD
UNIVERSITY PRESS

Archives
of
CLINICAL
NEUROPSYCHOLOGY

No Linear Association Between Number of Concussions or Years Played and Cognitive Outcomes in Retired NFL Players

Lindy Fields[1], Nyaz Didehbani[1], John Hart Jr.[1,2], C. Munro Cullum[1,*]

[1]*University of Texas Southwestern Medical Center, Dallas, TX, USA*
[2]*University of Texas at Dallas, Dallas, TX, USA*

*Corresponding author at: University of Texas Southwestern Medical Center, Department of Psychiatry, 5323 Harry Hines Blvd., Dallas, TX 75390-8846, USA. Tel.: +1-214-648-4646; fax: +1-214-648-4660.
E-mail address: Munro.Cullum@UTSouthwestern.edu (C.M. Cullum)

Editorial Decision 2 February 2019; Accepted 5 February 2019

Abstract

Objective: The aim of the current study is to examine whether concussion history and years played are linearly associated with cognitive outcomes in retired National Football League (NFL) players.
Method: Thirty-five retired NFL players over the age of 50 who had sustained at least one concussion completed a clinical interview and brief neuropsychological battery. Correlational analyses were conducted between exposure variables [number of total concussions, concussions with loss of consciousness (LOC), and years played] and cognitive performance as characterized by cognitive composite scores based on performance on neuropsychological measures (attention/processing speed, language, memory, and overall composite scores).
Results: Correlational analyses corrected for multiple comparisons did not reveal any statistically significant correlations between exposure variables and cognitive outcomes.
Conclusions: We did not find a significant linear association between cognitive outcomes and either number of total concussions, concussions with LOC, or years played in the NFL. These findings do not support a dose–response relationship between sports-related exposure to head impacts and cognitive outcomes later in life. Rather, the findings suggest that cognitive difficulties experienced by some retired players later in life are not directly linearly associated with quantified exposure to head impacts sustained throughout a football career, but related to factors or combinations of factors that have yet to be elucidated.

Keywords: Concussion; Football; NFL; Aging; Neuropsychology; Cognition

Introduction

There is currently significant interest in understanding how sports-related concussions and subconcussive hits may affect professional football players' cognitive status later in life. Present studies on the long-term effects of sports-related concussions and subconcussive impacts are currently mixed. Investigations of retired National Football League (NFL) players have yielded results ranging from isolated MRI abnormalities and neuropsychological inefficiencies in some players (Casson, Viano, Haacke, Kou & LeStrange, 2014; Hart et al., 2013; Strain et al., 2015, 2017), but not among the majority of players (Casson et al., 2014), to claims of a high prevalence of neuropathology such as chronic traumatic encephalopathy (CTE) and cognitive impairments among retired players (Mez et al., 2017). Whether there is an association between quantifiable indicators of exposure to head impacts (e.g., concussions, subconcussive hits, years played, etc.) and cognitive outcomes in this population remains a question.

A history of traumatic brain injury (TBI) has been associated with earlier onset of some neurodegenerative disorders (LoBue et al., 2017) and it has been theorized that TBI may contribute to setting the stage for neurodegeneration in some individuals through cerebrovascular mechanisms (Ramos-Cejudo et al., 2018). Milder TBIs, such as sports-related concussions, and repetitive sports-related impacts have been postulated as a risk factor for neuropsychological dysfunction later in life

