Cumulative Effects of Concussion History on Baseline Computerized Neurocognitive Test Scores: Systematic Review and Meta-analysis

Bara Alsalaheen, PT, PhD,*†‡§ Kayla Stockdale, DPT,† Dana Pechumer, DPT,† Alexander Giessing, MSc,‖ Xuming He, PhD,‖ and Steven P. Broglio, PhD, ATC¶

Context: It is unclear whether individuals with a history of single or multiple clinically recovered concussions exhibit worse cognitive performance on baseline testing compared with individuals with no concussion history.

Objective: To analyze the effects of concussion history on baseline neurocognitive performance using a computerized neurocognitive test.

Data sources: PubMed, CINAHL, and psycINFO were searched in November 2015. The search was supplemented by a hand search of references.

Study Selection: Studies were included if participants completed the Immediate Post-concussion Assessment and Cognitive Test (ImPACT) at baseline (ie, preseason) and if performance was stratified by previous history of single or multiple concussions.

Study Design: Systematic review and meta-analysis.

Level of Evidence: Level 2.

Data Extraction: Sample size, demographic characteristics of participants, as well as performance of participants on verbal memory, visual memory, visual-motor processing speed, and reaction time were extracted from each study.

Results: A random-effects pooled meta-analysis revealed that, with the exception of worsened visual memory for those with 1 previous concussion (Hedges $g = 0.10$), no differences were observed between participants with 1 or multiple concussions compared with participants without previous concussions.

Conclusion: With the exception of decreased visual memory based on history of 1 concussion, history of 1 or multiple concussions was not associated with worse baseline cognitive performance.

Keywords: concussion; mild traumatic brain injury; neurocognitive

With an estimated 3.8 million sports- and recreation-related mild traumatic brain injuries (ie, concussions) in the United States every year,12 concussion continues to be a public health concern. Concussion affects various parts of brain functioning that may result in temporary cognitive changes and symptoms.5 Because cognitive declines after concussion, as measured by current concussion test batteries, typically resolve or the patient returns to preinjury
cognitive performance within days to weeks from injury, the
effects of concussion are considered temporary.10 Because of
the growing concern of cumulative, long-term cognitive effects
of concussion21,51 as well as the lack of longitudinal studies to
quantify possible neurodegeneration after multiple concussions,
population-based differences in computerized neurocognitive
tests (CNTs) based on history of clinically recovered
concussions have been used to examine for possible cumulative
effects of concussions.8
Evidence for cumulative cognitive effects after concussion
remains inconclusive. While some investigations documented
small cognitive effects of multiple clinically recovered
concussions,35,52 others did not support possible cumulative effects
of previous concussions.34 Furthermore, some investigators
supported a dose-response relationship that differentiates between
the effects of a single concussion versus multiple concussions.20 A
meta-analysis of studies published prior to 2010 examined the
residual cognitive effects of multiple concussions but did not
examine the effects of a single previous concussion.9 This
meta-analysis included 8 studies reporting on 7 different cognitive
domains obtained from multiple cognitive testing batteries.3 The
differences in the psychometric properties of the testing batteries
coupled with the small number of reviewed studies (n = 8)
assessing multiple cognitive domains (k = 7) may have obscured
any actual cognitive differences in selective constructs of
neurocognitive function (eg, reaction time, verbal memory, etc.).2
Previous research suggests that cognitive effects of concussion
are construct specific, and therefore, an aggregated effect size
among multiple cognitive domains may dilute construct-specific
cognitive changes. For instance, although a previous analysis
demonstrated no significant aggregated cognitive declines after
concussion (d = 0.006), an exploratory analysis revealed lingering
effects of concussion on construct-specific domains such as
executive function (d = 0.24) and delayed memory (d = 0.16).7
The purpose of this study was to review possible cumulative effects of 1 or multiple concussions on construct-specific
baseline cognitive performance. To overcome possible
influences of multiple testing batteries, the evidence was
reviewed pertaining to a single CNT battery that systematically
collects the presence and number of previous concussions on
baseline testing, allowing for examination of our research
question. Additionally, this CNT battery was chosen because it is
the most widely used and validated CNT battery in individuals
with concussion.3 The Immediate Post-concussion Assessment
and Cognitive Test (ImPACT) has been used to quantify the
acute effects of concussions at all levels.7,14,18,50 For example,
ImPACT was used by 90% of athletic trainers in Division I
National Collegiate Athletic Association athletics.19 ImPACT
consists of 6 cognitive test modules (design memory, word
memory, symbol match, Xs and Os, color match, and 3-letter
memory). The 6 modules are utilized to generate 4 composite
scores (verbal memory, visual memory, visual-motor processing
speed, and reaction time).30,44,47,59 A number of investigations
have reported on the test’s validity and utility in identifying the
effects of concussion.25,27,61,65,66 However, several investigators
continue to be skeptical about the reliability of CNTs, including
ImPACT, and potential implications of fair to moderate reliability
on the utility of CNTs after concussion.26,55,58

