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Concussion History and Cognitive Function in a Large Cohort of Adolescent Athletes

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Abstract

Background: The incidence of reported concussions in the adolescent population is increasing, yet research on the effects of concussions in this population is minimal and inconclusive.

Purpose: To assess the association between concussion and performance on a cognitive test battery.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Using multivariate models, the authors assessed the association between concussion and performance on a cognitive test battery among 5616 high school and junior high school athletes. The researchers utilized a global cognitive score and scores for 5 domains: verbal memory, visual memory, visual motor, reaction time, and impulse control. Each cognitive score was converted to a *z* score with the mean and SD of the nonconcussed population. Results from

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each model were then interpreted as change in the standardized unit score. In the models, concussion was evaluated as ever having a concussion, number of concussions, time since last concussion, and age at first concussion.

Results: Ever having a concussion was associated with a mean decrease of 0.11 standardized units (95% CI, −0.20 to −0.01) on the global cognitive score and lower scores in all cognitive domains. Each additional concussion was associated with lower scores on global cognitive function (effect estimate, −0.06; 95% CI, −0.11 to −0.02), verbal memory, visual memory, and impulse control. Concussion in early childhood was associated with lower global cognition (effect estimate, −0.05; 95% CI, −0.08 to −0.01), visual memory, and motor visual scores as compared with concussions in later childhood. The associations between time since last concussion and cognitive test scores were nonlinear, and on all tests, lower scores were observed even ≥1 year after the concussion.

Conclusion: On the basis of objective performance metrics for cognitive function, concussions had a more persistent effect on cognitive function than previously thought. The age at which an individual has his or her first concussion may be an important factor in determining long-lasting cognitive effects.

Keywords

neurocognitive testing; adolescents; concussion; duration of effects; mTBI

An estimated 72% of children in middle school and high school play some form of organized sport.[58] Evidence suggests that the rate of reported sports-related head injuries within this population has been increasing over the past 10 years, with mild traumatic brain injuries (mTBIs) or concussions among individuals between the ages of 5 and 18 years old accounting for an estimated 65% of all sports-related mTBIs.[15,63] Whether this is related to an actual increase in the incidence of mTBIs or an increasing awareness of the risk factors related to mTBIs remains unclear. Nevertheless, given the prevalence of concussions in this population and the potential vulnerability of the still-developing brain,[21,37] it is imperative to evaluate the consequences of these types of injuries for cognitive function.

Whether concussion at early ages is associated with lasting changes in brain plasticity or evolving cognitive functions remains controversial.[13,24] Most studies evaluating the effect of concussions on cognitive function were conducted among collegiate and professional athletes. These studies generally reported short-term adverse effects on cognition, typically resolving within 2 weeks of the injury.[6,8,14,40,43,44] However, it is not clear if the findings from studies of adult populations (>18 years of age) are applicable to an adolescent population, particularly given differences in stages of brain development.[46] The evidence base for results of concussions among adolescents is scant, and much of the information that physicians and others provide to young athletes about concussion is based on opinion rather than data.[26,52] These data are important for clinical concussion management and return-to-play considerations.[44]

Studies that evaluated cognitive function after concussion among adolescents were largely inconclusive, with some studies showing a decrease in cognitive function across cognitive domains[18,35,36] and others finding no difference.[61] These differences in findings may be due to the limitation of the study methods, such as small sample sizes, insufficient follow-up time after a concussion, not accounting for potential confounders, and lack of consideration for the age at which the concussion(s) occurred.

In the current study, we evaluated the association between concussion and cognitive function in the largest cohort of adolescents to date—a racially diverse group of student athletes from Southern California—while accounting for many potential confounding factors. We also explored the influence of the age at which the concussion occurred and the persistence of associations many years after the concussion.

