Protocol for an Observational Study on Effects of Contact, Collision, and Non-Contact Sports Participation on Cognitive and Emotional Health

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Abstract

Background: Evidence suggests that sports participation improves wellbeing of youth. However, collision sports like football have become controversial due to evidence suggesting that football participation prior to the age of 12 may lead to worse cognitive and neuropsychiatric outcomes later in life. As few studies have examined how the intensity of collision and contact sports participation before age 12 relate to cognitive and emotional outcomes, we propose an observational study using the Adolescent Brain Cognitive Development (ABCD) dataset to determine how intensity of contact sports, collision sports, and non-contact sports participation during childhood relate to cognitive and emotional outcomes in early adolescence.

Methods: Our proposed study includes 9974 youths from the ABCD dataset. For each child, we calculated a collision sport participation volume, contact sport participation volume, and non-contact sport participation volume. Our two primary outcomes are measured when the youths are aged 8.9-11.1 years old: the NIH Toolbox Cognition total composite score and the Parent Child Behavior Checklist (CBCL) total emotional problems score. We will fit a linear mixed effects model with our primary outcomes as the dependent variable and with contact sports volume, collision sports volume, non-contact sports volume, and demographic covariates as fixed effects and with random intercepts for family and site ID. The study will also involve secondary analyses of current sports participation exposures, specific sport exposures, and incident of traumatic brain injury (TBI) as a possible mediator.

Discussion: This observational study will contribute to understanding how the volume of contact, collision, and non-contact youth sports participation relate to cognitive and emotional outcomes during a crucial developmental time window. This study will contribute to public health knowledge which will help stakeholders weigh benefits and risks of participation in different types of youth sports.

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1 Introduction

A large body of evidence suggests that sports participation improves physical, cognitive, and emotional well-being of youth. For example, sports participation improves cardiovascular markers in adolescents (Torres et al., 2020). Sports participation is correlated with less depressive symptoms, stress, and negative affect (Rodriguez-Ayllon et al., 2019). It is associated with self-image, happiness, and larger hippocampal volume (Gorham et al., 2019; Rodriguez-Ayllon et al., 2019).

Although sports participation seems largely beneficial, there are nuances within this relationship. Collision sports involve intentional physical contact with other players. Contact sports involve body-to-body contact, but intentional body-to-body contact is not allowed (Meehan et al., 2016). Contact and collision sports may put children at increased risk of sustaining concussions and subconcussive head impacts (Bahrami et al., 2016; Sarmiento et al., 2019). Personal history of brain injury, and particularly repetitive brain injury, has been associated with depressive symptoms and cognitive deficits, both in the near-term and later in life (Manley et al., 2017; Yang et al., 2019). While there are risks associated with contact and collision sports, it is important to weigh the benefits with the risks to help inform public health policy and personal and parental decisions regarding youth participation in sports with relatively high head injury risk, like football.

Recent years have seen controversy around football in particular, in light of evidence suggesting that football players are at risk for chronic traumatic encephalopathy (CTE) later in life due to repeated traumatic brain injury, but several subsequent studies did not replicate these findings (Iverson, Büttner, et al., 2021). Some studies suggest that participating in football prior to age 12 is associated with worse cognitive and neuropsychiatric outcomes later in life, among former professional and amateur football players. However, other studies suggest that there is no relationship between health outcomes and the age at which retired football players started playing football (Caccese et al., 2020).

Studies on short-term effects of head impacts due to sports among adolescents provide similar mixed findings. Deleterious influences of collision sports participation come from studies demonstrating that a single season of football resulted in decreased white matter integrity in 8-13 year olds without clinically diagnosed concussion (Bahrami et al., 2016). However, results of a separate study found that a single season of head impact exposure due to football was not associated with worse mental health in an adolescent sample (i.e., mean age 15.31 years) (Kercher et al., 2023). Furthermore, some evidence suggests a protective emotional health effect of contact and collision sports participation among high school athletes, with one sample reporting fewer anxiety and depressive symptoms at the time of sports participation, despite having more orthopedic injuries compared to subjects with no-or-limited contact sports participation (Howell et al., 2020).