METHODS

Data and Literature Sources
An electronic literature search of studies published between
January 1999 and November 2015 was completed. Studies
published before 1999 were not included in this search, as the
earlier version of ImPACT is no longer in use. The searched
databases included PubMed, CINAHL, and psycINFO. The search
terms used were the following: ImPACT OR immediate post-
concussion assessment and cognitive test OR impact testing OR
neurocognitive testing OR neurocognitive OR
neuropsychological testing OR neuropsychological AND
concussion OR mTBI OR mild traumatic brain injury OR post
concussive syndrome OR mild head injury OR closed head
injury. The search filters of English-language publications and
studies that included human participants were applied. A manual
search of the citations of reviewed studies and an electronic
search on the ImPACT test website were performed. Review
articles, abstracts, case studies, editorials, and gray literature were
excluded from the review. Gray literature was excluded because
it does not often include the necessary level of detail that allows
for thorough examination of methodological and reporting
qualities needed for inclusion in this meta-analysis.

Study Selection
Studies were included if participants completed the ImPACT test at
baseline (ie, preseason) and if performance was stratified by
history of single or multiple concussions. Studies were excluded if
they met at least 1 of the following exclusion criteria: (1) ImPACT
test modules or subscales were reported instead of composite
scores, (2) study utilized version 1.0 of ImPACT, (3) baseline scores
were not stratified by previous concussion history, or (4) ImPACT
scores were not baseline (eg, studies examining ImPACT
performance in patients currently recovering from concussion).

Data Extraction
Two reviewers identified potential studies after an independent
review of the titles and abstracts. The same 2 reviewers completed
an independent review of potential studies and extracted the data
using a piloted Microsoft Excel spreadsheet. Disagreement on the
extracted data was resolved by consensus between the 2 reviewers.
If disagreement remained, a third reviewer was consulted to
resolve the disagreement. Variables recorded included sample size,
demographic characteristics of participants, and performance of
participants on verbal memory, visual memory, visual-motor
processing speed, and reaction time of the ImPACT test.

Assessment of Reporting Quality
The reporting quality of each study was assessed using the
STROBE (Strengthening the Reporting of Observational studies
in Epidemiology) instrument.9 The STROBE instrument
addresses 22 fundamental aspects of the methods and reporting of observational studies. Each aspect was assigned a numerical value of “1” when explicitly described and a numerical value of “0” if inadequately described or absent. As such, a total score out of 22 was reported, with higher STROBE scores reflecting better reporting quality.55 Because of the potential disparity that can exist in the analysis based on the specific scale employed,38 reporting quality scores were not used as weights (ie, moderators) in the pooled analysis.

Statistical Analysis

Assessment of Heterogeneity

Heterogeneity refers the extent of variability between studies. Statistical tests are used to quantify the degree of heterogeneity between studies. In this meta-analysis, heterogeneity was assessed using the Q statistic as a test of the null hypothesis of homogeneity, examined at the null P value of P < 0.10. The I² index was used to estimate the degree of heterogeneity present across studies when the null hypothesis was rejected at P < 0.10.32,33 Higgins and Thompson32 described I² values in interpretation of magnitude as percentages of 25% (I² = 25), 50% (I² = 50), and 75% (I² = 75), indicating low, medium, and high heterogeneity, respectively. Given that the purpose of this meta-analysis is to generalize the findings to the overall population, we utilized the random-effects model to account for possible interstudy heterogeneity.