METHODS

Study Population

From 2009 to 2014, 5656 student athletes aged 13 to 19 years were administered cognitive function tests. All students were from school districts in San Bernardino and Riverside counties in California. Under bylaw 503 of the California Interscholastic Federation,[10] student athletes are required to have a sports physical examination <1 year before participation in any interscholastic sport. For many schools in these counties, cognitive tests were added to these preparticipation physicals as standard practice. The tests are usually administered in a classroom setting with ≥1 test proctors present to monitor the process. A small proportion of student athletes were administered these tests individually (n = 330). This would happen if a parent of an athlete sought to have the test administered at the clinic outside of the team testing, which would be independent of concussion status, or if a player had a recent head injury and the test was used as part of the return-to-play clearance process. We excluded individuals for whom concussion history was unknown or who took the test in a language other than English. We also excluded individuals who had tests that were flagged as incomplete. After exclusions (n = 40), the final sample included 5616 students.

Due to a lack of interaction with the participants and the use of de-identified data, this study was determined to be not human subject research by the Harvard Longwood Medical Area Human Research Administration.

Exposure and Covariate Assessment

Before students took the cognitive tests, information on pertinent variables was collected, including the number of concussions that they had experienced in the past. If they reported ever having a concussion, they were asked to provide the timing of the event. From these responses, we created a binary variable for ever having a concussion (yes/no) and a continuous number of concussions. From reported dates of concussions, we calculated (1) the age at first concussion and (2) the years since last concussion from the test date. We analyzed both of these as continuous variables.

Covariates considered in our analyses included sex (male, female), race/ethnicity (white, Hispanic, black, Asian, Hawaiian Pacific Islander, and Native American), current school district (1–12 as a nonordinal categorical variable), handedness (left, right, ambidextrous), age at date of assessment (continuous), grade (7–12, continuous), weight and height from which we calculated body mass index (kg/m^2, continuous), and first language (English, non-English). We also created a categorical variable for sport type based on classification by the American Academy of Pediatrics,[51] which includes 3 categories: contact or collision sport, limited-contact sport, and noncontact sport. Because football players have a higher incidence of concussions as compared with athletes of other sports,[22] for our analyses we split the first category into football specifically and other contact or collision sport.

Cognitive Testing

Cognitive performance was assessed with the validated computer-based Immediate Post-Concussion Assessment and Cognitive Test (ImPACT).[39,54] This test has become one of the most widely used batteries for measuring cognitive function among athletes across the United States. Five composite test scores were calculated from ImPACT data: verbal memory, visual memory, visual motor speed, reaction time, and impulse control. The score ranges vary by composite test; therefore, to more easily compare across tests for this study, we standardized each test to our nonconcussed population by calculating individual *z* scores from the mean ± SD of the nonconcussed participants for each composite score. Thus, the interpretation of a unit change in our standardized *z* score was a 1-SD change in the nonconcussed population for each composite score. Scores for impulse control and reaction time were inverted so that a higher score indicated better performance for all composite scores.

Statistical Analysis

To estimate the mean difference in standardized cognitive domain test score (*z* score) and its 95% CI by concussion history, we used multivariable linear regression, adjusting for covariates. To assess the association with overall cognitive function, we used linear mixed models for each exposure of interest, treating each composite test score as a repeated measure of global cognitive function within participants. Within each model, we included (1) a random intercept for each test score to account for the correlation in performance across students in a given cognitive domain and (2) a random intercept for each individual to account for the correlation in scores across the 5 domains for a given student. If all cognitive domains are similarly affected by concussion, this model provides an effect estimate that is more precise than those from the models of the specific domains. To evaluate potential heterogeneity of the effect of concussion across domains, we compared this model with a model without the random slope for each test, using the Akaike information criterion. If heterogeneity was detected across cognitive domains, we conducted domain-specific analyses.[16,49]

When assessing the association between cognitive function and both time since last concussion and age at first concussion, we also adjusted for the total number of concussions that each athlete had experienced. This analysis was conducted only among participants who had ever experienced a concussion and had provided information on the dates of the concussion. When evaluating age at first concussion, we excluded participants with a concussion within 2 years of testing. We did so to ensure that the observed effect estimate would not reflect the effect of having a concussion close to the test date. We assessed time since last concussion as the exposure of interest in a separate model. To assess whether these associations were linear, we compared the fit from a linear mixed model with that from a model containing natural splines for time since last concussion and age at first concussion. We assessed deviations from linearity by comparing the Akaike information criterion of the linear model with those of models with natural splines with 2 to 4 degrees of freedom, and we selected the model with the lowest Akaike information criterion as the best-performing model. If a nonlinear association was detected, we present the results graphically. Nonlinearity was assessed with a modified Wald test.