This study seeks to provide a better understanding of the impact of sports participation during the crucial developmental period of young adolescence. Despite the focus on collision sports participation before age 12, prior studies on collision sports typically involve a binary variable for participation before age 12. These studies typically do not measure collision sports exposure during childhood in terms of participation intensity. To fill this gap, our study calculates a contact and collision sport volume defined as the number of months times the number of sessions per week times the number of minutes per session which the child participated in contact and collision sports during the child's most active period. The present study aims to evaluate the influence of contact sports volume, collision sports volume, and non-contact sports volume during the child's most active period in relation to cognitive and emotional outcomes during adolescence.

2 Adolescent Brain Cognitive Development (ABCD) Study® dataset

The ABCD study is an ongoing longitudinal study that conducts physical, cognitive, social, emotional, environmental, behavioral, academic, neuroimaging, and biospecimen assessments among adolescents (Garavan et al., 2018). The study involves interviews with youth who were age 9-10 at baseline, as well as interviews with their parents. Youth and their parents complete interviews at annual (non-imaging) or biannual (imaging and bioassays) follow-up visits up until the youth are age 19-20. Because the ABCD study is over-sampled for twins and siblings, we use mixed-effects models to account for correlations among siblings and twins nested within families and families nested within site (Saragosa-Harris et al., 2022). We use ABCD Data Release 4.0.

Primary Outcomes

Our two co-primary outcomes include a measure of cognitive health and a measure of emotional health at baseline. We use the Cognition Total Composite Score Fully-Corrected T-score in the "ABCD Youth NIH TB Summary Scores" file as a global measure of cognitive function.

We measure emotional health using the Parent Child Behavior Checklist (CBCL) questionnaire, which includes items exemplifying internalizing, attention, and externalizing problems (Achenbach et al., 2017). At baseline visit, parents are asked to rate how much their child exhibits the behavior described in each item on an ordinal scale: 0 = not true, 1 = somewhat true, or 2 = very true. Ratings for internalizing, attention, and externalizing problems are summed to yield the Total Problems score. This score is compared to age-gender norms to yield a Total Problems t-score. We use the Total Problems t-score from the "ABCD Parent Child Behavior Checklist Scores Aseba (CBCL)" table.

Inclusion Exclusion Criteria

We considered NA and "Don't Know" to be missing data for variables measuring number of months, number of days, or time spent participating in a sport. The 1015 participants who were missing any of these variables were dropped from our analysis, as these variables are needed to calculate sports volume as detailed in the Exposure Characterization section. Any participant who was missing either of our co-primary outcomes was dropped from our analysis. An additional 887 subjects were excluded for this reason. Our final sample includes 9974 participants.

Potential Confounders

Potential confounders include age, sex, race, income to needs ratio, and Area Deprivation Index (ADI) measured at baseline. ADI measures neighborhood socioeconomic disadvantage in the U.S. For the primary address of each participant, the ABCD study records the scaled weighted sum of all ADI variables based on Kind et al. (2014). Income-to-needs ratio as defined by Rakesh et al. (2021) is the median income within the participant's household-income bracket divided by the 2022 federal poverty line for the participant's household size (Rakesh et al., 2021). We considered income-to-needs ratio to be missing for the two participants who reported outlier household sizes of 60 or 77. We considered “Don’t Know” and “Refuse to Answer” as missing data for confounders.

Table 1: Summary statistics for potential confounders included in our analysis.

N		9974
Age in months (mean (SD))		118.85 (7.50)
Sex (%)	F	4791 (48.0)
	M	5183 (52.0)
Race (%)	Asian	251 (2.5)
	Black	1516 (15.2)
	Other	1511 (15.1)
	White	6590 (66.1)
	Missing	106 (1.1)
Income To Needs (mean (SD))		3.34 (2.17)
Missing (%)		934 (9.4)
ADI (mean (SD))		94.35 (21.14)
Missing (%)		715 (7.2)

Comparisons Between Excluded and Included

We created a binary variable where “1” indicates that the child was included in our final sample and “0” indicates that the child was not included in our final sample. We binarized all continuous variables listed in the “Potential Confounders” section for analyses in this section. For each of the “Potential Confounders,” we fitted a mixed effects logistic regression: inclusion in final sample was the dependent variable; each potential confounder was the single fixed effect; and random intercepts for family ID and site ID were fitted. Compared to Asian individuals, individuals whose race was reported as Black or Other[*] were less likely to be included in our final sample (OR[†] [95% CI]: Black 0.62 [0.43-0.90], p = 0.01; Other 0.68 [0.48-0.98], p = 0.04), and there was no significant difference in the likelihood that White versus Asian individuals were included in our final sample. Older participants were less likely to be included (OR [95% CI]: 0.81 [0.73-0.90], p < 0.001). There was no significant difference in the probability that participants with male versus female sex were included. Participants who had a higher income to

[*] The category of Other race included Native Hawaiian, Guamanian, Samoan, Other Pacific Islander, American Indian / Native American, Alaska Native, and Multiracial individuals.
[†] OR: Odds Ratio

needs ratio were more likely to be included in our final sample (OR [95% CI]: 1.22 [1.09-1.37], $p < 0.001$). Participants living in areas with higher ADI were less likely to be included (OR [95% CI]: 0.75 [0.66-0.84], $p < 0.001$). TBI history did not predict inclusion.