doi:10.1093/arclin/acz008

(e.g., Guskiewicz et al., 2005; Montenigro et al., 2017), although evidence is mixed. Mild cognitive impairment (MCI) has been reported to be slightly more common among retired NFL players in their early 60s (Hart et al., 2013), and cognitive profiles of retired athletes with MCI appear similar to those of non-athlete MCI samples (Randolph, Karantzoulis & Guskiewicz, 2013). Guskiewicz and colleagues (2005) found that memory complaints and MCI were three times and five times more prevalent, respectively, among retired athletes age 50 and above with a history of multiple concussions (e.g., ≥3) compared to non-concussed peers, while others have found no correlation between the total number of reported concussions and neuropsychological functioning in retired athletes of similar age (Hart et al., 2013). Even when number of concussions has shown a correlation with structural imaging abnormalities among retired players age 30–60, this was not associated with neuropsychological dysfunction (Casson et al., 2014). Likewise, there is recent evidence to suggest that former professional football players age 55–65 with 0–1 concussions and those with at least 3 concussions perform similarly on neuropsychological measures (Clark et al., 2018). However, concussions with loss of consciousness (LOC) have been posited to pose a risk for reduced hippocampal volumes among older retired NFL players and for MCI among retired players above age 63 (Strain et al., 2015).

In addition to concussion history, exposure to repetitive head impacts (i.e., "subconcussive" hits) has been suggested by some investigators as a risk factor for neurocognitive problems in the short- and long-term. Exposure to repetitive head impacts has been found to correspond to white matter changes over the course of a football season as detected with in vivo imaging among youth and adolescent athletes (Bahrami et al., 2016; Davenport et al., 2016), though the lack of control groups makes it unclear as to whether these changes may reflect developmental rather than pathological processes. Among high school football players, findings have been mixed regarding whether white matter changes on diffusion tensor imaging (DTI) are associated with any changes in cognitive performance from pre- to post-season, even in studies using the same sample with different imaging metrics (Davenport et al., 2014, 2016). When head impact telemetry data are not available, such as when estimating exposure to repetitive head impacts retrospectively, athletic participation characteristics (e.g., position, years/games played, age of first exposure) often serve as a proxy for head impact exposure. For example, earlier participation in tackle football (before age 12) was associated with lower scores on several neuropsychological measures in one report of former NFL players age 40–69 (Stamm et al., 2015), although other studies have found no association between pre-high school exposure to football and later-in-life neurocognitive outcomes (Solomon et al., 2016). Some investigations have suggested a dose–response effect of repetitive head impacts sustained by non-professional (e.g., high school or college) football players and cognitive dysfunction later in adulthood (e.g., average age 47) (Montenigro et al., 2017). However, studies of retired NFL players found no association between number of games played and MCI in athletes above age 63 (Strain et al., 2015), as well as no correlation between years played and scores on neuropsychological measures (Hart et al., 2013; Randolph et al., 2013). There is also evidence that cognitive performance among former football players later in adulthood (e.g., ages 52–65) may not differ based on career level (e.g., college vs. professional), despite former professional athletes having played on average approximately 9 more years than collegiate athletes (Clark et al., 2018). Additionally, recent large-scale studies of former high school football players later in life (e.g., over age 60) found no association between participation in high school football and cognitive impairment (Deshpande et al., 2017), and a similar prevalence of neurodegenerative conditions among former football players and non-athletes (Savica, Parisi, Wold, Josephs & Ahlskog, 2012). Thus, it is not yet known whether a linear association may exist between football exposure variables, such as years played, and cognitive outcomes.

Despite significant interest, it remains unclear the extent to which sports-related exposure to head impacts may be associated with later-life cognition. The aim of this study was to examine whether concussion history and years played are associated with cognitive outcomes in retired NFL players. Our investigation focuses on specific exposure variables that are relatively easy to quantify during clinical interview: number of total concussions, concussions with LOC, and years played in the NFL. Supplemental analyses were also done in order to explore these factors within subgroups of our sample.