Assessment of Publication Bias

Because studies documenting positive findings are more likely to be published compared with studies with negative findings, meta-analyses can be subject to publication bias. In this meta-analysis, publication bias was examined by visual inspection of the funnel plots. For outcomes where funnel plots indicated asymmetry as potential evidence of publication bias, the Egger regression intercept test (beta coefficient, t value, P value) was used against a 1-tailed test (P < 0.05). Statistical evidence of publication bias was further investigated using the nonparametric data augmentation trim and fill method described by Duval and Tweedie.22

Mean Differences and Effect Size Calculations

To examine the possible chronic effects of concussion, a pooled random-effects analysis was completed where the ImPACT composite scores for participants with 1 concussion (μ̂₁) and for participants with 2 or more concussions (μ̂₂) were compared with participants reporting no previous concussions (μ̂₀).

Effect size (ES) is a calculation that allows researchers to describe the size of an effect beyond the level of statistical significance.51 Effect size provides interpretable data that are independent of units of measurement and influence of sample size.51 The effect size (ie, Hedges g) of concussion history groups was calculated by subtracting the mean score of the individuals with a history of concussion (μ̂₁ or μ̂₂) from the mean scores of individuals without a history of concussion (μ̂₀). The differences between groups were then divided by the pooled standard deviation. A positive effect size for verbal memory, visual memory, and visual-motor processing speed indicates that participants with no concussion exhibited better baseline scores when compared with participants with concussion history. A positive effect size for reaction time indicates that participants with no concussion history exhibited worse baseline scores when compared with participants with concussion history. All effect sizes were adjusted using the Hedges sample size bias correction before being entered in the analysis.51 The Hedges g effect sizes were interpreted as small (g ≤ 0.2), medium (g = 0.2-0.5), and large (g ≥ 0.8).13 All statistical analyses were completed using R statistical software with the Metafor package.64

To examine whether the results of the meta-analysis were influenced by 1 study, a leave-1-out estimation sensitivity analysis was completed. During this analysis, 1 study was dropped, and the parameters were then estimated without it.16

RESULTS

Identification of Studies

The initial search identified 5968 studies. After removal of duplicates (n = 321), 5647 abstracts were screened by 2 reviewers. The majority of the identified studies included the word “impact,” which is unrelated to the acronym “ImPACT” that is the subject of this review. After reviewing full texts, 17 samples that were obtained from 13 studies were included in the quantitative analysis to examine the effects of 1 and of multiple concussions on baseline ImPACT performance (Figure
1). Participants included 2423 without concussion history, 877 participants with 1 concussion, and 578 participants with multiple concussions. Participants included high school-aged athletes, college-aged athletes, and professional athletes.

Quality Scores and Heterogeneity Assessment

The reporting quality for the studies examined was moderate to high, with STROBE scores ranging from 17 to 21 (Table 1). The heterogeneity observed for the ImPACT scores was low to medium, ranging from 0% to 35.4% for the analysis of 1 concussion and from 20.7% to 53.5% for the analysis of multiple concussions (Table 2).

Publication Bias

The Egger regression intercept test suggested that there were no asymmetries present for the effects of 1 concussion (Table 2). However, visual inspection of funnel plots suggested a possible asymmetry for verbal memory and for visual memory (see Figure A1 in the Appendix, available in the online version of this article). After filling for potential missing studies (see Figure A2 in the Appendix), the effects of 1 concussion did not differ from the effects reported below. For the analysis of multiple concussions, the Egger regression intercept test suggested that there were no asymmetries present (see Figure A3 in the Appendix). Nonetheless, the Duval and Tweedie trim and fill method was used and revealed that all effects remain insignificant, even after adjustment for several possible missing studies (see Figure A4 in the Appendix).