3 Analysis Plan

3.1 Exposure Characterization

The Parent Sports and Activities Involvement Questionnaire (SAIQ) asks parents about their child's lifetime involvement in each sport or activity: *"[p]lease indicate whether your child has EVER participated in any of the following sports and activities continuously for 4 months or more (e.g., for a season in sports, or at least four months of lessons, group participation, etc). We will then ask you some follow-up questions*." Parents are then asked to rate their child's activity during the child's most active period for each sport. The questionnaire measures the following during the most active period: (1) the number of months a child participated in each sport, (2) the number of days per week the child participated in that sport, (3) the number of minutes the child participated in that sport per session. For each sport, we calculated sports volume by multiplying these three values, thereby creating an approximation of overall lifetime participation in that sport up to adolescence for each child.

We calculate a measure of team sports volume, individuals sports volume, collision sports volume, contact sports volume, and non-contact sports volume for each child. Table 2 and 3 describe the classification of sports into team vs individual and collision vs contact vs non-contact. We add the sports volume for all contact sports to form the contact sports volume for the child; likewise, we calculate a collision sports, non-contact sports, team sports, and individual sports volume.

To assess potential bias due to missing outcome data, we created a binary variable where "1" indicates that the child had both the NIH Toolbox Cognition score and CBCL Total Problems score and where "0" indicates that the child was missing at least one of these two scores. We binarized total sports participation volume into a "high" category and a "low" category. We then fitted a mixed effects logistic regression, with availability of primary outcomes as the dependent variable, sports volume as the single fixed effect, and family-specific and site-specific random intercepts. Sports volume did not predict availability of our primary outcomes, which suggests that there was no significant difference in level of sports participation between subjects included in our study and remaining subjects in the ABCD dataset.

Table 2. Non-contact vs. Contact vs. Collision Sports Categories

Non-contact	Contact	Collision
Track/running/cross-country	Baseball	Football
Volleyball	Soccer	Wrestling
Ballet/dance	Basketball	Martial arts
Swimming/water polo	Field hockey	Ice hockey
Tennis	Ice/inline skating	Lacrosse
Climbing		Rugby
Surfing		
Yoga		
Horseback riding		
Skiing		
Gymnastics		
Skateboarding		

We largely follow Meehan, III et al. (2016) definitions of collision and contact sports.

Table 3. Team versus Individual Sports Categories

Team	Individual
Soccer	Ballet/dance
Baseball	Gymnastics
Basketball	Horseback riding
Field hockey	Martial arts
Football	Wrestling
Ice hockey	Swimming/water polo
Lacrosse	Tennis
Rugby	Track/running/cross-country
Volleyball	Climbing
	Ice/inline skating
	Skiing
	Yoga
	Surfing
	Skateboarding

This is the same categorization used in Hoffman et al. (2022) except that we add to the “individual sports” category other potentially-competitive physical activity (i.e., climbing, ice/inline skating, skiing, surfing, skateboarding, and yoga).

3.2 Linear Mixed Effects Regression

Team sports tend to be collision sports and individual sports tend to be non-contact sports by the nature of these activities. Indeed, team sports volume was highly correlated with contact sports volume (Pearson's correlation coefficient r = 0.88) and individual sports was highly correlated with non-contact sports (r = 0.88) as shown in Table 4. To avoid multicollinearity, we thus only include non-contact sports volume, collision sports volume, and contact sports volume as predictors in our main linear mixed effects regression model. We will fit a linear mixed effects model with NIH Toolbox Cognition score as the outcome and with collision sports volume, contact sports volume, non-contact sports volume, and demographic covariates as predictors. Similarly, we will fit another linear mixed effects model with the same predictors and with CBCL Total Problems t-score as the outcome. We use multiple imputation to handle missing data in covariates (Schafer, 1999).