Tests for interaction were done for race, sex, and sport category. This was conducted by including a multiplicative term between the potential modifier and the exposure in the model and by using the interaction coefficient–specific t test to evaluate statistical differences in sex on the effect of concussion on the composite scores. All models were evaluated in the full population, and when effect modification was found, we present stratified results for that variable. To account for the small amount of missing covariate data (<3% total), we used multiple imputation with 10 imputations.[25,27,34] Analyses were conducted with SAS software (v 9.3; SAS Institute) and, for models that contained splines, R statistical software (v 3.1.1; R Development Core Team).

RESULTS

Our study population included 807 (14.4%) student athletes with a history of concussion and 4809 without (Table 1). The students were predominantly Hispanic, and football was the sport most commonly played. Female students represented approximately 25% of our population. The mean ± SD age of all students at the time of cognitive testing was 15.6 ± 1.2 years. Football players were more likely to have a history of concussion than were those in other sports. Among those who had had a concussion, the number of concussions before the test date ranged from 1 to 7, and the mean age at first concussion was 13.9 ± 3.5 years. The mean years between the last concussion and cognitive testing was 1.7 ± 2.8 years (Table 1). The mean ± SD used to calculate the standardized score for each test is presented in Table 2.

Ever having a concussion was associated with a lower score by 0.11 standardized units (95% CI, −0.20 to −0.01) on the global cognitive test score in the adjusted model (Table 3). The adjusted associations with specific domains were also negative, although the analysis suggested heterogeneity across cognitive tests, indicating that the association was stronger for some (eg, impulse control) than others (eg, reaction time). There was a stronger negative association with a history of concussion among female athletes versus male athletes, which seemed driven by more negative associations with verbal and visual memory. However, the only statistically significant difference in score by sex was for the visual memory composite, which was on average 4 times lower than the male score ($P = .009$). For all other tests, there was no appreciable statistically significant difference by sex ($P > .05$), despite point estimates for the girls being more negative. For all models evaluated, there were no significant interactions between race/ethnicity or sport category and concussion. We therefore do not present stratified results for any of these variables.

For each additional concussion before the test date, scores were lower by −0.06 standardized units (95% CI, −0.11, −0.02) on the global cognitive combined score. However, our analysis again suggested heterogeneity across the specific domains, and for visual motor and reaction time, the effect estimates were comparatively smaller (Table 4). The sex-stratified results showed that the negative association with the number of concussions was stronger for female athletes than male athletes, with the exception of the reaction time composite. Again, this was driven by stronger associations with verbal and visual memory. In addition, while differences in the point estimates were seen between the sexes on the composite test scores by number of concussions, only the visual memory composite showed a statistically significant interaction between sex and a history of concussion, with female athletes scoring on average 2.4 times lower ($P = .04$) for each increase in the number of concussions.

We assessed the associations with time since last concussion among the 593 (73%) students with a past concussion who provided information on the dates of their concussions. Those missing dates of concussion performed slightly worse (global cognition z score = −0.11, SD = 1.01) than those who provided dates (global cognition z score = −0.07, SD = 1.09). Among the students who provided the dates of their concussions, there were more pronounced deficits on cognitive function test performance with more recent concussions. However, the associations appeared to be nonlinear because, for all domains, the best-fit models for the association with time since last concussion were produced with splines with 3 degrees of freedom (Figure 1). As in previous analyses, we detected heterogeneity across the domains for time since last concussion. For the global cognition score, there was a significant nonlinear effect ($P < .001$) where those who had concussions shortly before their cognitive assessment had a 0.4-SD unit reduction in score as compared with those who had a concussion 1.5 to 2.0 years before their cognitive assessment, where the effect of time since concussion began to level off. This indicates that a worse performance occurred for about 1.5 to 2 years after the concussion. More pronounced deficits within that time frame were observed for visual motor and reaction time. For postconcussion intervals >2 years, little additional impairment was generally evident for any of the domains, except perhaps verbal memory. Stratified analyses by sex did not produce statistically different effect estimates (with CIs overlapping) on any of the composite scores evaluated; therefore, only the combined results are presented.