Methods

Participants

Participants were 35 retired NFL players over age 50 (range = 52–78, Mean = 65.49, *SD* = 7.58), selected from a larger sample of retired NFL players. They were recruited from the local NFL Players Association and word of mouth among study participants. The current sample size is smaller than in some of our prior publications with this cohort due to our inclusion and exclusion criteria that required subjects to be at least 50 years of age and had sustained at least 1 concussion. Exclusion criteria included the presence of a significant neurological or medical condition or event that would be expected to impair cognitive functioning (e.g., stroke, heart attack, ALS), as determined through clinical interview with the cognitive neurologist. Twenty-eight

players were Caucasian and seven were African American. Education ranged from 14 to 19 years (Mean = 16.34, *SD* = 1.03). Number of concussions ranged from 1 to 17 (Mean = 5.83, *SD* = 3.86), and most (28 of 35) players had at least 1 concussion with LOC (Range = 0–14, Mean = 2.14). Athletes played an average of 8.57 years in the NFL (Range = 2–15, *SD* = 3.36). Of the 35 players, six reported current antidepressant treatment and none met criteria for a current substance abuse disorder. Twenty-one of the athletes were cognitively normal and 14 were cognitively impaired (e.g., MCI or dementia) based upon consensus clinical diagnosis by the neurologist and neuropsychologists using standard diagnostic criteria for MCI (Albert et al., 2011) and dementia (American Psychiatric Association, 2013). All subjects were determined to have adequate vision and hearing for testing. This study was approved by the Institutional Review Board at the affiliated university and academic medical center sites, and all participants provided informed consent.

Measures

Each retired athlete underwent a standard neurological examination with the cognitive neurologist, as well as a clinical interview that reviewed each subject's medical, psychiatric, neurological, developmental, educational, and concussion history. Retrospective concussion history was obtained through the clinical interview with the cognitive neurologist and in accordance with American Academy of Neurology guidelines (American Academy of Neurology, 1997), including systematic review of total number of concussions and number of concussions with LOC. Participants were asked to describe all suspected and/or diagnosed concussions sustained throughout their lifetime (i.e., childhood, high school, college, professional career, and other), and each suspected concussion was discussed in detail with the cognitive neurologist (e.g., signs, symptoms, presence and duration of post-traumatic amnesia or LOC) to further aid in classification of concussion history. Information regarding number of years played in the NFL was also gathered during the interview.

Players completed a brief neuropsychological battery, including measures of attention/processing speed [WAIS-IV Coding, Trails A & B], language [Animal Fluency (Animals), Boston Naming Test (BNT), Controlled Oral Word Association Test (COWAT)], and memory [California Verbal Learning Test – Second Edition (CVLT-II), Rey-Osterrieth Complex Figure (Rey-O)]. Scores were compared to demographically-adjusted norms and interpreted by a neuropsychologist who reviewed neuropsychological profiles independent of other factors (e.g., concussion history and neurological examination) and considered test scores in the context of each athlete's estimated longstanding abilities. Results of this independent review were then compared to clinical diagnoses that had been made separately by the neurologist based on medical history, clinical interview, and neurological examination. Final decisions regarding clinical diagnosis were based upon a consensus of the cognitive neurologist and the neuropsychologists after a review of all available data and consideration of standard diagnostic criteria for MCI and dementia. A brief self-report measure of depressive symptoms [Beck Depression Inventory – II (BDI-II)] was also administered.

Data Analyses

Neuropsychological measures were grouped according to domain, creating composite scores for data reduction purposes in order to limit the number of statistical comparisons and enhance power. Raw test scores were transformed to T-scores and averaged to create three domain composite scores: (1) Attention/Processing Speed (WAIS-IV Coding, Trails A & B), (2) Language (Animals, BNT, COWAT), and (3) Memory (CVLT-II Total Learning, CVLT-II Long Delay Free Recall, Rey-O Immediate Recall, Rey-O Delayed Recall). An overall composite score was created by calculating a mean of the three domain composite scores.

For our primary analyses, Pearson *r* and Spearman's rho correlations examined the relationship between cognitive composite scores and each of the exposure variables: (1) number of total concussions, (2) concussions with LOC, and (3) years played in the NFL. As results did not significantly differ between Pearson and Spearman's rho analyses, we report only Pearson correlations. We used Benjamini and Hochberg's (1995) False Discovery Rate (FDR) to correct for multiple comparisons (12 correlations), and we report unadjusted *p*-values. Since depressive symptoms can influence cognitive functioning in some cases, we followed up our Pearson correlational analyses with partial correlations between exposure variables (e.g., total concussions, concussions with LOC, and years played) and cognitive composites, controlling for BDI-II, again correcting for multiple comparisons.