Effects of Concussion History on Baseline ImPACT Performance

With the exception of visual memory, no significant mean differences (Table 2) and no significant effect sizes were observed between patients with a history of 1 concussion (n = 877) when compared to participants with no concussion history (n = 2423) (Figure 2a, 2c, and 2d). Participants with 1 previous concussion demonstrated a significantly worse visual memory score (mean difference, 1.31; \( P = 0.006 \)) when compared with...
Table 2. Assessment of heterogeneity, publication bias, and mean differences in baseline ImPACT scores among concussion history groups

| Test Category                | Cochran Q, \(P\) Value | \(I^2\)  | Egger Regression Intercept Test | Parameter | Parameter Estimate (95%CI) | SE   | \(P\) Value |
|------------------------------|-------------------------|---------|---------------------------------|-----------|---------------------------|------|-------------|
| **Differences between participants with no concussion and participants with 1 concussion** |                        |         |                                 |           |                           |      |             |
| Verbal memory                | 9.8, 0.6                | 0%      | \(t = 1.45, P = 0.17\)          | \(\tau_1^2\) | 0.00                      | 0.58 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_1\) | 0.25 (-0.47, 0.97) | 0.37 | 0.502       |
| Visual memory                | 9.98, 0.6               | 0%      | \(t = 0.54, P = 0.60\)          | \(\tau_1^2\) | 0.00                      | 0.93 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_1\) | 1.31 (0.39, 2.23)    | 0.47 | 0.006       |
| Visual-motor processing speed| 17.43, 0.1              | 9.0%    | \(t = 1.30, P = 0.22\)          | \(\tau_1^2\) | 0.12                      | 0.39 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_1\) | 0.49 (-0.09, 1.07)   | 0.29 | 0.098       |
| Reaction time                | 16.81, 0.2              | 35.4%   | \(t = -0.45, P = 0.66\)         | \(\tau_1^2\) | 0.82                      | 0.99 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_1\) | -0.47 (-1.28, 0.35)  | 0.42 | 0.262       |
| **Differences between participants with no concussion and participants with 2 or more concussions** |                        |         |                                 |           |                           |      |             |
| Verbal memory                | 38.83, 0.001            | 53.5%   | \(t = 0.72, P = 0.48\)          | \(\tau_2^2\) | 5.64                      | 3.41 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_2\) | 0.71 (-0.80, 2.22)   | 0.77 | 0.356       |
| Visual memory                | 29.61, 0.02             | 28.9%   | \(t = -0.21, P = 0.84\)         | \(\tau_2^2\) | 3.63                      | 3.46 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_2\) | -0.07 (-1.62, 1.49)  | 0.80 | 0.934       |
| Visual-motor processing speed| 20.83, 0.2              | 20.7%   | \(t = 0.81, P = 0.43\)          | \(\tau_2^2\) | 0.84                      | 1.05 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_2\) | 0.17 (-0.70, 1.04)   | 0.44 | 0.702       |
| Reaction time                | 34.16, 0.005            | 45.4%   | \(t = -1.26, P = 0.23\)         | \(\tau_2^2\) | 2.35                      | 1.72 | —           |
|                              |                         |         |                                 | \(\mu_0 - \mu_2\) | 0.00 (-0.70, 1.04)   | 0.55 | 0.997       |

participants with no concussion history (Table 2). However, closer inspection revealed a small effect size (Hedges \(g = 0.10; P = 0.012\)) (Figure 2b).

The comparison between participants with no concussion (\(n = 2423\)) when compared with participants with 2 or more concussions (\(n = 578\)) revealed no significant mean differences on any of the ImPACT scores (Table 2). Similarly, the analysis of the effect sizes revealed no significant effect sizes for the history of multiple concussions on baseline ImPACT performance (Figure 3).