Among the 139 students with concussions >2 years before the cognitive testing, the mean age at first concussion was 9.8 ± 4.2 years, and the mean time since last concussion was 5.7 ± 4.0 years. We detected no deviations from linearity between age at first concussion and cognitive function. We found worse performance when the first concussion occurred at younger ages (Table 5). Again, there was heterogeneity across cognitive domains, with all domains showing worse performance with earlier age at first concussion except for impulse control—for which the association was in the opposite direction, with no evidence that it was different from zero. In analyses that did not include impulse control, there was no heterogeneity across the remaining domains, and the association with global cognition was −0.05 standardized units (95% CI, −0.08 to −0.01) worse for each year earlier that the first concussion occurred. There was an insufficient number of female athletes who had head injuries in early life (3 girls aged <9 years) to allow for a stratified analysis; therefore, these results are not presented.

DISCUSSION

Our findings suggest that adolescents suffering a concussion achieved lower scores on tests of multiple domains of cognitive function. We found that the more recent the concussion, the worse the cognitive performance. For the global score, associations with concussion history and number of concussions on average were worse for female athletes than males, seemingly driven by more negative associations with the verbal and visual memory composites, although only the difference in visual memory met statistical significance. Prior research supports worse performance on cognitive batteries after a concussion for females versus males.[17,47] Reduced cognitive performance appeared to persist for 1.5 to 2 years after the concussion. Our findings also suggest that there is an incremental decrease in cognitive function with each additional concussion and that having a concussion at a younger age is associated with worse cognitive function in adolescence.

The decreases in cognitive function that we saw in relation to concussions were not large. The 0.4-SD lower score on the global cognition score seen for those concussed shortly before the cognitive assessment would be equivalent to a 6-point lower score on an archetypal test on a 100-point scale (SD, 15). The 0.11-SD lower score overall on the global cognitive test score among those reporting concussion would be equivalent to a 1.65-point lower score on the same archetypal test. It should be noted, however, that this is an average difference across all time spans between concussion and cognitive testing and is also averaged across all concussed participants, some of whom could have had more severe changes. In addition, although some of the average changes may be small on an individual level, when applied to the larger population of adolescents with concussion, these results would have important population-level consequences. This is similar to what is often discussed in relation to effects of lead exposure on child neurodevelopment.[7,23] Specifically, a small decrease in the average cognitive score at the individual level, if occurring in a large population of concussed individuals, would shift the entire distribution of scores in that group down, leading to many more being classified as cognitively impaired.[32]

Most studies evaluating concussions and cognitive function primarily focused on recovery from short-term transient effects.[35,48,56] While it was reported that self-reported symptoms diminish after a few days or weeks, it was found that objective deficits can persist longer than this.[9,42,62] A recent review of concussion effects on long-term cognitive impairment among children and adults found that 88% (n = 508) with a history of a single mTBI showed cognitive impairment as far as 8 years out after an injury, among the 11 studies that followed people for longer than a year.[45] Only 2 of these studies included adolescents but were not restricted to this age range. One found a strong improvement after 1 year but saw a leveling off from this change at the follow-up visit 2 years later, which is consistent with our findings.[29] The second study found cognitive impairment on a prospective memory test 5 years out.[41] This contradicts current wisdom that most concussion symptoms are resolved between 3 and 6 months.[19,50] Our study is the first to include only adolescents and examine effects of concussion beyond 6 months. Our results suggest that, as seen in a few studies of populations >18 years old, the initial effect of concussion on cognitive function may last well beyond even 6 months.