As results may differ depending on cognitive status (normal or impaired), we conducted correlational analyses separately among cognitively normal players and cognitively impaired players (i.e., MCI or dementia), based on consensus clinical diagnosis. We also conducted a one-way ANOVA between cognitively normal and cognitively impaired players to look for differences in player characteristics (e.g., education, age, depressive symptoms) and exposure variables. Lastly, we split the overall

sample into tertiles based on overall composite *T*-score ($T \leq 45.00$, $45.00 < T < 51.08$, $T \geq 51.08$) and conducted a one-way ANOVA to look for group differences in the previously mentioned variables of interest (player characteristics, exposure variables). All supplemental analyses were corrected for multiple comparisons using $p < .01$ to determine significance.

Results

Descriptive data (*T*-scores) for cognitive measures and composites are presented in Table 1. Across the sample as a whole, the mean overall composite was in the average range. The mean overall composite score for the cognitively impaired group was in the low average range, with mean composite scores for cognitive domains ranging from average to mildly impaired.

In the overall sample, correlational analyses revealed no significant association between any of the cognitive composite scores and either total number of concussions (range for *r* values: −.108 to .013, range for *p*-values: .543 to .944, all FDR values = 0.944), concussions with LOC (range for *r* values: −.132 to .055, range for *p*-values: .458 to .834, all FDR values = 0.944), or years played (range for *r* values: −.389 to −.214, range for *p*-values: .023 to .225, range for FDR values: 0.15 to 0.675) (see Table 2). Results remained similar when controlling for BDI-II and multiple comparisons, as neither total concussions (range for *r* values: −.162 to −.027, range for *p*-values: .369 to .884), concussions with LOC (range for *r* values: −.133 to .039, range for *p*-values: .459 to .924), nor years played (range for *r* values: −.388 to −.203, range for *p*-values: .026 to .257) were significantly associated with cognitive composite scores. Additionally, BDI-II scores (range = 0–38, mean = 8.20, *SD* = 7.60) were not significantly correlated with total concussions (*r* = .220), concussions with LOC (*r* = .098), or years played (*r* = −.075) (range for *p*-values: .205 to .669), nor with cognitive outcomes (range for *r* values: .012 to .209; range for *p*-values: .235 to .945).

Supplemental Analyses

To further explore a relationship between cognitive status (i.e., cognitively normal or impaired, based on clinical diagnosis) and exposure variables (concussion history and years playing football), we repeated the analyses in subjects with and without

Table 1. Descriptive cognitive performance data

Composite	Measure	Overall *N* = 35 Mean (*SD*)	Cognitively Normal *n* = 21 Mean (*SD*)	Cognitively Impaired *n* = 14 Mean (*SD*)
Attention/Processing Speed		*49.51 (7.04)*	*51.24 (5.88)*	*46.47 (8.10)*
	Coding	50.61 (8.44)	52.38 (7.24)	47.50 (9.76)
	Trails A	48.83 (7.31)	48.71 (7.11)	49.00 (7.87)
	Trails B	49.49 (10.28)	52.62 (7.95)	44.79 (11.80)
Language		*46.83 (8.28)*	*49.37 (7.43)*	*42.74 (8.19)*
	Animals	48.74 (12.02)	52.71 (11.36)	42.79 (10.76)
	BNT	43.47 (10.99)	46.81 (9.64)	38.08 (11.22)
	COWAT	48.37 (9.96)	48.57 (8.37)	48.07 (12.30)
Memory		*47.43 (12.44)*	*52.96 (9.64)*	*38.48 (11.41)*
	CVLT-II Total Learning	46.82 (11.92)	51.67 (11.56)	39.00 (7.79)
	CVLT-II Long Delay Free Recall	45.74 (12.68)	50.95 (11.47)	37.31 (9.92)
	Rey-O Immediate Recall	48.66 (15.44)	54.19 (13.30)	40.36 (15.07)
	Rey-O Delayed Recall	48.11 (16.87)	55.05 (12.83)	37.71 (17.22)
Overall		*47.85 (7.20)*	*51.19 (6.06)*	*42.01 (5.03)*