For investigations of NIH Toolbox Cognition as the outcome, our primary hypotheses is that at least one of collision sports volume, contact sports volume, or non-contact sports volume will significantly affect cognition score. Let $\beta_a, \beta_b, \beta_c$ denote fixed-effect regression coefficients for collision, contact, and non-contact sports respectively, We will test the null hypothesis $H_0: \beta_a = \beta_b = \beta_c = 0$ against the alternative hypothesis $H_1: at\ least\ one\ of\ \beta_a, \beta_b, \beta_c \neq 0$. We will use a Likelihood Ratio Test to test this primary hypothesis by comparing the full model against a model without these sports-volume fixed effects. If our primary null hypothesis is rejected, we will investigate in further detail which types of sports affect cognition. Specifically, we will test each null hypothesis $H_i : \beta_i = 0$ via a Wald Test for each $i = a, b, c$. We will not use a Bonferroni correction, as there are a small number of preplanned hypotheses and we are equally concerned about making both Type I and Type II errors (Armstrong, 2014). We test all hypotheses at $\alpha = 0.05$.

Analogously to the procedures outlined in the preceding paragraph, we perform hypothesis tests using CBCL Total Problems as the outcome.

Table 4. Correlation Matrix Among Measures of Sports Volume

	Non-Contact	Contact	Collision	Team	Individual
Non-Contact	1	0.101252	0.115735	0.098728	0.882002
Contact	0.101252	1	0.154043	0.883099	0.120097
Collision	0.115735	0.154043	1	0.391334	0.46104
Team	0.098728	0.883099	0.391334	1	0.089542
Individual	0.882002	0.120097	0.46104	0.089542	1

3.3 Secondary Analyses

Post Hoc Sports Analyses

The high correlations between individual sports volume and non-contact sports volume occurred because all non-contact sports are individual sports except volleyball. We will explore specific sport effects to better understand the results of our primary analysis.

Effect on Brain Injury

The "ABCD Sum Scores Traumatic Brain Injury" file records the number of TBI with loss of consciousness (TBI-LOC) each child has experienced. Due to small numbers of participants with 2 or more TBI-LOC, we binarize this variable where "1" indicates 1 or more TBI-LOC and "0" indicates no history of TBI-LOC.

We hypothesize that participants with greater collision sports participation will have the highest likelihood of brain injury, followed by contact sports participants; non-contact sports participants will have the lowest incidence of brain injury. To test this hypothesis, we fit a logistic mixed effects regression with TBI-LOC as the outcome and collision sports, contact sports, non-contact sports, and demographic covariates as predictors, using multiple imputation for missing data. Again, let β_a , β_b , β_c denote regression coefficients for collision, contact, and non-contact sports respectively. We then use a Wald test to test the null hypothesis $H_0: \beta_a = \beta_b$ against the alternative hypothesis $H_1: \beta_a - \beta_b > 0$. We also use a Wald test to test the null hypothesis $H_0: \beta_b = \beta_c$ against the alternative hypothesis $H_1: \beta_b - \beta_c > 0$. We use the R package `clubSandwich` to perform the Wald test. We also use a Wald test to test the hypothesis that β_a is significantly greater than 0, indicating that collision sports volume is positively associated with brain injury.

Brain Injury Mediator

To investigate TBI-LOC as a potential mediator, we will use the R package `mediation` for causal mediation analysis (Tingley et al., 2014), as much of the work on formally expressing effects of *categorical* mediators has involved a potential outcomes framework (Tofighi & Thoemmes, 2014). The package includes functions for estimating the causal mediation effect, which is the difference in potential outcome when the mediator takes the potential value it would take under the "treatment" condition as opposed to the control condition, assuming that "treatment" status is held constant. Since "treatment" versus "control" is categorical within this framework, we need to turn the "treatment" in our analysis, a continuous sports volume measure, into a categorical variable. We will therefore sort subjects into "no participation" versus "participation" for each of the three types of sports participation.