Studies on the long-term effects of pediatric head injury were generally quite small and had somewhat conflicting findings.[1,20,64] These studies also typically did not follow children into the teenage years. In our very large sample, results suggest that the earlier the age of concussion, the worse the performance is in several cognitive domains. This supports a growing body of evidence suggesting that early childhood exposure to traumatic brain injuries and subconcussive impacts may result in worse functional outcomes when compared to those who are are exposed to these factors later in life.[3,4,59] Intriguingly, this did not appear to be the case for impulse control in this study. However, this could correspond to a later age of maturation of brain areas critical for impulse control. Significant neuronal maturation and myelination of white matter in the prefrontal cortex, a critical brain region for impulse control, occur around puberty and later.[5,31] In contrast, neural systems underlying the other domains tested undergo significant development in earlier childhood.[12] In animal models, prefrontal lesions affected brain development, which resulted in a variety of behavioral changes. These changes were associated with the developmental stage that the animals were in when they had their injury.[28] Additionally, rodent models demonstrated that traumatic brain injuries in juvenile rodents can negatively affect brain plasticity and disrupt normal myelination, which could have age-dependent implications on long-term brain circuit function.[11,33,55] This suggests that concussions at the time of rapid development of a given neural system may be more important for cognitive functions subserved by that system than concussions that occur earlier or later. However, more research in this area is needed to confirm this.

Our findings may help explain why there have been conflicting findings among studies evaluating chronic effects of concussion. If age at concussion and time since concussion are not accounted for in analyses, then results could differ depending on the distribution of those variables in the population under study. In addition, most previous studies had limited covariate adjustment. In our analyses, the unadjusted effect estimates tended to be smaller than the adjusted estimates. If a similar situation was the case in other study settings, then inadequate control for potential confounders could underestimate the effect of concussions.

A limitation of our study is the use of self-reported concussions. We know that concussions tend to be underreported to clinicians in athletic populations.[60] When former athletes were surveyed about their concussion history, they also tended to report more concussions than what had previously come to medical attention.[30] The primary reason for this discordance was a tendency of athletes not to disclose potential concussions during playing years for various reasons, including perceived lack of severity, not wanting to miss a game or practice, or no medical staff present. While there may be low agreement between clinically diagnosed concussion and self-reported concussion, self-reported concussion history may be able to capture additional concussions that would not be captured in medical records. However, self-reported history may include concussions that may not have met criteria for a concussion had it been evaluated at the time of the event. Importantly, reporting of history of concussions in our population would not have had any effect on whether an athlete was allowed to play a sport, and so there was not that incentive to underreport. Nonetheless, if there was underreporting and it was similar regardless of cognitive function scores or worse among those with worse cognitive function, then this would result in our observed effect estimates underestimating true associations. To account for finding worse cognitive scores among those with a concussion closer to the testing date, such underreporting would have to be preferentially among those with better cognitive scores, which seems unlikely. Furthermore, with respect to error in the recall of age at first concussion, which requires a longer recall time, for our findings to be explained by error in the reporting of the timing, our lower-scoring individuals would have had to be more likely to report concussions earlier in life, which again seems unlikely. There were also some missing data for dates of concussion, and those missing dates scored slightly worse. If the missing dates tended to be closer in time to the testing, that could have contributed to more recent concussions appearing worse; if the missing dates tended to be in the more distant past, that could have contributed to concussions at earlier ages appearing worse. We also do not have data on the severity of reported concussions; thus, our results must be considered as average effects over the different severities in our study population.