Note: BNT = Boston Naming Test; COWAT = Controlled Oral Word Association Test; CVLT-II = California Verbal Learning Test – Second Edition; Rey-O = Rey-Osterrieth Complex Figure.

Table 2. Correlations between cognitive composites and head impact exposure variables

		Attention/Processing Speed	Language	Memory	Overall
Total Concussions	***r***	**.013**	**−.108**	**−.028**	**−.057**
	p-value	*.944*	*.543*	*.876*	*.752*
Concussions with LOC	***r***	**.055**	**.037**	**−.132**	**−.048**
	p-value	*.761*	*.834*	*.458*	*.793*
Years Played	***r***	**−.235**	**−.214**	**−.388**	**−.389**
	p-value	*.187*	*.225*	*.023*	*.025*

Note: R-values are in bold and p-values are in italics.

diagnosed cognitive impairment, correcting for multiple comparisons (significance level of $p < .01$). Analyses conducted separately among cognitively normal players showed no significant linear association between cognitive composite scores and either total concussions (range for p-values: .584 to .797), concussions with LOC (range for p-values: .624 to .957), or years played (range for p-values: .076 to .712), and this remained the case when controlling for BDI-II (range for p-values: .047 to .957). There was no significant association between BDI-II scores and exposure variables (total concussions, concussions with LOC, or years played) among cognitively normal players (range for r values: −.114 to .206; range for p-values: .371 to .910).

Similarly, Pearson correlations revealed no significant linear associations among cognitively impaired players between any of the cognitive composite scores (domains or overall) and either total concussions (range for p-values: .155 to .976), concussions with LOC (range for p-values: .186 to .858), or years played (range for p-values: .341 to .945), and this remained the case when controlling for BDI-II (range for p-values: .117 to .965). There was no significant association between BDI-II scores and exposure variables (total concussions, concussions with LOC, or years played) among cognitively impaired players (range for r values: .584 to .612; range for p-values: .020 to .028).

One-way ANOVA between cognitively normal and cognitively impaired groups revealed a significant difference in age ($p = .003$), with cognitively impaired players being older (Mean age = 70) than cognitively normal players (Mean age = 62.48). There were no significant group differences in total concussions ($p = .409$), concussions with LOC ($p = .129$), years played ($p = .064$), education ($p = .207$), or BDI-II scores ($p = .165$). Additionally, one-way ANOVA for group differences between tertile groups (low, middle, high overall composite scorers) revealed no significant differences between tertile groups on number of total concussions ($p = .983$), concussions with LOC ($p = .404$), years played ($p = .01$), age ($p = .012$), education ($p = .217$), or BDI-II scores ($p = .303$), after correcting for multiple comparisons.

Discussion

Among our sample of retired NFL players, we did not find any significant linear relationship between cognitive outcomes and either concussion history (total concussions or number of concussions with LOC) or years played in the NFL. These findings do not support a dose–response relationship between sports-related exposure to head impacts and cognitive outcomes. Rather, the findings suggest that cognitive difficulties that some retired players experience later in life are not directly linearly associated with quantified exposure to head impacts sustained throughout a football career, but related to factors or combinations of factors that have yet to be elucidated. Among retired athletes with a history of concussion, exploration of the various complex factors that may relate to perceived cognitive difficulties (e.g., stress, emotional factors) or actual cognitive decline (e.g., substance abuse, medical conditions, genetic risk factors) will be helpful in this regard.