**DISCUSSION**

This review indicates that, with the exception of reduced visual memory in participants with 1 concussion, no differences were found in baseline ImPACT performance when comparing those with and those without concussion history. Some researchers have suggested there is a dose-response relationship between concussion history and cognitive performance. However, outside of the likely single spurious association reported here (decreased visual memory between those with and without 1 concussion), the lack of relationship between concussion history and cognitive performance in 7 of the 8 comparisons conducted in this meta-analysis (87.5%) did not support this theory. These findings are comparable to those that report no significant long-term cognitive effects in individuals with history of multiple concussions.

One of many possibilities can explain the lack of a discernible relationship between concussion history and baseline cognitive performance. First, despite the case reports demonstrating neurodegeneration of former athletes, no prospective investigation with adequate controls has demonstrated that...
these declines are present outside of a highly selective sample, which suggests that there may be no long-term cognitive consequences to concussion. Second, should long-term cognitive changes exist, they may be subtle and may not be captured using brief computerized neurocognitive tests designed to document larger cognitive effects resulting from a current concussion (eg, ImPACT). A comprehensive and individualized multifaceted cognitive examination that allows for incremental difficulties in cognitive loading may enable investigation of possible subtle long-term concussion cognitive effects. For instance, some individuals with previous concussions exhibited subtle cognitive declines when examined

---

**Figure 2.** Effect of 1 concussion on baseline ImPACT (Immediate Post-concussion Assessment and Cognitive Test) performance.
while using tasks that require greater cognitive loading. Third, all participants in the reviewed studies were adolescents or young adults. Therefore, any possible long-term changes may have been masked by cognitive reserve. Last, participants with history of concussion may have taken the test multiple times and may have experienced a learning effect that may offset possible cognitive changes.

Recent evidence demonstrated that effects of concussion are heterogeneous. Therefore, individuals with multiple concussions may experience lingering effects that are not

![Figure 3. Effect of multiple concussions on baseline ImPACT (Immediate Post-concussion Assessment and Cognitive Test) performance.](image-url)
cognitive in nature.31,37,57 This explanation is supported by previous investigations demonstrating long-term effects of concussion on functional magnetic resonance imaging (fMRI) that were not captured through cognitive task performance.31,37,57 For instance, persistent changes in electrophysiology have been demonstrated in those 3.4 years postinjury when compared with those with no concussion history, while ImPACT scores did not differ between the 2 groups.9 Utilizing other evaluative measures, such as advanced imaging and biomarkers, may provide additional understanding of possible long-term effects of multiple concussions by identifying changes in brain physiology that may not result in observable cognitive changes.7,59,68

Although this study focused on history of concussion and long-term neurocognitive decline, it should be noted that concussion history may not be the only factor pertinent to long-term neurocognitive health. Future studies should examine the cumulative effects of number and magnitude of subconcussive blows on long-term neurocognitive performance. This study is not without limitations, including the search strategy that was limited to the ImPACT test. Although the ImPACT test systematically collects injury surveillance on history and on the number of previous concussions, this information was self-reported and subject to recall bias.40 Similar to a previous meta-analysis examining cognitive declines after concussion,41 self-reported concussion history may affect the findings of this review. Because participants in all groups considered for this investigation are subject to recall bias, it is unlikely to introduce systematic bias.1 Although it would have been ideal to examine whether time between prior concussion and subsequent baseline ImPACT testing is a moderator of cumulative effects, time since injury is not reported in the majority of the retrieved studies. Additionally, many of the reviewed studies were retrospective or were completed in various testing environments that may have affected cognitive performance.42 The ImPACT test scores could be affected by suboptimal performance of test takers, which then results in invalid baseline scores.28 The ImPACT test has built-in validity indicators to document invalid baselines. However, most studies did not explicitly report that scores were examined to ensure their validity against built-in validity indicators.

CONCLUSION

With the exception of decreased visual memory based on history of 1 concussion, history of 1 or of multiple concussions was not associated with worsened baseline cognitive performance.

REFERENCES

1. Abus K, Shenk TE, Poole VN, et al. Alteration of default mode network in high school football athletes due to repetitive subconcussive mild traumatic brain injury: a resting-state functional magnetic resonance imaging study. Brain Connect. 2015;5:91-101.