Despite the popularity of the ImPACT test for cognitive testing of athletes, its validity and clinical function are often scrutinized. Although not extensive, a few studies compared the ImPACT with other cognitive batteries, with each battery having its own limitations.[2,38,39,57] Two sister studies found that all ImPACT composite scores except for impulse control met convergent validity when compared with a battery of validated domain-specific cognitive tests but that only the ImPACT reaction composite was not significantly correlated with the other composite tests, indicating that the composite tests did not meet discriminant validity.[38,39] An additional study found that after application of a factor analysis, the scores from the ImPACT test loaded onto 5 factors that only partially corresponded to the composite scores of the ImPACT test.[2] These 3 studies support the conclusion of Maerlender et al,[38] who indicated that the composite scores for the 5 cognitive constructs defined by the ImPACT may have good construct sensitivity but may be lacking in construct specificity. The widespread use of ImPACT is what made our large-scale study possible. The fact that we found the associations that we did using ImPACT and that some of our findings are similar to previous work with other tests[59] may suggest that the ImPACT testing is capturing relevant aspects of cognitive function, but future studies of the issues that we address here on other cognitive batteries are warranted.

In this study, we were able to evaluate the effect of concussion on cognitive function in a very large racially and ethnically diverse adolescent population, with male and female athletes and across multiple sports. This inclusive population allowed us to adjust for several potential confounding variables. These are attributes that were lacking in prior studies, which led to questions about the generalizability of such studies to populations that did not have similar distributions of potential confounders.

In conclusion, our results suggest that the initial effects of concussion on cognitive function may last much longer than generally thought. Our findings also suggest that concussions in early life may be particularly important for future cognitive development. While we acknowledge the numerous benefits of participating in sports during childhood and adolescence, these findings support a growing body of evidence suggesting that minimizing the exposure risk for concussions is important in youth sports. Furthermore, while many student athletes are cleared to play in a matter of days or weeks after a concussion,[53] our findings suggest that cognitive effects may not have resolved completely at this point. Future studies of such young athletes should follow participants long enough to explore the timing issues that we explored. These findings should be taken into consideration when reassessing guidelines for concussion management and return to play.

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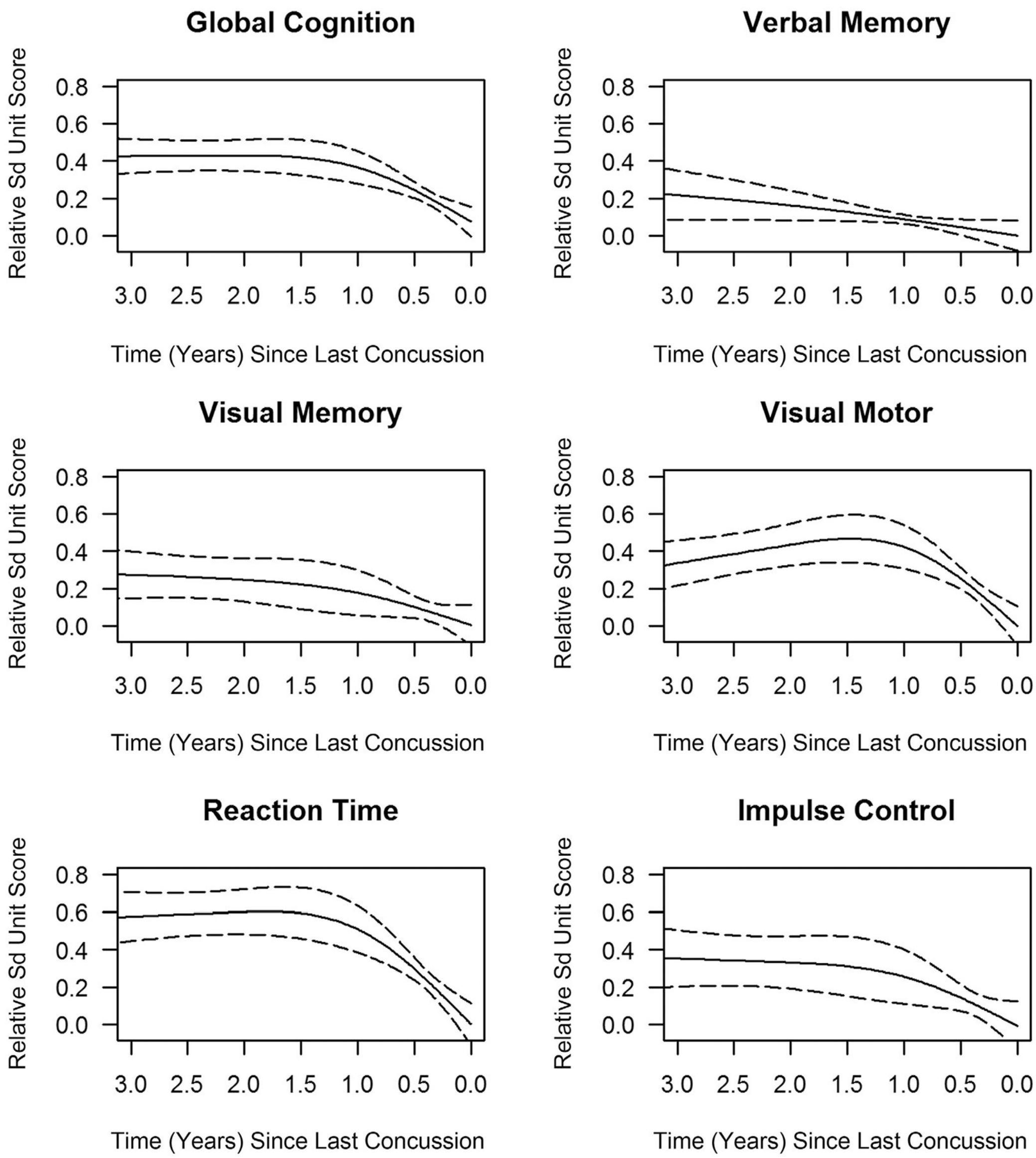