Our findings give pause to suggestions that there is a simple or direct dose–response relationship between exposure to sports-related concussion and later-life cognitive dysfunction. While concussion has previously been identified as a risk factor for cognitive dysfunction later in life for some individuals, our results suggest that any possible relationship between concussion and long-term cognitive outcomes (as demonstrated by neuropsychological performance) is more complicated than a simple additive effect of exposure to impacts. Prior findings have shown structural abnormalities and cognitive difficulties in some retired athletes with a history of concussion (e.g., Strain et al., 2015). Thus, it is possible that concussion history (as with any neurological insult to the brain) may exacerbate a predisposition or vulnerability toward neurocognitive dysfunction in some individuals, establishing an "at-risk" state such that further insults could lead to cognitive dysfunction, or may combine with other factors to lead to neurodegeneration or dysfunction, though such an investigation is outside the scope of the present study.

The literature regarding potential long-term effects of concussive and subconcussive impacts has thus far been mixed. This is likely somewhat attributable to disparate methodologies in regards to sample selection, methodology, and classification of concussion history and exposure to head impacts. Some samples are comprised of retired football players who report clinical features concerning for neurodegenerative disorders (e.g., behavioral, cognitive, psychiatric symptoms) (Stamm et al., 2015) or regarding whom family has expressed concern for CTE post-mortem (Mez et al., 2017), whereas other samples are comprised of retired athletes who may or may not have such symptoms or a history of concussion (Casson et al., 2014; Hart et al., 2013; Strain et al., 2015). Methodologies vary from record review (Savica et al., 2012), to retrospective report by either family/informant (Mez et al., 2017) or player over-the-phone or by survey/questionnaire (Guskiewicz et al., 2005), to clinical interview with in-person formal neuropsychological testing (Casson et al., 2014; Clark et al., 2018; Hart et al., 2013; Strain et al., 2015, 2017). Lastly, studies have used various methods of characterizing concussion history and level of exposure to head impacts, with some studies looking at presence or absence of concussion (Strain et al., 2015), concussion history based on categories (Clark et al., 2018; Guskiewicz et al., 2005), actual number of concussions (Casson et al., 2014; Hart et al.,

2013), only concussions with LOC (Strain et al., 2015), or estimated number of impacts based on formulas and calculations (Montenigro et al., 2017). Given our methodology, including only players over age 50 and use of continuous variables to characterize exposure to impacts, we hope that our study's results help to fill in some gaps in the current literature.

Our results expand upon prior studies of former high school football players that found no association between participation in football and later-life cognitive impairment (Deshpande et al., 2017; Savica et al., 2012), as we found no linear relationship between indicators of exposure to head impacts (concussion history and years played) and neuropsychological performance later in life. These results suggest that the higher rates of cognitive difficulties found in prior studies of retired NFL players (e.g., Hart et al., 2013) may relate to more complex factors than a simple dose–response effect of head impacts. Whereas an association between the presence of concussion with LOC and MCI was found among athletes above age 63 in a prior study (which included some individuals from the current sample; Strain et al., 2015), our current results clarify that any association between LOC and cognitive impairment does not appear to be linear and dose-dependent in nature. Although prior findings suggest the presence of LOC may predispose aging athletes (e.g., above age 63) to MCI, our current results suggest the presence of LOC itself does not necessarily equate to cognitive dysfunction among a larger sample that includes middle-age retired athletes (e.g., age 50 and above). Thus, further exploration is warranted regarding how established risk factors (e.g., concussion with LOC) may exert effects later in life in some individuals. Better understanding of cognitive risk factors among retired NFL players is needed, as our results argue against a simple linear relationship between repetitive head impacts (concussive or subconcussive) and later-life cognitive dysfunction.