The `mediation` package can handle mixed effects models and datasets generated through multiple imputation through the `mediations` and `amelidiate` functions. On each simulated dataset generated through multiple imputation, we will fit a logistic mixed effects model with TBI-LOC as the dependent variable and the three types of sports volume and covariates as fixed effects (Model 1). We will then fit a linear mixed effects model with the health outcome variable as the dependent variable and with TBI-LOC, the three sports volume variables, and covariates as fixed effects on each simulated dataset (Model 2). Finally, we can combine models from each simulated dataset to estimate the average casual mediation effect, which is the population average of causal mediation effects (ACME). If the `medsens` functions can handle results generated from the `mediations` and `amelidiate` functions, we will also use the `medsens` function to conduct a sensitivity analysis to examine how much a non-zero ACME changes as a function of confounding due to unobserved confounders affecting both the mediator and the outcome. This unobserved confounding is measured by the correlation between the residuals of Model 1 and the residuals of Model 2.

Current Sports Participation

We will examine whether current sports participation is associated with cognitive and emotional health. We repeat the same sports volume calculations detailed in Section 3.1, except using data from when parents were asked "Since we last saw you, how many months per year did your child participate?" and similar questions regarding days per week and minutes per session of recent sports participation. This exposure data differs from the exposure data used in our primary analysis, which reflected sports participation during the child's "most active period." We repeat the primary analysis, except now using current sports participation data.

4 Discussion

We describe an observational study on the effects of collision, contact, and non-contact youth sports participation on cognitive and emotional health in young adolescents.

Childhood and adolescence are important developmental time periods (Casey et al., 2008; Gualtieri & Finn, 2022; National Institute of Mental Health (NIMH), 2023) which warrant careful study. There has been focus on the effects of participation in football before the age of 12. While some studies suggest that football participation before age 12 leads to negative cognitive and emotional outcomes (Iverson, Büttner, et al., 2021; Stamm et al., 2015), other studies find no significance difference in cognitive and emotional health outcomes among those who participated in collision sports before age 12 versus those who did not (Brett et al., 2019; Iverson, Caccese, et al., 2021). The equivocal evidence is compounded by the fact that prior studies are rarely able to characterize the intensity of collision sports participation before the age of 12. The ABCD dataset is especially suitable for studying childhood sports participation because the detailed ABCD questionnaire captures intensity of participation. In this study using ABCD data, we calculate a collision sports volume, as well as a contact sports volume and a non-contact sports volume for each child, which measures how much a child participated in these types of sports during the child's most active period. By potentially uncovering a dose-response relationship between collision sports participation and brain health, this study could provide more conclusive evidence on the effects of collision sports participation on brain health.

In addition to studying potential risks of collision sports and sports-related traumatic brain injury, this study also weighs the benefits of sports participation alongside its risks. The U.S. Surgeon General recently published an article titled, "Physical Activity: An Untapped Resource to Address Our Nation's Mental Health Crisis Among Children and Adolescents" (Murthy, 2023). This article highlights the importance of physical activity, including sports participation, in improving young adolescent mental health. It is crucial that concerns regarding the risks of collision sports do not overshadow the benefits of sports participation, if the risks of collision sports are minimal compared to its benefits. By studying the effects of collision sports and other types of sports on mental and cognitive health in adolescents, this study assesses how much the benefits of various sports may or may not outweigh the risks.

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References

Achenbach, T. M., McConaughy, S. H., Ivanova, M. Y., & Rescorla, L. A. (2017). *Manual for the ASEBA Brief Problem Monitor™ for Ages 6-18 (BPM/6-18)*.

Armstrong, R. A. (2014). When to use the Bonferroni correction. *Ophthalmic and Physiological Optics*, *34*(5), 502–508. https://doi.org/10.1111/opo.12131

Bahrami, N., Sharma, D., Rosenthal, S., Davenport, E. M., Urban, J. E., Wagner, B., Jung, Y., Vaughan, C. G., Gioia, G. A., Stitzel, J. D., Whitlow, C. T., & Maldjian, J. A. (2016). Subconcussive Head Impact Exposure and White Matter Tract Changes over a Single Season of Youth Football. *Radiology*, *281*(3), 919–926. https://doi.org/10.1148/radiol.2016160564

Brett, B. L., Huber, D. L., Wild, A., Nelson, L. D., & McCrea, M. A. (2019). Age of First Exposure to American Football and Behavioral, Cognitive, Psychological, and Physical Outcomes in High School and Collegiate Football Players. *Sports Health*, *11*(4), 332–342. https://doi.org/10.1177/1941738119849076