Figure 1.

Difference in cognitive test score (standardized units) for global cognitive function and each domain-specific test relative to scores of a hypothetical student tested immediately after a concussion where a higher value on the *y*-axis indicates better performance and a lower value, a worse performance. Thus, the interpretation of the effect estimate at any point on the *x*-axis is the estimate relative to the score of a student tested immediately after a concussion. The solid black line shows the estimated score difference, and the dashed lines indicate the 95% CI.

TABLE 1

Characteristics of Study Population by Concussion History[a]

	No Prior Concussion (n = 4809)	Prior Concussion (n = 807)
No. of concussions	0	1–7
Age at first concussion, y	NA	13.9 ± 3.5
Time since last concussion, y	NA	1.7 ± 2.8
Age at date of cognitive test visit, y	15.5 ± 1.2	15.9 ± 1.2
BMI at date of cognitive test visit	23.5 ± 4.6	24.1 ± 4.8
Sex		
Female	1236 (25.7)	134 (16.6)
Male	3573 (74.3)	673 (83.4)
Race/ethnicity		
Hispanic	1928 (40.1)	196 (24.3)
White	1084 (22.5)	217 (26.9)
Mixed	697 (14.5)	126 (15.6)
Black	518 (10.8)	98 (12.1)
Asian	82 (1.7)	3 (0.4)
Hawaiian Pacific Islander	60 (1.2)	8 (1.0)
Native	26 (0.5)	4 (0.5)
Missing	414 (8.6)	155 (19.2)
Sport class		
Football	2359 (49.1)	537 (66.5)
Other contact or collision sport	1761 (36.6)	208 (25.8)
Limited contact sport	497 (10.3)	43 (5.3)
Noncontact sport	168 (3.5)	15 (1.9)
Missing	24 (0.5)	4 (0.5)

[a]Values are presented as mean ± SD or n (%). BMI, body mass index; NA, not applicable.