Limitations of the current study include a relatively small sample size, though this sample size is in line with other in-person studies involving cohorts of current and/or former athletes (e.g., Davenport et al., 2016). Our characterization of career length was focused solely on years played in the NFL, and we did not collect data regarding years played in youth, high school, or college football. Whereas some researchers have reported that earlier exposure to tackle football may be related to lower cognitive performance later in life (Stamm et al., 2015), this remains controversial due to mixed findings across studies (Solomon et al., 2016), and participation in high school football was not found to be associated with reduced cognitive function in a large-scale investigation (Deshpande et al., 2017). Nevertheless, it will be useful to explore pre-NFL exposure to head impacts (years played across lifetime, age of first exposure) in future investigations. It is also worth noting that our study did not include a control group and focused specifically on exposure to head impacts in football; thus, it is unclear the extent to which these findings may generalize to head impacts sustained in other contact sports or non-sport activities. Last, we gathered concussion history retrospectively and corroborating documentation of concussions was not available, though in a prior study we documented that our NFL sample is reliable in their self-report of concussion history over time (Didehbani et al., 2017) and, more broadly, older adults (whether cognitively normal or impaired) have been shown to be reliable in their self-report of TBI over time (Wilmoth et al., 2018).

Overall, we did not find a significant linear association between cognitive outcomes and either number of total concussions, concussions with LOC, or years played in the NFL in our sample of retired NFL players. These results are encouraging in that they provide additional perspective in this area of discussion. More research in this complex area is needed, including future investigations of how additional factors such as individual differences (e.g., genetics, lifestyle, medical conditions) and career-related characteristics (e.g., position, speed vs. non-speed position, games played) may relate to cognitive outcomes in aging retired NFL players.

Funding

This work was supported in part by the Texas Institute for Brain Injury and Repair in the Peter J. O'Donnell Jr. Brain Institute at UT Southwestern Medical Center.

Conflict of Interest

None declared.

Acknowledgements

Statistical Support: Thank you to Paul Nakonezny, Ph.D. for consultation regarding statistical analyses.

References

Albert, M. S., DeKosky, S. T., Dickson, D., Dubois, B., Feldman, H. H., Fox, N. C., et al. (2011). The diagnosis of mild cognitive impairment due to Alzheimer's disease: Recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's disease. *Alzheimer's & Dementia: The Journal of the Alzheimer's Association*, *7*, 270–279.

American Academy of Neurology. (1997). Practice parameter: The management of concussion in sports (summary statement): Report of the Quality Standards Subcommittee. *Neurology*, *48*, 581–585.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5)*. Arlington, VA: American Psychiatric Publishing.

Bahrami, N., Sharma, D., Rosenthal, S., Davenport, E. M., Urban, J. E., Wagner, B., et al. (2016). Subconcussive head impact exposure and white matter tract changes over a single season of youth football. *Radiology*, *281*, 919–926.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society*, *57*, 289–300.

Casson, I. R., Viano, D. C., Haacke, E. M., Kou, Z., & LeStrange, D. G. (2014). Is there chronic brain damage in retired NFL players? Neuroradiology, neuropsychology, and neurology examinations of 45 retired players. *Sports Health*, *6*, 384–395.

Clark, M. D., Varangis, E. M., Champagne, A. A., Giovanello, K. S., Shi, F., Kerr, Z. Y., et al. (2018). Effects of career duration, concussion history, and playing position on white matter microstructure and functional neural recruitment in former college and professional football athletes. *Radiology*, *286*, 967–977.

Davenport, E. M., Apkarian, K., Whitlow, C. T., Urban, J. E., Jensen, J. H., Szuch, E., et al. (2016). Abnormalities in diffusional kurtosis metrics related to head impact exposure in a season of high school varsity football. *Journal of Neurotrauma*, *33*, 2133–2146.

Davenport, E. M., Whitlow, C. T., Urban, J. E., Espeland, M. A., Jung, Y., Rosenbaum, D. A., et al. (2014). Abnormal white matter integrity related to head impact exposure in a season of high school varsity football. *Journal of Neurotrauma*, *31*, 1617–1624.