Caccese, J. B., Bodt, B. A., Iverson, G. L., Kaminski, T. W., Bryk, K., Oldham, J., Broglio, S. P., McCrea, M., McAllister, T., Buckley, T. A., & CARE Consortium Investigators. (2020). Estimated Age of First Exposure to Contact Sports and Neurocognitive, Psychological, and Physical Outcomes in Healthy NCAA Collegiate Athletes: A Cohort Study. *Sports Medicine (Auckland, N.Z.)*, *50*(7), 1377–1392. https://doi.org/10.1007/s40279-020-01261-4

Casey, B. J., Getz, S., & Galvan, A. (2008). The adolescent brain. *Developmental Review*, *28*(1), 62–77. https://doi.org/10.1016/j.dr.2007.08.003

Garavan, H., Bartsch, H., Conway, K., Decastro, A., Goldstein, R. Z., Heeringa, S., Jernigan, T., Potter, A., Thompson, W., & Zahs, D. (2018). Recruiting the ABCD sample: Design considerations and procedures. *Developmental Cognitive Neuroscience*, *32*, 16–22. https://doi.org/10.1016/j.dcn.2018.04.004

Gorham, L. S., Jernigan, T., Hudziak, J., & Barch, D. M. (2019). Involvement in Sports, Hippocampal Volume, and Depressive Symptoms in Children. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *4*(5), 484–492. https://doi.org/10.1016/j.bpsc.2019.01.011

Gualtieri, S., & Finn, A. S. (2022). The Sweet Spot: When Children's Developing Abilities, Brains, and Knowledge Make Them Better Learners Than Adults. *Perspectives on Psychological Science*, *17*(5), 1322–1338. https://doi.org/10.1177/17456916211045971

Howell, D. R., Kirkwood, M. W., Laker, S., & Wilson, J. C. (2020). Collision and Contact Sport Participation and Quality of Life Among Adolescent Athletes. *Journal of Athletic Training*, *55*(11), 1174–1180. https://doi.org/10.4085/1062-6050-0536.19

Iverson, G. L., Büttner, F., & Caccese, J. B. (2021). Age of First Exposure to Contact and Collision Sports and Later in Life Brain Health: A Narrative Review. *Frontiers in Neurology*, *12*, 727089. https://doi.org/10.3389/fneur.2021.727089

Iverson, G. L., Caccese, J. B., Merz, Z. C., Büttner, F., & Terry, D. P. (2021). Age of First Exposure to Football Is Not Associated With Later-in-Life Cognitive or Mental Health Problems. *Frontiers in Neurology*, *12*. https://www.frontiersin.org/articles/10.3389/fneur.2021.647314

Kercher, K. A., Steinfeldt, J. A., Rettke, D. J., Zuidema, T. R., Walker, M. J., Martinez Kercher, V. M., Silveyra, P., Seo, D.-C., Macy, J. T., Hulvershorn, L. A., & Kawata, K. (2023). Association Between Head Impact Exposure, Psychological Needs, and Indicators of Mental Health Among U.S. High School Tackle Football Players. *Journal of Adolescent Health*, *72*(4), 502–509. https://doi.org/10.1016/j.jadohealth.2022.11.247

Kind, A. J., Jencks, S., Brock, J., Yu, M., Bartels, C., Ehlenbach, W., Greenberg, C., & Smith, M. (2014). Neighborhood Socioeconomic Disadvantage and 30 Day Rehospitalizations: An Analysis of Medicare Data. *Annals of Internal Medicine*, *161*(11), 765–774. https://doi.org/10.7326/M13-2946

Manley, G., Gardner, A. J., Schneider, K. J., Guskiewicz, K. M., Bailes, J., Cantu, R. C., Castellani, R. J., Turner, M., Jordan, B. D., Randolph, C., Dvořák, J., Hayden, K. A., Tator, C. H., McCrory, P., & Iverson, G. L. (2017). A systematic review of potential long-term effects of sport-related concussion. *British Journal of Sports Medicine*, *51*(12), 969–977. https://doi.org/10.1136/bjsports-2017-097791

Meehan, W. P., Taylor, A. M., Berkner, P., Sandstrom, N. J., Peluso, M. W., Kurtz, M. M., Pascual-Leone, A., & Mannix, R. (2016). Division III Collision Sports Are Not Associated with Neurobehavioral Quality of Life. *Journal of Neurotrauma*, *33*(2), 254–259. https://doi.org/10.1089/neu.2015.3930

Murthy, V. H. (2023). Physical Activity: An Untapped Resource to Address Our Nation's Mental Health Crisis Among Children and Adolescents—Vivek H. Murthy, 2023. *Public Health Reports*, *138*(3). https://journals-sagepub-com.proxy.library.upenn.edu/doi/10.1177/00333549231175458