2. Alsalalheen B, Stockdale K, Pechumer D, Broglio SP. Measurement error in the Immediate Postconcussion Assessment and Cognitive Testing (ImPACT): systematic review. J Head Trauma Rehabil. 2016;31:212-251.

3. Alsalalheen B, Stockdale K, Pechumer D, Broglio SP. Validity of the Immediate Post Concussion Assessment and Cognitive Testing (ImPACT). Sports Med. 2016;46:1487-1501.

4. Belanger HG, Spiegel E, Vanderploeg RD. Neuropsychological performance following a history of multiple self-reported concussions: a meta-analysis. J Int Neuropsychol Soc. 2010;16:262-267.

5. Broglio SP, Cantu RC, Gioia GA, et al. National Athletic Trainer's Association. National Athletic Trainers' Association position statement: management of sport concussion. J Athl Train. 2014;49:245-265.

6. Broglio SP, Ferrara MS, Macciocci SN, Baumgartner TA, Elliott R. Test-retest reliability of computerized concussion assessment programs. J Athl Train. 2007;42:509-514.

7. Broglio SP, Ferrara MS, Piland SG, Anderson RB, Collie A. Concussion history is not a predictor of computerised neurocognitive performance. Br J Sports Med. 2006;40:802-805.

8. Broglio SP, Macciocci SN, Ferrara MS. Sensitivity of the concussion assessment battery. Neuropsychol. 2007;60:1050-1057.

9. Broglio SP, Pontifex MB, Cvitkovitch D, Hillman CH. The persistent effects of concussion on neuroelectric indicators of attention. J Neurotrauma. 2009;26:1463-1470.

10. Broglio SP, Pratz TW. The effect of sport concussion on neuropsychometric function, self-report symptoms and postural control: a meta-analysis. Sports Med. 2008;38:53-67.

11. Brooks BS, McKay CD, Muzik M, Barlow KM, Meuwese WH, Emery CA. Subjective, but not objective, lingering effects of multiple past concussions in adolescents. J Neuroltrauma. 2013;30:1469-1475.

12. Chen JK, Johnston KM, Frey S, Petrides M, Wosley K, Pito A. Functional abnormalities in symptomatic concussion: athletes with an MRI study. Neuroimage. 2004;22:68-82.

13. Cohen J. Statistical Power Analysis for the Behavioral Sciences. New York, NY: Routledge Academic; 1988.

14. Cole WR, Arieux JP, Schwab K, Ivins BJ, Qasdu FM, Lewis SC. Test-retest reliability of four computerized neuropsychological assessment tools in an active duty military population. Arch Clin Neuropsychol. 2013;28:732-742.

15. Collins MW, Kontos AP, Reynolds E, Murawski CD, Fu FH. A comprehensive, targeted approach to the clinical care of athletes following sport-related concussion. Knee Surg Sports Traumatol Arthrosc. 2014;22:235-246.

16. Cooper H, Hedges L, Valentine J. Handbook of Research Synthesis and Meta-Analysis. New York, NY: Russell Sage Foundation; 2009.

17. Covassin T, Elbin R, Kontos A, Larson E. Investigating baseline neurocognitive performance between male and female athletes with a history of multiple concussion. J Neurol Neurosurg Psychiatry. 2010;81:597-601.

18. Covassin T, Elbin R III, Stiller-Ostrowski JL. Current sport-related concussion teaching and clinical practices of sports medicine professionals. J Athl Train. 2009;44:400-404.

19. Covassin T, Morran R, Wilhelm K. Concussion symptoms and neurocognitive performance of high school and college athletes who incur multiple concussions. Am J Sports Med. 2013;41:2889-2899.

20. Covassin T, Seume D, Elbin R. Concussion history and postconcussion neurocognitive performance and symptoms in collegiate athletes. J Athl Train. 2008;43:119-124.

21. Dean PJ, Stern A. Long-term effects of mild traumatic brain injury on cognitive performance. Front Hum Neurosci. 2013;7:30.