TABLE 2

Mean and SD of Each Composite Score in the Nonconcussed Group

Test	Mean ± SD
Verbal memory	80.82 ± 11.21
Visual memory	70.46 ± 13.74
Visual motor	33.36 ± 7.23
Reaction time	1.78 ± 0.11
Impulse control	115.39 ± 6.37

TABLE 3

Mean Difference in Cognitive Test Score (Standardized Units) Between Those With and Without a Concussion[a]

	Entire Population		Stratified[b]	
Test	**Unadjusted**	**Adjusted[b]**	**Male**	**Female**
Global cognition	−0.09 (−0.20 to 0.03)	−0.11 (−0.20 to −0.01)	−0.08 (−0.18 to 0.01)	−0.23 (−0.41 to −0.04)
Verbal memory	−0.09 (−0.16 to −0.01)	−0.11 (−0.19 to −0.03)	−0.08 (−0.16 to 0.01)	−0.25 (−0.45 to −0.06)
Visual memory	−0.10 (−0.17 to −0.02)	−0.13 (−0.21 to −0.05)	−0.08 (−0.16 to 0.01)	−0.37 (−0.55 to −0.18)
Visual motor	−0.01 (−0.08 to 0.07)	−0.08 (−0.16 to −0.01)	−0.08 (−0.16 to 0.001)	−0.10 (−0.28 to 0.08)
Reaction time	−0.03 (−0.11 to 0.04)	−0.09 (−0.16 to −0.01)	−0.09 (−0.18 to −0.01)	−0.06 (−0.25 to 0.12)
Impulse control	−0.22 (−0.29 to −0.14)	−0.21 (−0.29 to −0.14)	−0.21 (−0.30 to −0.12)	−0.23 (−0.41 to −0.04)

[a] Values in parentheses indicate 95% CI.

[b] Adjusting for sex (only in entire population analysis), body mass index, race, age, age^2, school district, sport category, first language, grade, and handedness.

TABLE 4

Mean Difference in the Cognitive Test Score (Standardized Units) Per Concussion[a]

	Entire Population		Stratified[b]	
Test	Unadjusted	Adjusted[b]	Male	Female
Global cognition	−0.05 (−0.12 to 0.03)	−0.06 (−0.11 to −0.02)	−0.06 (−0.11 to −0.01)	−0.12 (−0.13 to −0.11)
Verbal memory	−0.07 (−0.12 to −0.03)	−0.09 (−0.14 to −0.04)	−0.07 (−0.13 to −0.02)	−0.17 (−0.29 to −0.05)
Visual memory	−0.06 (−0.11 to −0.01)	−0.08 (−0.13 to −0.03)	−0.05 (−0.11 to 0.002)	−0.19 (−0.30 to −0.08)
Visual motor	0.02 (−0.03 to 0.06)	−0.03 (−0.08 to 0.01)	−0.08 (−0.02 to −0.01)	−0.06 (−0.17 to 0.05)
Reaction time	−0.01 (−0.05 to 0.04)	−0.04 (−0.09 to 0.01)	−0.04 (−0.09 to 0.01)	−0.05 (−0.16 to 0.06)
Impulse control	−0.10 (−0.15 to −0.05)	−0.10 (−0.15 to −0.05)	−0.10 (−0.15 to −0.04)	−0.13 (−0.24 to −0.02)

[a] Values in parentheses indicate 95% CI.

[b] Adjusting for sex (only in entire population analysis), body mass index, race, age, age^2, school district, sport category, first language, grade, and handedness.

TABLE 5

Mean Change in the Cognitive Test Score (Standardized Units) for Every 1-Year Decrease in Age at First Concussion[a]

	Entire Population	
Test	Unadjusted	Adjusted[b]
Global cognition	−0.04 (−0.09 to 0.01)	−0.03 (−0.06 to 0.01)
Verbal memory	−0.01 (−0.05 to 0.03)	−0.01 (−0.05 to 0.04)
Visual memory	−0.05 (−0.09 to −0.01)	−0.06 (−0.11 to −0.01)
Visual motor	−0.10 (−0.14 to −0.06)	−0.08 (−0.13 to −0.04)
Reaction time	−0.04 (−0.08 to 0.01)	−0.03 (−0.08 to 0.02)
Impulse control	0.01 (−0.03 to 0.04)	0.04 (−0.01 to 0.09)

[a] Values in parentheses indicate 95% CI.

[b] Adjusting for number of concussions, body mass index, sex, race, age, age^2, school district, sport category, first language, grade, and handedness.