National Institute of Mental Health (NIMH). (2023). *The Teen Brain: 7 Things to Know*. National Institute of Mental Health (NIMH). https://www.nimh.nih.gov/health/publications/the-teen-brain-7-things-to-know

Rakesh, D., Zalesky, A., & Whittle, S. (2021). Similar but distinct – Effects of different socioeconomic indicators on resting state functional connectivity: Findings from the Adolescent Brain Cognitive Development (ABCD) Study®. *Developmental Cognitive Neuroscience*, *51*, 101005. https://doi.org/10.1016/j.dcn.2021.101005

Rodriguez-Ayllon, M., Cadenas-Sánchez, C., Estévez-López, F., Muñoz, N. E., Mora-Gonzalez, J., Migueles, J. H., Molina-García, P., Henriksson, H., Mena-Molina, A., Martínez-Vizcaíno, V., Catena, A., Löf, M., Erickson, K. I., Lubans, D. R., Ortega, F. B., & Esteban-Cornejo, I. (2019). Role of Physical Activity and Sedentary Behavior in the Mental Health of Preschoolers, Children and Adolescents: A Systematic Review and Meta-Analysis. *Sports Medicine*, *49*(9), 1383–1410. https://doi.org/10.1007/s40279-019-01099-5

Saragosa-Harris, N. M., Chaku, N., MacSweeney, N., Guazzelli Williamson, V., Scheuplein, M., Feola, B., Cardenas-Iniguez, C., Demir-Lira, E., McNeilly, E. A., Huffman, L. G., Whitmore, L., Michalska, K. J., Damme, K. S., Rakesh, D., & Mills, K. L. (2022). A practical guide for researchers and reviewers using the ABCD Study and other large longitudinal datasets. *Developmental Cognitive Neuroscience*, *55*, 101115. https://doi.org/10.1016/j.dcn.2022.101115

Sarmiento, K., Thomas, K. E., Daugherty, J., Waltzman, D., Haarbauer-Krupa, J. K., Peterson, A. B., Haileyesus, T., & Breiding, M. J. (2019). Emergency Department Visits for Sports- and Recreation-Related Traumatic Brain Injuries Among Children—United States, 2010-2016. *MMWR. Morbidity and Mortality Weekly Report*, *68*(10), 237–242. https://doi.org/10.15585/mmwr.mm6810a2

Schafer, J. L. (1999). Multiple imputation: A primer. *Statistical Methods in Medical Research*, *8*, 3–15.

Stamm, J. M., Koerte, I. K., Muehlmann, M., Pasternak, O., Bourlas, A. P., Baugh, C. M., Giwerc, M. Y., Zhu, A., Coleman, M. J., Bouix, S., Fritts, N. G., Martin, B. M., Chaisson, C., McClean, M. D., Lin, A. P., Cantu, R. C., Tripodis, Y., Stern, R. A., & Shenton, M. E. (2015). Age at First Exposure to Football Is Associated with Altered Corpus Callosum White Matter Microstructure in Former Professional Football Players. *Journal of Neurotrauma*, *32*(22), 1768–1776. https://doi.org/10.1089/neu.2014.3822

Tingley, D., Yamamoto, T., Hirose, K., Keele, L., & Imai, K. (2014). **mediation**: *R* Package for Causal Mediation Analysis. *Journal of Statistical Software*, *59*(5). https://doi.org/10.18637/jss.v059.i05

Tofighi, D., & Thoemmes, F. (2014). Single-level and multilevel mediation analysis. *The Journal of Early Adolescence*, *34*(1), 93–119.

Torres, W., Cayres-Santos, S. U., Urban, J. B., de Moraes-Chagas, L. G., Christofaro, D. G. D., Turi-Lynch, B. C., Codogno, J. S., & Fernandes, R. A. (2020). Participation in Non-professional Sports and Cardiovascular Outcomes Among Adolescents: ABCD Growth Study. *Maternal and Child Health Journal*, *24*(6), 787–795. https://doi.org/10.1007/s10995-020-02919-1

Yang, M. N., Clements-Nolle, K., Parrish, B., & Yang, W. (2019). Adolescent Concussion and Mental Health Outcomes: A Population-based Study. *American Journal of Health Behavior*, *43*(2), 258–265. https://doi.org/10.5993/AJHB.43.2.3