22. Duval S, Tweedie R. Trim and fill: a simple funnel-plot-based method of testing for publication bias in meta-analysis. J Res Mkt Res. 2000;56:455-463.

23. Elbin RJ, Covassin T, Hakim J, et al. Do brain activation changes persist in athletes with a history of multiple concussions who are asymptomatic? Brain Inj. 2012;26:1217-1225.

24. Ellis MJ, Leddy JI, Willer B. Physiological, vestibulo-ocular and cervicovagal post-concussion disorders: an evidence-based classification system with directions for treatment. Brain Inj. 2015;29:239-248.

25. Fritz CO, Morris PE, Richter JR. Effect size estimates: current use, calculations, and interpretation. J Exp Psychol Gen. 2012;141:2-18.

26. Gardner A, Shores EA, Batchelor J. Reduced processing speed in rugby union players reporting three or more previous concussions. Arch Clin Neuropsychol. 2010;25:174-181.

27. Gardner A, Shores EA, Batchelor J, Hornan CA. Diagnostic efficiency of ImPACT and CogSport in concussed rugby union players who have not undergone baseline neurocognitive testing. Appl Neuropsychol Adult. 2012;19:99-107.

28. Gaudet CE, Weyandt LL. Immediate Post-Concussion and Cognitive Testing (ImPACT): a systematic review of the prevalence and assessment of invalid performance. Clin Neuropsychol. 2017;31:43-58.

29. Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. JAMA. 2003;290:2549-2555.
30. Hedges L, Olkin I. *Statistical Methods for Meta-Analysis*. Orlando, FL: Academic Press; 1985.
31. Henry LC, Elbin RJ, Collins MW, Marchetti G, Kontos AP. Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*. 2016;78:232-241.
32. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med*. 2002;21:1539-1558.
33. Huedo-Medina TB, Sánchez-Meca J, Marín-Martínez F, Botella J. Assessing heterogeneity in meta-analysis: Q statistic or I² index? *Psychol Methods*. 2006;11:193-206.
34. Iverson GL, Brooks BL, Lovell MR, Collins MW. No cumulative effects for one or two previous concussions. *Br J Sports Med*. 2006;40:72-75.
35. Iverson GL, Echemendia RJ, Lamarr AK, Brooks BL, Gaetz MB. Possible lingering effects of multiple past concussions. *Rehabil Res Pract*. 2012;2012:316575.
36. Iverson GL, Lovell MR, Collins MW. Validity of ImPACT for measuring processing speed following sports-related concussion. *J Clin Exp Neuropsychol*. 2005;27:683-689.
37. Jantzen KJ, Anderson B, Stenbergl FG, Kelso JA. A prospective functional MR imaging study of mild traumatic brain injury in college football players. *AJNR Am J Neuroradiol*. 2014;25:758-765.
38. Juni P, Witschi A, Bloch R, Egger M. The hazards of scoring the quality of clinical trials for meta-analysis. *JAMA*. 1999;282:1054-1060.
39. Karantouzis S, Randolph C. Modern chronic traumatic encephalopathy in retired athletes: what is the evidence? *Neuropsychol Rev*. 2013;23:350-360.
40. Kerr ZY, Mihalik JP, Guskiewicz KM, Johnston KM, Bradley JP. Agreement between athlete-recalled and clinically documented concussion histories in former collegiate athletes. *Am J Sports Med*. 2015;43:606-615.
41. Kontos AP, Braithwaite R, Dakan S, Elbin RJ. Computerized neurocognitive testing within 1 week of sport-related concussion: meta-analytic review and analysis of moderating factors. *J Int Neuropsychol Soc*. 2014;20:324-332.
42. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil*. 2006;21:375-378.
43. Lichtenstein JD, Moser RS, Schatz P. Age and test setting affect the prevalence of invalid baseline scores on neurocognitive tests. *Am J Sports Med*. 2014;42:479-484.
44. Lovell MR, Collins MW, Iverson GL, Johnston KM, Bradley JP. Grade 1 or ‘ding’ concussions in high school athletes. *Am J Sports Med*. 2004;32:47-54.
45. Maerlender A, Flashman L, Kessler A, et al. Discriminant construct validity of ImPACT: a companion study. *Clin Neuropsychol*. 2013;27:290-299.
46. Maerlender A, Flashman L, Kessler A, et al. Examination of the construct validity of ImPACT: computerized test, traditional, and experimental neuropsychological measures. *Clin Neuropsychol*. 2010;24:1309-1325.
47. Manon JC, Lovell MR, Noeig J, Poddell K, Powell JW, Hart R. Cerebral concussion in athletes: evaluation and neuropsychological testing. *Neurosurgery*. 2000;47:659-669.
48. McKay CD, Brooks BL, Mrazik M, Jubenville AL, Emery CA. Psychometric properties and reference values for the ImPACT neurocognitive test battery in a sample of elite youth ice hockey players. *Arch Clin Neuropsychol*. 2014;29:141-151.
49. Meehan WP III, d’Hemecourt P, Collins CL, Taylor AM, Comstock RD. Computerized neurocognitive testing for the management of sport-related concussions. *Pediatrics*. 2012;129:56-61.
50. Moore RD, Pardini DA, Scudder MR, Raine LB, Hillman CH. The persistent influence of pediatric concussion on attention and cognitive control during flanker performance. *Biol Psychol*. 2015;105:93-102.
51. Moser RS, Schatz P, Jordan BD. Prolonged effects of concussion in high school athletes. *Neurosurgery*. 2005;57:800-806.
52. Nelson LD, LalRoeche AA, Pfaller AT, et al. Prospective, head-to-head study of three computerized neurocognitive assessment tools (CNTs): reliability and validity for the assessment of sport-related concussion. *J Int Neuropsychol Soc*. 2016;22:24-37.
53. Nelson NA, DeKosky ST, Hamilton RL, et al. Chronic traumatic encephalopathy in a National Football League player: part II. *Neurosurgery*. 2006;59:1086-1092.
54. Omalu BI, DeKosky ST, Hamilton RL, et al. Chronic traumatic encephalopathy in a National Football League player: part II. *Neurosurgery*. 2006;59:1086-1092.
55. Orr CA, Allbaugh MD, Watts R, et al. Neuroimaging biomarkers of a history of concussion observed in asymptomatic young athletes. *J Neurotrauma*. 2016;33:803-810.
56. Pardini JE, Pardini DA, Becker JT, et al. Postconcussive symptoms are associated with compulsory cortical recruitment during a working memory task. *Neurosurgery*. 2010;67:1020-1027.
57. Resch J, Driscoll A, McCaffrey N, et al. ImPact test-retest reliability: reliably unreliable? *J Athl Train*. 2013;48:506-511.
58. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol*. 2006;21:91-99.
59. Solomon GS, Haase RF. Biopsychosocial characteristics and neurocognitive test performance in National Football League players: an initial assessment. *Arch Clin Neuropsychol*. 2008;23:565-577.
60. Solomon GS, Haase RF, Kuhn A. The relationship among neurocognitive performances and biopsychosocial characteristics of elite National Football League draft picks: an exploratory investigation. *Arch Clin Neuropsychol*. 2013;28:9-20.
61. Solomon GS, Kuhn A. Relationship between concussion history and neurocognitive test performance in National Football League draft picks. *Am J Sports Med*. 2014;42:934-939.
62. Van Kampen DA, Lovell MR, Pardini JE, Collins MW, Fu FH. The ‘value added’ of neurocognitive testing after sports-related concussion. *Am J Sports Med*. 2006;34:1630-1635.
63. Viechtbauer W. Conducting meta-analyses in R with the metafor package. *J Stat Softw*. 2010;36:1-48.
64. von Elm E, Altman DG, Egger M, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement guidelines for reporting observational studies. *Ann Intern Med*. 2007;147:575-577.

For reprints and permission queries, please visit SAGE’s Web site at http://www.sagepub.com/journalsPermissions.nav.