Deshpande, S. K., Hasegawa, R. B., Rabinowitz, A. R., Whyte, J., Roan, C. L., Tabatabaei, A., et al. (2017). Association of playing high school football with cognition and mental health later in life. *JAMA Neurology*, *74*, 909–918.

Didehbani, N., Wilmoth, K., Fields, L., LoBue, C., Strain, J., Spence, J., et al. (2017). Reliability of self-reported concussion history in retired NFL players. *Annals of Sports Medicine and Research*, *4*, 1115.

Guskiewicz, K. M., Marshall, S. W., Bailes, J., McCrea, M., Cantu, R. C., Randolph, C., et al. (2005). Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery*, *57*, 719–726.

Hart, J., Kraut, M. A., Womack, K. B., Strain, J., Didehbani, N., Bartz, E., et al. (2013). Neuroimaging of cognitive dysfunction and depression in aging retired National Football League players: A cross-sectional study. *JAMA Neurology*, *70*, 326–335.

LoBue, C., Cullum, C. M., Didehbani, N., Yeatman, K., Jones, B., Kraut, M. A., et al. (2017). Neurodegenerative dementias after traumatic brain injury. *The Journal of Neuropsychiatry and Clinical Neurosciences*, *30*, 7–13.

Mez, J., Daneshvar, D. H., Kiernan, P. T., Abdolmohammadi, B., Alvarez, V. E., Huber, B. R., et al. (2017). Clinicopathological evaluation of chronic traumatic encephalopathy in players of American football. *JAMA*, *318*, 360–370.

Montenigro, P. H., Alosco, M. L., Martin, B. M., Daneshvar, D. H., Mez, J., Chaisson, C. E., et al. (2017). Cumulative head impact exposure predicts later-life depression, apathy, executive dysfunction, and cognitive impairment in former high school and college football players. *Journal of Neurotrauma*, *34*, 328–340.

Ramos-Cejudo, J., Wisniewski, T., Marmar, C., Zetterberg, H., Blennow, K., de Leon, M. J., et al. (2018). Traumatic brain injury and Alzheimer's disease: The cerebrovascular link. *EBioMedicine*, *28*, 21–30.

Randolph, C., Karantzoulis, S., & Guskiewicz, K. (2013). Prevalence and characterization of mild cognitive impairment in retired National Football League players. *Journal of the International Neuropsychological Society*, *19*, 873–880.

Savica, R., Parisi, J. E., Wold, L. E., Josephs, K. A., & Ahlskog, J. E. (2012). High school football and risk of neurodegeneration: A community-based study. *Mayo Clinic Proceedings*, *87*, 335–340.

Solomon, G. S., Kuhn, A. W., Zuckerman, S. L., Casson, I. R., Viano, D. C., Lovell, M. R., et al. (2016). Participation in pre–high school football and neurological, neuroradiological, and neuropsychological findings in later life: A study of 45 retired National Football League players. *The American Journal of Sports Medicine*, *44*, 1106–1115.

Stamm, J. M., Bourlas, A. P., Baugh, C. M., Fritts, N. G., Daneshvar, D. H., Martin, B. M., et al. (2015). Age of first exposure to football and later-life cognitive impairment in former NFL players. *Neurology*, *84*, 1114–1120.

Strain, J. F., Didehbani, N., Spence, J., Conover, H., Bartz, E. K., Mansinghani, S., et al. (2017). White matter changes and confrontation naming in retired aging National Football League athletes. *Journal of Neurotrauma*, *34*, 372–379.

Strain, J. F., Womack, K. B., Didehbani, N., Spence, J. S., Conover, H., Hart, J., et al. (2015). Imaging correlates of memory and concussion history in retired National Football League athletes. *JAMA Neurology*, *72*, 773–780.

Wilmoth, K., LoBue, C., Clem, M. A., Reddy, R., Hynan, L. S., Didehbani, N., et al. (2018). Consistency of traumatic brain injury reporting in older adults with and without cognitive impairment. *The Clinical Neuropsychologist*, *32*, 524–529.